

COMPARATIVE STUDY OF AXIAL BEARING CAPACITY FOR PILE FOUNDATION BASED ON EMPIRICAL, NUMERICAL METHOD AND PILE DRIVING ANALYZER TEST

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Abstract: Axial bearing capacity is an important factor in designing of foundation. It must be able to carry the load of upper structure without any significant deformation due to important role in pile design. A part from empirical and numerical methods, axial pile bearing capacity can be predicted by pile driving analyzer test that use wave equation analysis during the test. Prediction of the axial bearing capacity and its distribution can be achieved by combining wave equation analysis with dynamic pile monitoring. This paper compares the axial capacity of pile obtained from PDA records with predicted axial capacities obtained using empirical, numerical, and interpretation of static load test method. The empirical method used NSPT data from bore testing that conduct in site, finite element method that uses in this study is Plaxis 8.6. Both of them was compared with PDA test result of axial bearing capacity. There is a difference value of the calculation results of axial pile bearing capacity and foundation settlement. Comparing with PDA, from empirical method has smallest deviation for axial bearing capacity which equal to -268.45 kN with percentage -6.05%, smallest settlement equal to 0,0044 m. Plaxis result shows that distinction between Qult result equal to -11.00 kN with percentage -0.24% and settlement of foundation equal to 0,005 m. From interpretation of static loading test method smallest deviation for Qult which equal to -40,00 kN, with percentage -0,90%, and smallest settlement equal to 0,0055 m. So, from all method the smallest deviation for Qult and PDA result is used finite element method. This is due to many data parameters has been inputted and analyzed in the Plaxis program, so the results of calculation analysis are more detailed and closer to the situation in the research site. Differences in axial bearing capacity can be caused by the test was carried out which depends on the accuracy of operator and parameters that used in the calculations.

Keywords: Axial bearing capacity, empirical method, static load testing method, finite element method, PDA

ИССЛЕДОВАНИЕ НЕСУЩЕЙ СПОСОБНОСТИ СВАЙ НА ОСНОВЕ ЭМПИРИЧЕСКИХ ДАННЫХ, ДИНАМИЧЕСКИХ ИСПЫТАНИЙ И ЧИСЛЕННОГО МОДЕЛИРОВАНИЯ

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Аннотация: Несущая способность на вдавливание является важным фактором при проектировании фундамента. Он должен нести нагрузку от сооружения без значительных деформаций. Помимо эмпирических и численных методов, несущая способность свай на вдавливание может быть предсказана с помощью анализатора забивки свай PDA, принцип работы которого основан на оценке параметров волнового уравнения во время испытаний. Прогнозирование несущей способности на вдавливание и ее распределения может быть выполнено путем оценки параметров волнового уравнения при динамическом мониторинге забивки свай. В данной работе сравнивается несущая способность свай на вдавливание, полученная по данным PDA, с эмпирическими данными, результатами численного моделирования и испытаний статической нагрузкой. Эмпирические данные о несущей способности NSPT были получены по результатам испытаний в скважинах. Численное моделирование выполнено по методу конечных элементов в программном комплексе Plaxis 8.6. Полученные результаты сравнивались с результатами испытаний PDA несущей способности на вдавливание. Выявлено, что результаты расчетов несущей способности свай на вдавливание и осадки фундамента по различным методам оценки различаются. По сравнению с PDA, эмпирический метод имеет наименьшее отклонение, которое составило -268.45 кН или -6.05%. Наименьшая осадка равна 0,0044 м. Результат моделирования в Plaxis показывают, что различие между результатом Qult составило -11.00 кН или -0.24%. Осадка фундамента при этом равна 0,005 м. Для метода статического нагружения наименьшее отклонение Qult было -40,00 кН или -0,90%. А наименьшая

осадка составила 0,0055 м. Таким образом, из всех методов наименьшее отклонение для Qult по сравнению с данными динамических испытаний, выполненных с использованием PDA, имеет метод конечных элементов. Это связано с тем, что использовалось большое число исходных параметров, которые были введены в программе Plaxis. Поэтому результаты расчетного анализа более детальны и приближены к ситуации на объекте исследования. Различия в несущей способности на продавливание могут быть вызваны тем, какие именно испытания проводились. Это зависит от квалификации оператора и параметров, которые используются в расчетах.

Ключевые слова: несущая способность на вдавливание, эмпирический метод, метод статических испытаний, метод конечных элементов, Pile driving analyzer (PDA)

INTRODUCTION

Foundation is the main structure that very important in every building construction, and has function to transmitting load of upper structure to the soil layer below. In some cases, foundations are insufficient to support the structural load, and deep foundations are required [1]. Various type of deep foundations is classified into categorized according to geologic condition, installation method, structural material, ground effect, function, cross-section, loading, isolation, inclination, and other characteristics [2]. Axial pile bearing capacity is a maximum vertical axial load on foundation that can support before it reaches the ultimate capacity. To determine axial pile bearing capacity it can be use empirical and numerical method. The use of different design methods, resulting in various estimates of axial bearing capacity, selection of appropriate and accurate design schemes to minimize errors due to axial bearing capacity predictions are required [3]. Estimation of the axial bearing capacity has an important role in pile design. Part of semi-empirical and numerical methods, the axial bearing capacity of piles can be predicted through static loading tests and dynamic load test [4]. Several studies compared pile bearing capacity of analytical and field test [5], [6], [7]. One of common method used to measure and analyze the dynamic response of piles is PDA. The results show that PDA data can provide the best prediction of axial pile bearing capacity. Subsequent research discussed the pile bearing capacity using PDA and CAPWAP, which is standard practice for testing offshore piles [8]. Testing of piles under axial loads has been

carried out on in-situ piles. Simulation has carried out for a single pile with axial load at the top of pile, so it can be evaluate the settlement of the pile [9].

Various analytical, numerical and software approaches using Plaxis 2D software, with design results of more than 30 heaps, for the piles analyzed the largest relative error between theoretical and numerical method in this study was around 14%, these errors can be reduced significantly by modifying the meshing and making it smoother [10]. Analysis in plaxis software use several model parameters such as Mohr-Coulomb, soft soil, hard soil, and many more [11].

The problem of predicting and assessing pile bearing capacity is complex. The most important thing is to determine the method used to predict and evaluate pile bearing capacity based on the level of accuracy and consistency values required [12]. Knowing the characteristics of the axial bearing capacity of concrete piles embedded in soil layer is important before carrying out tests [13].

This study was conducted to compare the axial pile bearing capacity of foundation with several methods. Empirical method formulated of geotechnical expert, numerical method of finite element method (FEM) and interpretation of static load testing method. All of them were compared and validated with PDA test result in research location.

METHODS

This study is located in Cirebon, West Java, Indonesia. The method of studies is divided into

several stages. First stage is the analysis and data processing based on Standard Penetration Test (SPT) using empirical methods and soil parameters through laboratory tests. At this stage it calculates axial pile bearing capacity using empirical formula developed by, Luciano Decourt, Meyerhoff, Briaud et al and Shioi & Fukui. Two problems arise when determining soil qualities through laboratory testing: (1) Difficulties in obtaining an "undisturbed" soil sample, and (2) sample size limitations. Data from in-situ test such as Standard Penetration Test (SPT) indicate a significant amount of soil. The test is relatively simple and data information is easy to obtain during the site investigation. The cross-section of soil layers in this study can be shown in the Figure 1.

Second stage is the modeling stage using numerical method. At this stage Finite Element Method (FEM) modeling with Plaxis software using Mohr-Coloumb. Soil parameters that used in this program are young's modulus (E), Poisson ratio (ν), unit weight of saturated soil (γ_{sat}), unit weight of unsaturated soil (γ_{unsat}), Cohesion (c), friction angle (ϕ), and dilatation angle (ψ). Result from this modeling is axial bearing capacity, soil settlement, and safety factor.

Third stage is interpretation of static load test method using Mazurkiewicz (1972) and Davisson (1973). The final stage is to compare both analytical, numerical, and static load test method by Pile Driving Analyzer that conducted in this research location.

RESULTS AND DISCUSSION

The soil test data for this study were collected from a project that located in Cirebon, West Java, Indonesia. Prestressed concrete pile type spun pile with diameter 600 mm and 35 m length. Site investigation data includes laboratory tests data, material properties from SPT within 70.45 m depth.

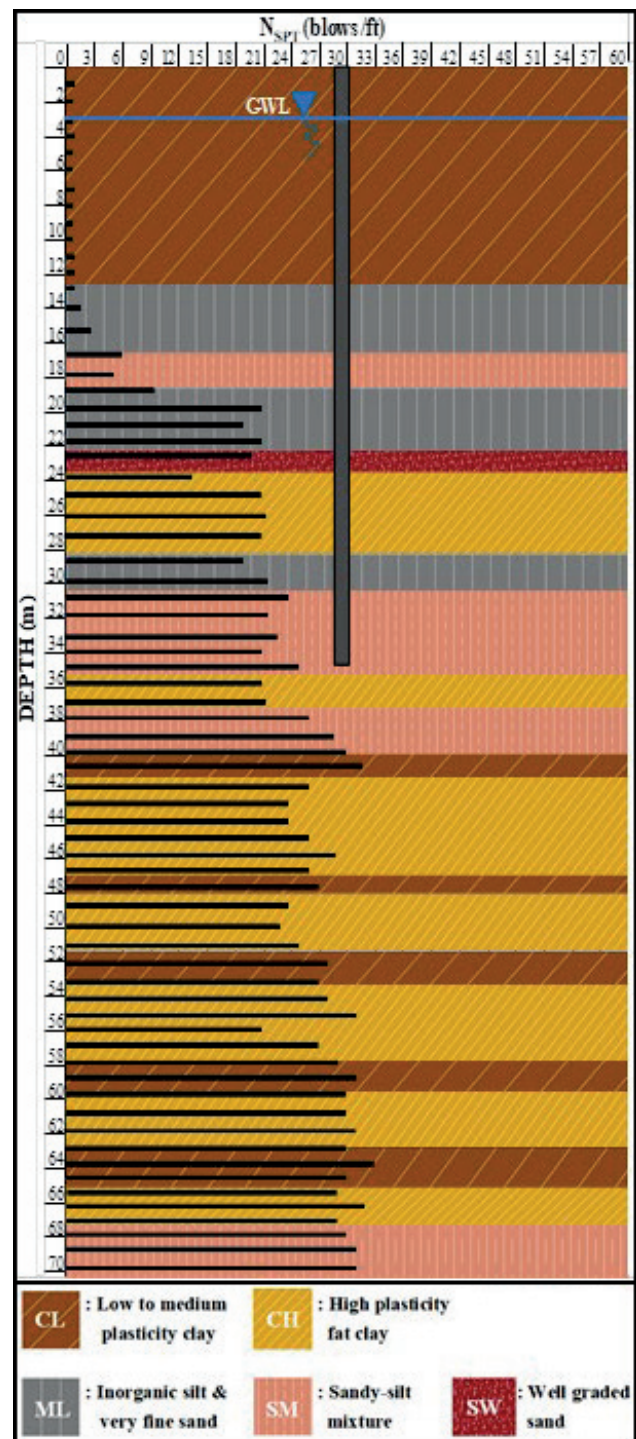


Figure 1. Cross-section profile of soil layer

Empirical Method

Empirical method of Luciano Decourt (1982), Meyerhoff (1956), Briaud et al (1985), and Shioi & Fukui (1982) are utilized in this study can be shown in Table 1 and Figure 2.

Table 1. Axial pile bearing capacity based on empirical method

Empirical Method	Axial Pile Bearing Capacity			PDA Test	Deviation	
	End Bearing	Skin Resistance	Total Axial Capacity		Q _{ult}	Q _{ult}
	Q _p (kN)	Q _s (kN)	Q _{ult} (kN)		(kN)	(%)
L. Decourt (1982)	1.696,46	3.653,91	5.350,37	4.440	910,37	20,50
Meyerhoff (1956)	2.375,04	1.796,51	4.171,55		268,45	-6,05
Briaud et al (1985)	1.722,19	3.151,27	4.873,46		433,46	9,76
Shioi & Fukui (1982)	195,09	1.796,51	1.991,60		2,448,40	-55,14

The ultimate axial pile bearing capacity (Q_{ult}) based on the planning design is 4,500 kN. PDA testing was carried out three times. This because during first PDA test, the axial bearing capacity result had a high difference from the design plan, so a re-test was carried out. From the results of PDA test, the Q_{ult} value of 4,440 kN is used as a reference for compare the bearing capacity of empirical and numerical methods. From the result above Luciano Decourt method has Q_{ult} equal to 5,350.37 kN, is the highest value compared to other methods, because soil coefficient is used as a multiplier.

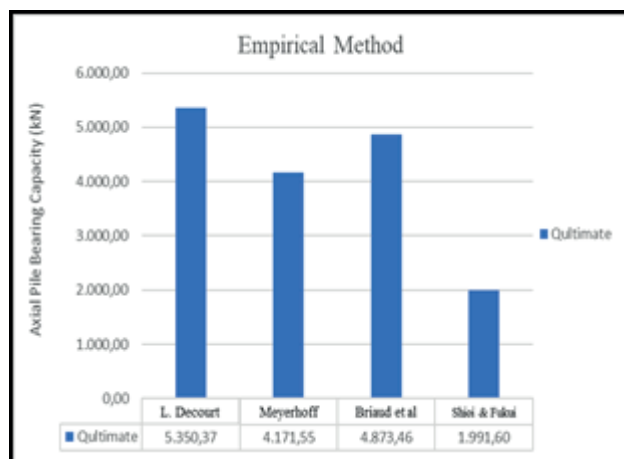


Figure 2. Graph of Axial Pile Bearing Capacity Calculation Based on NSPT Data (Empirical Method)

Compared with PDA test result, based on the calculation analysis of the axial bearing capacity of the empirical method above, the Meyerhoff method has the smallest deviation, with value -268.45 kN and percentage of 6.05%, Briaud et al method has a deviation 433.46 kN with a percentage of 9.76%, followed by the L. Decourt method with a deviation 910.37 kN and a percentage of 20.50%. The biggest deviation is using the Shioi & Fukuni method with a value of -2,298.40 kN and a deviation percentage of -55.14%.

Meyerhoff method is usually used on non-cohesive soils or sandy soils, based on the results of borelog testing of the soil layers at the research study, which are classified as soft soils. The borelog test was carried out to a depth of 70.45 m, the composition ratio of soft soil and sandy soil layers was 68% for soft soil and 32% for sandy soil. The pile foundation used in this study has a length of 35 m. The composition of the layers of soft soil and sandy soil along the foundation is 50% for soft soil and 50% for clay, this affects the analysis of the empirical method used. Pile was embedded in a layer of sandy soil at 35 m depth, so Meyerhof method can be used in this research study, and has the smallest difference compare with other empirical formula validated by Pile Driving Analyzer test result.

Finite Element Method (FEM)

FEM is numerical method that divides a problem into a finite number of elements to represent a problem that actually has an infinite number of elements (continuum). The interactions between these small parts are determined based on the physical phenomena to be resolved. Material of soil that used in Plaxis is Mohr-Coulomb model. Parameter data for this method comes from secondary data and correlation calculations, it can be shown in Table 2.

To calculate Young's Modulus (E.) using Schmermann (1970) formula:

$$E = 766 \cdot \text{NSPT} \quad (1)$$

$$E = 2 \cdot q_c \quad (2)$$

Correlation of clay soil

Clay soil *normally consolidated* (NC)

$$E = 250 C_u - 500 C_u \quad (3)$$

Clay Soil *over consolidated* (OC)

$$E = 750 C_u - 1000 C_u \quad (4)$$

Another parameter was found from laboratory testing. Parameter profile of the pile foundation must be included during Plaxis analysis, it can be shown in Table 3.

Table 2. Mohr-Coloumb Parameter of Soil layer

Parameter	Value		Source
	1 st Soil Layer (0.00 m – 3.00 m)	4 th Soil Layer (13.00 m – 17.00 m)	
USCS Chart	CL	ML	Secondary data
Material Model	Mohr-Coulomb	Mohr-Coulomb	-
Material Behavior	Undrained	Drained	-
Unit weight of unsaturated soil (γ_{unsat})	6,68 kN/m ³	9,06 kN/m ³	Calculation
Unit weight of saturated soil (γ_{sat})	14,90 kN/m ³	15,00 kN/m ³	Secondary data
Young's Modulus (E)	3125 kN/m ²	2298 kN/m ²	Correlation and calculation
Poisson Ratio (ν)	0,2	0,3	Secondary data
Cohesion (c)	6,25 kN/m ²	0,35 kN/m ²	Secondary data
Friction ratio (ϕ)	18,87°	21,71°	Secondary data
Dilatation angle (ψ)	0°	0°	

Table 3. Pile foundation specification

Parameter	DP6	Unit
Pile Test No	DP6-7	
Foundation Type	Spun PC-Pile	mm
Diameter	600	mm
Thickness	100	mm
Length	35	m
Area	0,28	m ²
Modulus Elasticity	33.892.182	kN/ m ²
Fc' of Pile	52	Mpa
Allowable stress	15,49	Mpa

Allowable compressive stress	38	Mpa
E	33892182	kN
I	5,2 x 10 ⁻⁴	m ⁴
EI	17457,46	kNm ² /m
EA	9582789	kNm ² /m
W	3,768	kN/m
V	0.2	

Based on the results of the Plaxis analysis, the allowable pile bearing capacity (Qall), settlement, safety factor (MSF), load-deformation curves are obtained. The results of the analysis can be seen in Figure 3.

Based on the results of the plaxis analysis, the Qall value equal to 3.720 kN and the MSF equal to 1.1906. So to get the value of the axial bearing capacity (Qult) using the formula :

$$\begin{aligned} Q_u &= Q_{all} \times \Sigma MSF \\ &= 3.720 \times 1.1906 \\ &= 4.429 \text{ kN.} \end{aligned}$$

Compared with the axial bearing capacity (Qult) from the PDA test results of 4,440 kN, the Qult deviation is very small, equal to -11.00 kN with a percentage of -0.24%.

By using plaxis, deformation occurs on the soil layer can be determined. Figures 4 and 5 shows the typical deformation that occurs in soil due to loading on continuous foundation. On the left and right side of the foundation there is heaving, i.e, ballooning. This is due to the soil under the foundation pushed in all directions, which is eventually it will also push the ground above it. Pile foundation with a diameter of 0.6 m and a length of 35 m, deformation of 0.005 m will occur in the soil layer around pile. Effective stress from plaxis can be shown in Figure 6.

Plaxis analysis can be used as a modeling pile load test at the study site. The relationship curve between the total multiplier load (Sum-Mload) and settlement can be seen in Figure 7. Based on the curve, the ultimate Sum-Mload is 66.419.

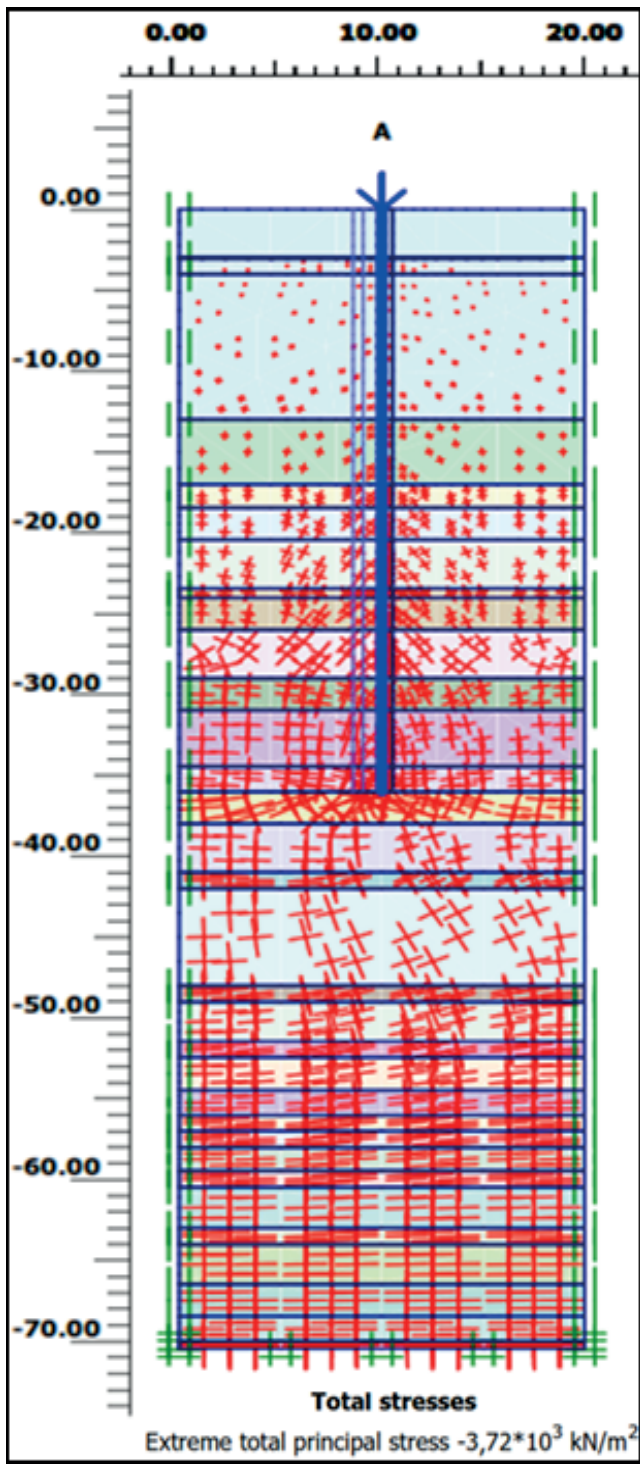


Figure 3. Allowable pile bearing capacity (Q_{all})

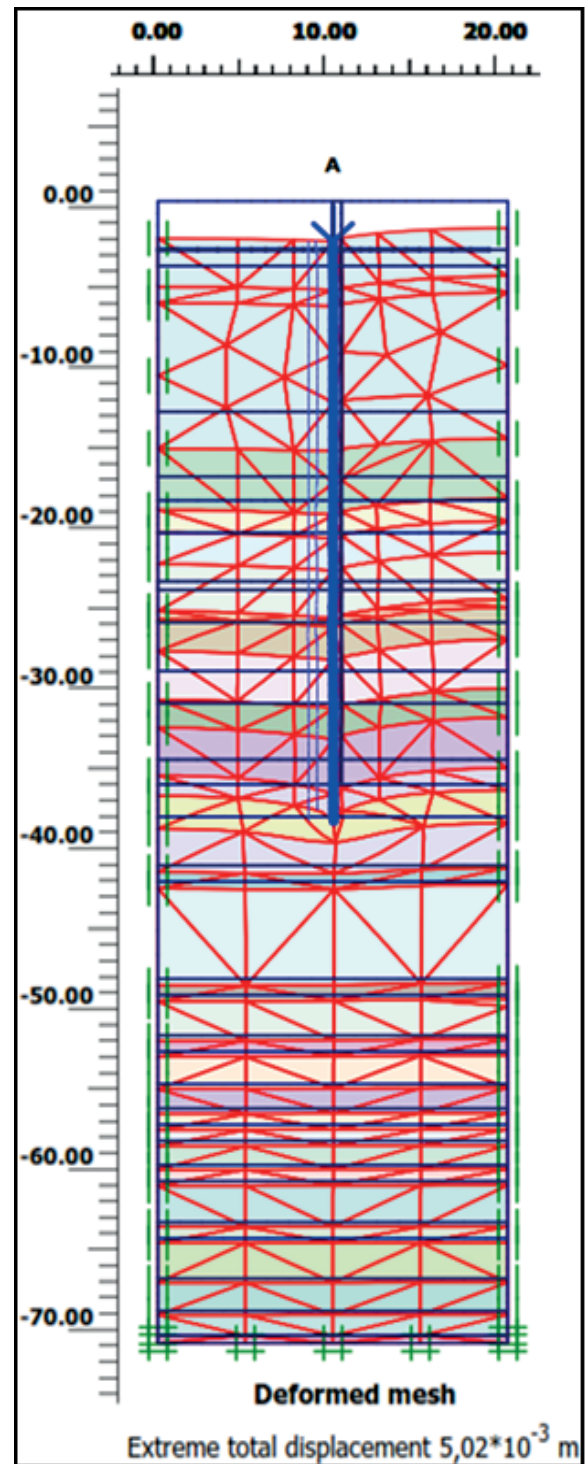


Figure 4. Soil deformation due to pile foundation loads

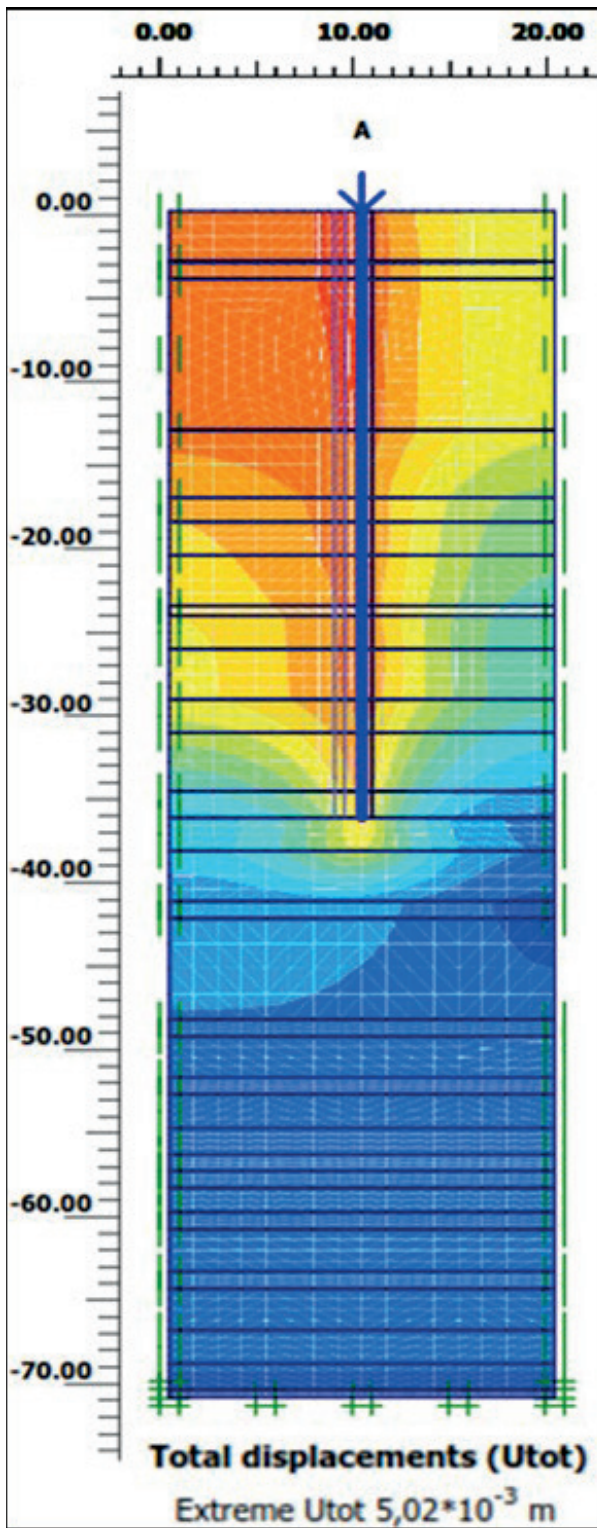


Figure 5. Soil deformation

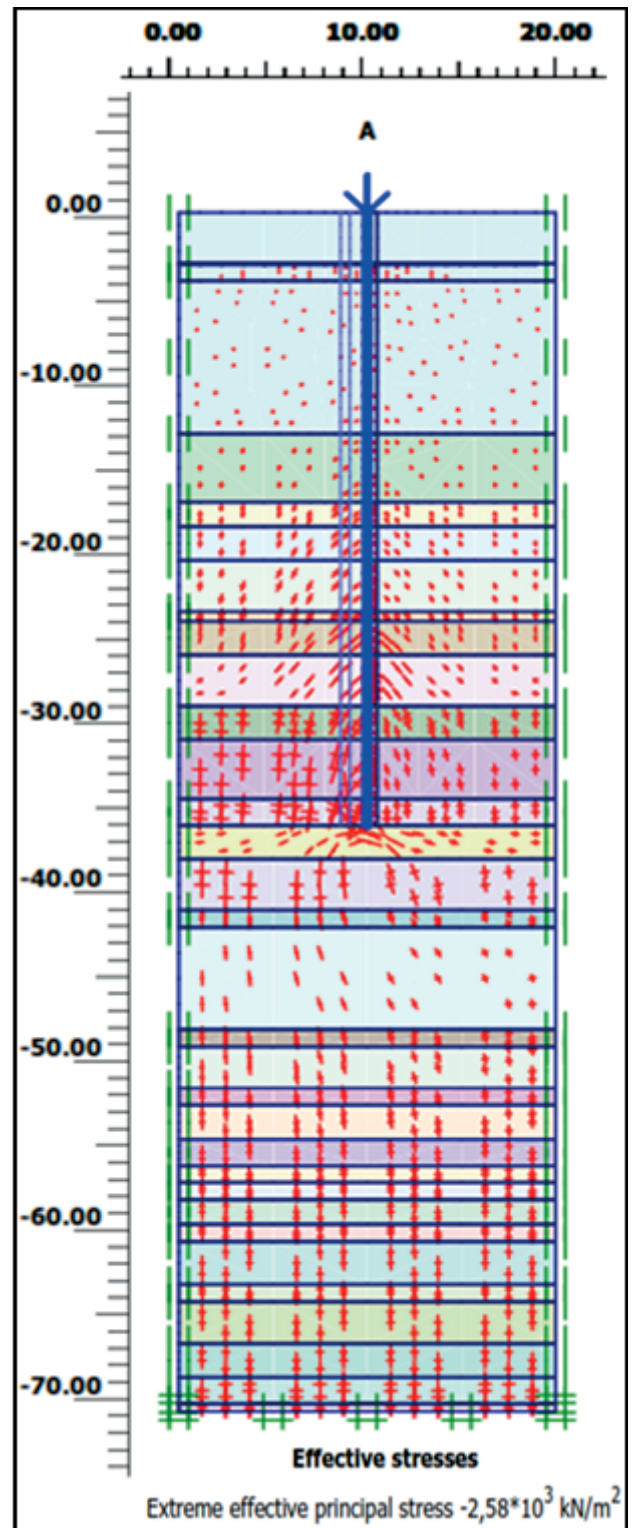


Figure 6. Effective stress from Plaxis analysis

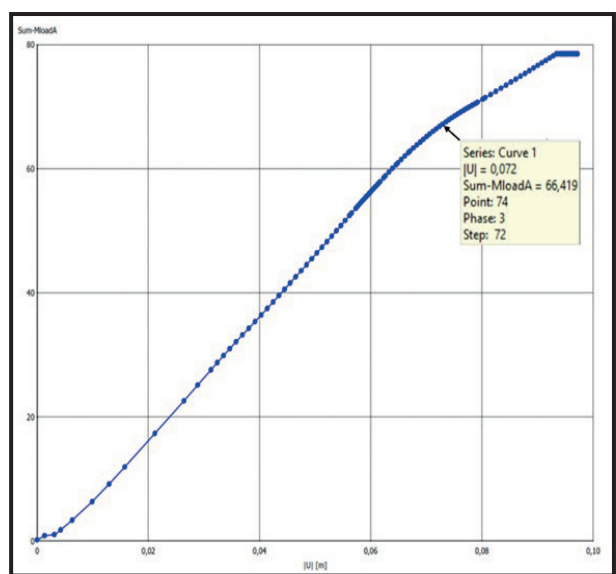


Figure 7. Curve of load-settlement of soil

Static Load Test Interpretation Method

Interpretation of loading test data using the Mazurkiewicz (1972) and Davisson (1973) can be shown in Figures 8 and 9.

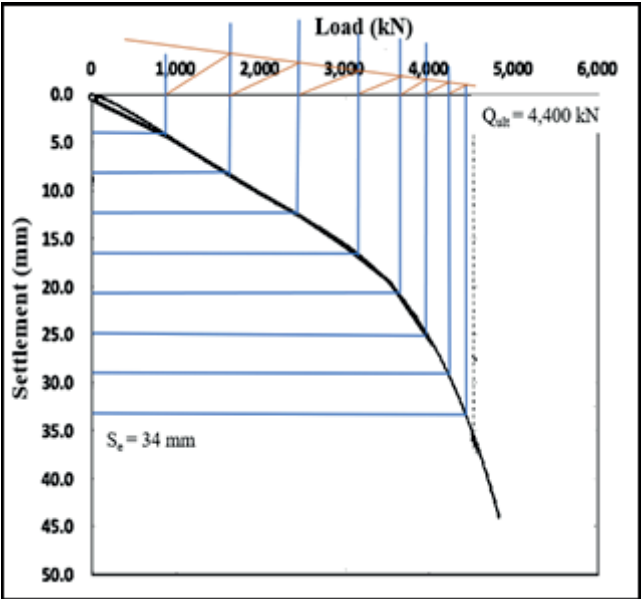


Figure 8. Load and settlement curve with the interpretation of Mazurkiewicz method (1972)

Result from Mazurkiewicz method for piles with a diameter of 0.6 m with a concrete quality (f_c) of 52 MPa after plotting the relationship curve between load and settlement of the pile load test obtains an ultimate load value of 4,400 kN with a decrease of 0.034 m.

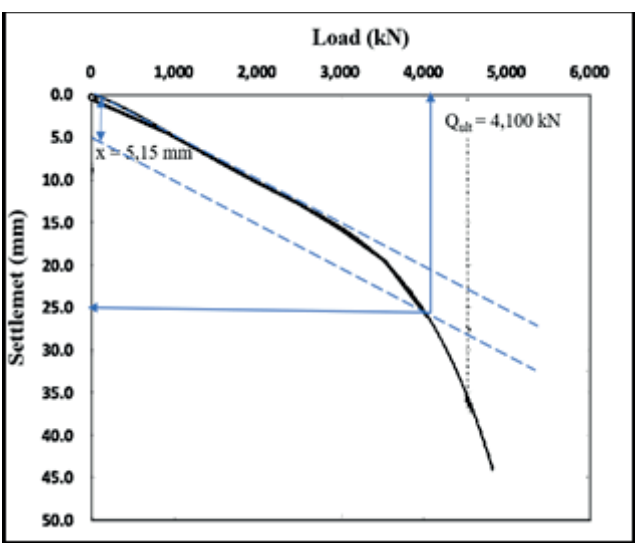


Figure 9. Load and settlement curve with the interpretation of Davisson method (1973)

Result from Davisson method, obtains an elastic settlement value (S_e) of 0.00548 m. To determine the ultimate load, the value of X based on the pile diameter is 5.15 mm. After plotting the relationship curve between load and settlement, an ultimate load of 4,100 kN is obtained with a settlement of 0.025 m.

Pile Foundation Settlement

Pile foundation settlement based on empirical, and numerical method can be shown in Table 4 and Figure 10.

Table 4. Soil Settlement of Pile Foundation

Method		Settlement (m)
Empirical	L. Decourt (1982)	0,0129
	Meyerhoff (1956)	0,0121
	Briaud et al (1985)	0,0121
	Shioi & Fukui (1982)	0,0044
FEM	Mohr-Coulomb Parameter	0,0050
Static load test	Mazurkiewicz (1972)	0,0340
	Davisson (1973)	0,0055

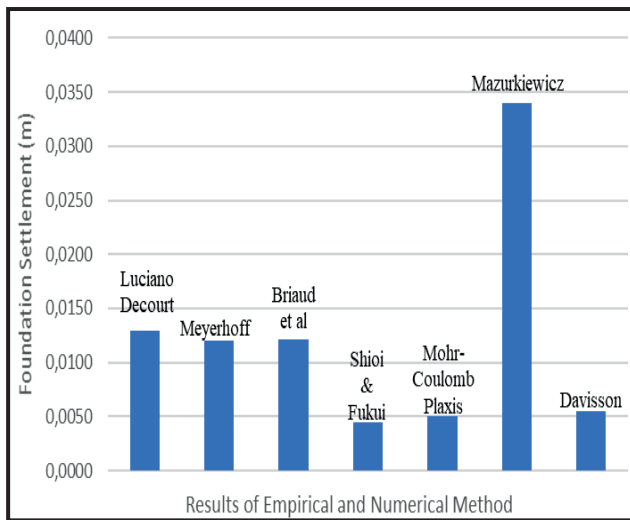


Figure 10. Pile foundation settlement graph uses three interpretation methods

Allowable foundation settlement (S_{all}) is 10% of the diameter of the foundation used, then S_{all} equal to 0.06 m. Based on pile foundation settlement calculation using empirical methods, Shioi & Fukui (1982) has the smallest settlement with value 0.0044 m, while the largest settlement of pile foundations using static load test interpretation method of Mazurkiewicz (1972) with a value 0.034 m. The results pile foundation settlement analysis by Shioi & Fukui method, this due to end bearing capacity of the soil under tip point of pile foundation (Q_p) and skin friction bearing capacity from shear force or adhesion between pile and soil (Q_s) in this method has a small result, because it affects the results of foundation settlement. The greater the value of Q_p and Q_s directly proportional to pile foundation settlement.

Both empirical and numerical methods show that pile foundation settlement is declared safe to use because the $S_{total} < S_{all}$. Based on the finite element method using plaxis software with the parameters of the Mohr-Coulomb model, the pile foundation settlement is 0.005 m. The results of this decrease are still within safe limits because $S_{total} < S_{all}$.

Comparison of Axial Pile Bearing Capacity

Comparison between axial pile bearing capacity of empirical and numerical method with PDA test result can be shown in Table 5 and Figure 11.

Table 5. Comparison of Axial Pile Bearing Capacity Using three interpretation methods and PDA testing

Methods		Q_{ult} (kN)	PDA Test RMX (kN)	Q _{ult} Deviation	
				(kN)	(%)
Empirical	L. Decourt (1982)	5.350,37	4.440,00	910,37	20,50
	Meyerhoff (1956)	4.171,55		-268,45	-6,05
	Briaud et al (1985)	4.873,46		433,46	9,76
	Shioi & Fukui (1982)	1.991,60		-2.448,40	-55,14
Finite Element	Mohr-Coulomb Parameter	4.429,00		-11,00	-0,25
Static Load Test	Mazurkiewicz (1972)	4.400,00		-40,00	-0,90
	Davisson M.T. (1973)	4.100,00		-340,00	-7,66

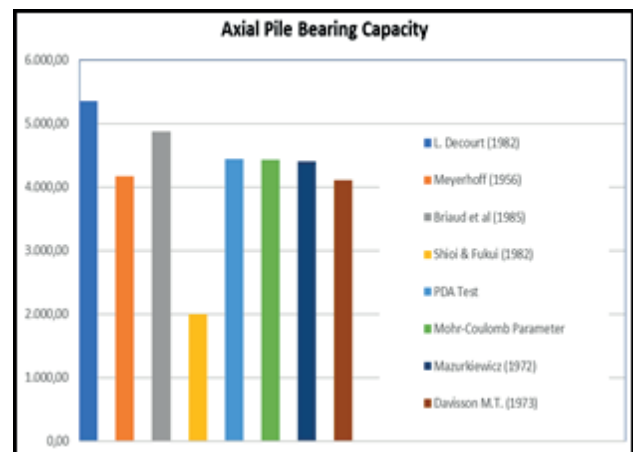


Figure 11. Graph of axial pile bearing capacity

Axial pile bearing capacity (Q_{ult}) based on empirical and numerical method, compared with PDA test results shows that, the smallest difference is using the finite element method with Mohr-Coulomb parameter model. The resulting Q_{ult} difference is -11.00 kN with percentage of -0.25%. This is due to many data parameters has been inputted and analyzed in the Plaxis program, so the results of calculation analysis are more detailed and closer to the situation in the research site.

The next closest Q_{ult} was generated using the static load testing interpretation method by Mazurkiewicz (1972) with deviation of Q_{ult} equal to -40.00 kN and a percentage -0.90%. Next closest Q_{ult} was generated through empirical methods by Meyerhoff (1956)

deviation of Qult equal to -268.45 kN and percentage of -6.05%. Level of results the comparison of Qult with the PDA test is the Davisson. (1973) method with a Qult difference of -340.00 kN and a percentage of -7.66%, Briaud et al. (1985) method has deviation of Qult equal to of 433.46 kN and a percentage of 9.76%, the L. Decourt method. (1982) with a Qult difference 910.37 kN and percentage of 20.50%, and the largest difference was obtained by calculating the Shioi & Fukui method. (1982) with deviation of Qult value -2,448.40 kN and a percentage of -55.14%.

CONCLUSION

Based on the results of comparison between axial pile bearing capacity on soil with PDA test result, it can be concluded that:

1. The result of finite element analysis shows that the ultimate axial pile bearing capacity is in good agreement with the axial capacities obtained using pile driving analyzer (PDA) test result.
2. From the results of empirical and numerical methods, it's observed that axial pile bearing capacity obtained by those method is quite variable hence they must be validated with other reliable methods such as PDA and static load test.
3. Differences in axial bearing capacity can be caused by the test was carried out which depends on the accuracy of operator and parameters that used in the calculations.

REFERENCES

1. **M. Budhu**, Soil Mechanics and Foundations Engineering, 3rd ed. Hoboken: John Wiley & Sons, Inc, 2011.
2. **W.F. Chen and L. Duan**, Bridge Engineering Handbook Substructure Design, 2nd Editio. CRC Press, 1999.
3. **G.H. Sara, C.J. Reza, and E. Abolfazl**, "Reliability based assessment of axial pile bearing capacity: static analysis, SPT and CPT-based methods", Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, vol. 14, issue 3, 2020.
4. **E. Momeni, H. Maizir, N. Gofar, and R. Nazir**, "Comparative study on prediction of axial bearing capacity of driven piles in granular materials", Jurnal Teknologi (Sciences and Engineering), 61(3) 15-20, 2013.
5. **R.A. Mangushev**, "Analytical and Field Evaluation Methods of The Bearing Capacity of Deep Piles and Barrettes in Soft Soil at St. Petersburg," Architecture and Engineering, vol. 1, no. 1, pp. 54–59, 2016, doi: 10.23968/2500-0055-2016-1-1-54-59.
6. **S. Henrina, E. Bahsan, and T. Ilyas**, "Comparison of direct SPT method for calculating axial capacity of piles in Jakarta Area Comparison of direct SPT method for calculating axial capacity of piles in Jakarta Area," 2019, doi: 10.1088/1757-899X/673/1/012027.
7. **E. Anamali, N. Shkodrani, and L. Dhimitri**, "Axial Load Capacity of Cast in Place Piles from SPT and CPTU Data," no. May, pp. 100–108, 2014.
8. **R. Gohil, and C. Parthasarathy**, "Intelligent Assessment of Axial Capacity of Pipe Piles Using High Strain Dynamic Pile Load Tests in Offshore Environment", Lecture Notes in in Civil Engineering, 2023, 296 271-287.
9. **S. Thounaojam, and ParbinSultana**, "Prediction of bearing capacity of bored cast- in situ pile", IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), vol.1, no.6, 2015.
10. **V. Ghiasi, and S. Eskandari**, "Comparing a single pile's axial bearing capacity using numerical modeling and analytical techniques", Results in Engineering, 17, March, 100893, 2023.

11. **A. Al-Dawoodi, F. Rahil, and M. Waheed**, “Numerical Simulation of Shallow Foundation Behavior Rested on Sandy Soil”, IOP Conference Series: Earth and Environmental Science, 2021, 856(1).
12. **H. Maizir, and R. Suryanita**, “Evaluation of axial pile bearing capacity based on pile driving analyzer (PDA) test using Neural Network”, IOP Conference Series: Earth and Environmental Science, 2018, 106(1).
13. **W. Deng, X. Ding, and Y. Peng**, “A study of vertical bearing capacity of expansive concrete pile in coral sand foundation”, Yantu Lixue/Rock and Soil Mechanics, 41(8), 2814-2820, 2020.
6. **S. Henrina, E. Bahsan, and T. Ilyas**, “Comparison of direct SPT method for calculating axial capacity of piles in Jakarta Area Comparison of direct SPT method for calculating axial capacity of piles in Jakarta Area,” 2019, doi: 10.1088/1757-899X/673/1/012027.
7. **E. Anamali, N. Shkodrani, and L. Dhimitri**, “Axial Load Capacity of Cast in Place Piles from SPT and CPTU Data,” no. May, pp. 100–108, 2014.
8. **R. Gohil, and C. Parthasarathy**, “Intelligent Assessment of Axial Capacity of Pipe Piles Using High Strain Dynamic Pile Load Tests in Offshore Environment”, Lecture Notes in in Civil Engineering, 2023, 296 271-287.
9. **S. Thounaojam, and ParbinSultana**, “Prediction of bearing capacity of bored cast- in situ pile”, IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), vol.1, no.6, 2015.
10. **V. Ghiasi, and S. Eskandari**, “Comparing a single pile's axial bearing capacity using numerical modeling and analytical techniques”, Results in Engineering, 17, March, 100893, 2023.
11. **A. Al-Dawoodi, F. Rahil, and M. Waheed**, “Numerical Simulation of Shallow Foundation Behavior Rested on Sandy Soil”, IOP Conference Series: Earth and Environmental Science, 2021, 856(1).
12. **H. Maizir, and R. Suryanita**, “Evaluation of axial pile bearing capacity based on pile driving analyzer (PDA) test using Neural Network”, IOP Conference Series: Earth and Environmental Science, 2018, 106(1).
13. **W. Deng, X. Ding, and Y. Peng**, “A study of vertical bearing capacity of expansive concrete pile in coral sand foundation”, Yantu Lixue/Rock and Soil Mechanics, 41(8), 2814-2820, 2020.

СПИСОК ЛИТЕРАТУРЫ

1. **M. Budhu**, Soil Mechanics and Foundations Engineering, 3rd ed. Hoboken: John Wiley & Sons, Inc, 2011.
2. **W.F. Chen and L. Duan**, Bridge Engineering Handbook Substructure Design, 2nd Editio. CRC Press, 1999.
3. **G.H. Sara, C.J. Reza, and E. Abolfazl**, “Reliability based assessment of axial pile bearing capacity: static analysis, SPT and CPT-based methods”, Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, vol. 14, issue 3, 2020.
4. **E. Momeni, H. Maizir, N. Gofar, and R. Nazir**, “Comparative study on prediction of axial bearing capacity of driven piles in granular materials”, Jurnal Teknologi (Sciences and Engineering), 61(3) 15-20, 2013.
5. **R.A. Mangushev**, “Analytical and Field Evaluation Methods of The Bearing Capacity of Deep Piles and Barrettes in Soft Soil at St. Petersburg,” Architecture and Engineering, vol. 1, no. 1, pp. 54–59, 2016, doi: 10.23968/2500-0055-2016-1-1-54-59.

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