

Finite Element Modelling of Prestressed Concrete Piles in Soft Soils, Case Study: Northern Jakarta, Indonesia

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SUBMITTED 20 July 2021 REVISED 14 September 2021 ACCEPTED 04 October 2021

ABSTRACT Jakarta is faced with limited land resources due to its position as the capital city of Indonesia. Therefore, numerous high-rise buildings are being constructed to solve this problem and provide accommodations for a large number of Jakarta residents. Studies have shown that prestressed concrete piles (spun piles) are commonly used as the foundations of high-rise buildings in metropolitan cities across Indonesia, especially in the Northern Jakarta Coastal area, which is predominant with deep soft soils deposit. To further assess and verify the ultimate capacity of the pile, a static loading test was conducted. However, not all results from the field test produced ideal, accurate, precise, and reliable load-settlement curve (until failure) results. Therefore, this study aims to determine the soil properties for the analysis of prestressed concrete spun piles with a diameter of 600 mm in the Northern Jakarta coastal area based on the standard penetration test values (SPT-N). It is a case study of a well-documented static pile load test using the kentledge system. Back analyses were performed by the finite element method to obtain the extrapolated load-settlement curve. Furthermore, the effect of interface strength between pile and soil on the load-settlement curve was also investigated. The results showed that a reduction of interface strength leads to a smaller load-settlement curve. In addition, several geotechnical engineering parameters of soil, such as the undrained shear strength and effective young's modulus, were established using data from an in-situ soil site investigation and empirical correlations with SPT-N.

KEYWORDS Finite Element Modeling; Axial Load Test; Load-Settlement Curve; Back Analysis; Prestressed Concrete Piles.

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1 INTRODUCTION

According to the Indonesian Central Bureau of Statistics, Jakarta has an estimated population of over 10.5 million people, and it is expected to keep growing yearly. Due to the shortage of land resources and the increase of urban population, many construction projects in Jakarta and several metropolitan cities worldwide choose to build high-rise buildings. Generally, prestressed concrete piles (spun piles) are used as the foundations for high-rise buildings, especially in the Northern Jakarta Coastal area, predominantly with deep soft soil deposits. There are several advantages associated with spun piles, such as durability, cost-effectiveness, and being less prone to cracking during the driving process.

Numerous studies have been conducted on numerical modeling analyses to investigate the soil-structure interaction problem of the pile

foundation. Most of these studies examined the behavior of piles when subjected to axial compression (Rojas *et al.*, 1999; Kitiyodom *et al.*, 2004; Lu *et al.*, 2005; Said *et al.*, 2009; Dijkstra *et al.*, 2011; Li *et al.*, 2012; Karlsrud, 2014; Mahmoud *et al.*, 2014; Dias & Bezuijen, 2018). The result showed that numerical modelings can properly reproduce the load-settlement curves, such as the finite element model. Furthermore, Zhou *et al.* (2013) simulated full-scale destructive field tests of static drill rooted nodular pile in soft soil areas and stated that the bearing capacity is approximately 8% to 10% higher than the bored pile. Moreover, studies on dynamic and static load testing of model piles driven into dense sand and in heterogeneous soil areas showed that the pile's capacity was in good agreement with the test results (Bruno & Randolph, 1999; Crispin *et al.*,

2018; Nasrollahzadeh & Hataf., 2019). Randolph (2003) stated that the most integral factors of pile analyses still depend on empirical correlations based on experimental observations from laboratory and full-scale in situ testing. Therefore, field soil investigations and laboratory testing need to be carried out to determine the soil properties from the assumptions validated with the initial load–settlement curve from the field loading test results. Unfortunately, there are limited studies on soil properties of Northern Jakarta Coastal area clay (Taqwa *et al.*, 2018; Hutabarat *et al.*, 2019). Therefore, this study aims to back-analysis the properties of soft soil, such as Undrained Shear Strength (S_u) and Effective Soil Young's Modulus (E') for designing prestressed concrete piles at North Jakarta area based on the standard penetration test values (SPT-N). Besides, the effect of interface strength between pile and soil on the load-settlement curve was also investigated. A well-documented case study of apartment construction in the Northern Jakarta coastal area was selected to validate and verify the finite element analysis, namely PLAXIS 2D 2019. Finally, some empirical correlations to determine soil properties were proposed for further practice.

2 METHODS

2.1 Project Description

The apartment project has 11 towers located at the North Coast of Jakarta area, known as Dadap, and dominated by thick and soft soil, as shown in Figure 1. This study focused on the spun pile, namely A1204, embedded in the Tower 1 area and driven about 44.5 m below the ground level, with 600 mm of diameter and a compressive concrete (f_c') strength of 45 MPa.

2.2 Soil Stratification

In this project, Soil boring and Standard Penetration Tests (SPT-N) were carried out to accommodate soil samples and their stratification information. The SPT-N test was followed by ASTM-D1586, also known as Borehole 01 (BH-01), as shown in Figure 2. In general, the soil layers were divided into 5, dominated by medium to hard clays. From +0.0 to

-1.0, the soil was very soft silty clay soil, followed by a loose sand layer from -1.0 to -7.0. In addition, very soft silty clay was found from -7.0 to -31.0 and continued with a layer of dense sand from -31.0 to -39.0. Lastly, the hard silty clay soil layer was identified from -39.0 to -69.0, with the groundwater table located -0.5 m below the surface. The detail of the sub-soil stratifications is shown in Table 1 and Figure 3.

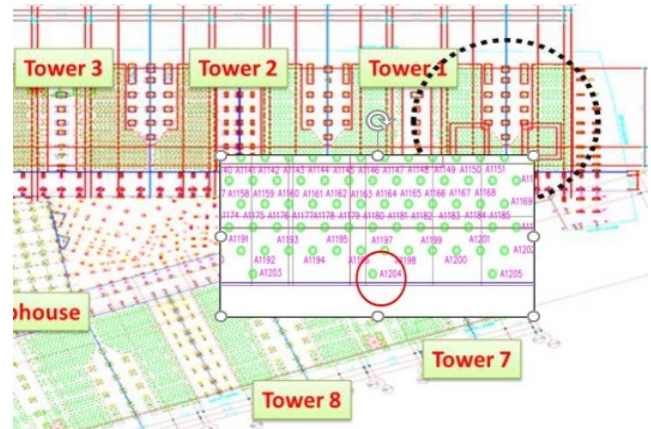


Figure 1. Location of tested prestressed concrete spun pile (Pile A1204 – Tower 1)



Figure 2. Location of Borehole 01 (BH-01)

Table 1. Soil stratification of BH – 01

Elevation Depth (m)	Soil Type	USCS Symbol	SPT-N
0.0 – 1.0	Very Soft – Silty Clay	CL	2
1.0 – 7.0	Loose – Sand	SW	8
7.0 – 31.0	Very Soft – Silty Clay	CL	2
31.0 – 39.0	Dense – Sand	SW	32
39.0 – 69.0	Hard – Silty Clay	CL	26
69.0 – 80.0	Dense – Sand	SW	27

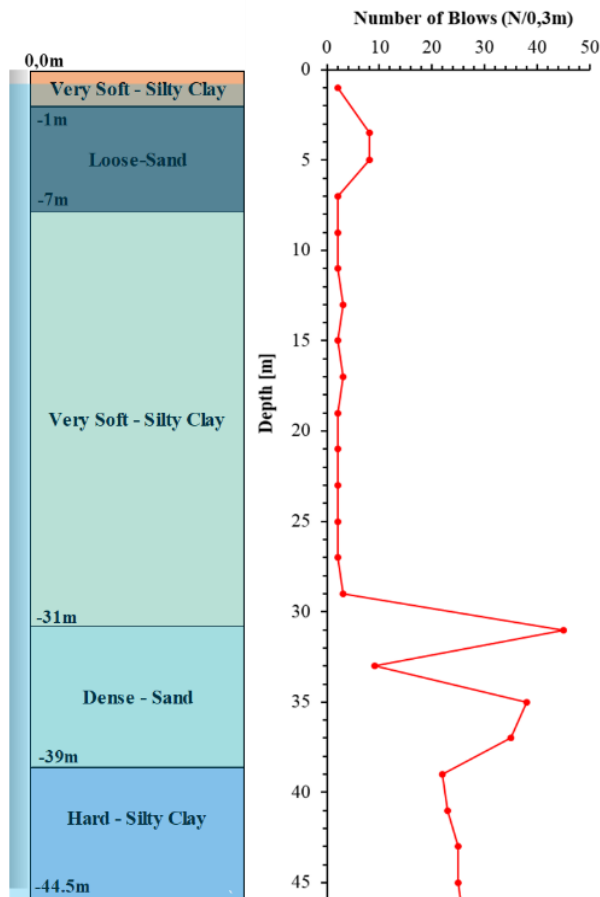


Figure 3. Soil stratification and SPT-N value of BH-01

2.3 Pile Loading Test

The acceptable axial load capacity is an important geotechnical requirement for the design of a deep foundation because it is used to support working loads. Therefore, this led to the development of various methods of assessing the axial load of the piles by geotechnical engineers, such as the full-static load test (Coduto, 2001). Generally, there are two types of pile loading tests, namely the constant rate of penetration (CRP) and the Maintained Load (ML) tests. This study focused on the ML test procedure, which requires accurate increment in loading data at constant periods. According to Tomlinson (1994), the rate of piling borders from ICE decreases when the movement is above 0.25 mm/h. This indicates that it is important to ensure the time at each load increases to obtain a similar degree of soil consolidation because the slower the rate of load increment, the smaller the ultimate failure. The sequence of this test includes loading, unloading, and reloading to the working level. Afterward, the

load was raised until the maximum axial pile capacity was achieved. In this case, the testing sequence incorporated an initial loading value of 700 kN (50% of Working Load (WL)), which is commonly known as cycle A1. This is followed by a second, third, fourth, and fifth loading and unloading cycle of 1400 kN (100% WL), 2100 kN (150% WL), 2800 kN (200% WL), and 3500 kN (250% WL) using cycles A2, A3, A4, and A5 to reach the maximum capacity of the hydraulic jacks.

Table 2. Pile A1204 – Tower 1 Loading test result

%	Load (kN)	Settlement (m)
0	0	0.00000
25	350	0.00163
50	700	0.00376
75	1050	0.00591
100	1400	0.00806
125	1750	0.01026
150	2100	0.01265
175	2450	0.01504
200	2800	0.01768
225	3150	0.02086
250	3500	0.02517

The balance deformation or the settlement of the pile depends on the period of each particular loading step. The benchmark to describe this condition was determined when the applied load for each loading step was maintained for one hour or the rate of settlement attained was lower than 0.25 mm/h. Figure 4 showed a schematic of the loading test system, which consists of multiple supports of concrete weights used to determine the reaction for a hydraulic jack, which is then used to provide the test load. The settlement of the top pile head was controlled by 4 different electronic displacement transducers attached to a rigid steel beam with an accuracy resolution of 0.001 mm. Therefore, to limit any further interaction effects, it is located far from the test piles.

The load pressure cell was used to organize the hydraulic pressure in the jacking system. Overall, this system is much more stable and less prone to collapse, although it is expensive and cumbersome.

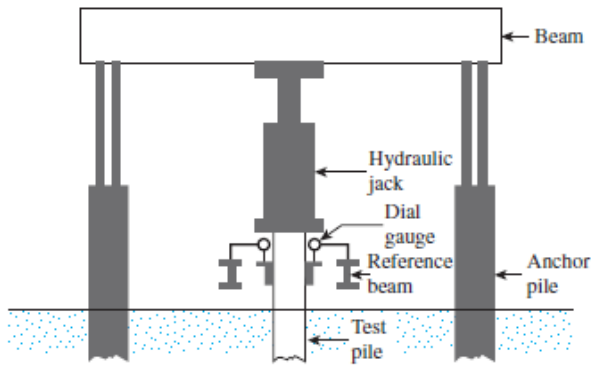


Figure 4. Schematic design of pile load test arrangement (Das, 2016)

For this study case, Pile A1204 was selected and installed on April 16th, 2019, before conducting the axial load test on May 28th, 2019. Furthermore, this study showed the behavior of the load–settlement curve obtained from this fifth cycle static pile load test result after it was numerically simulated through finite element analysis.

2.4 Finite Element Model

The numerical simulation of the single pile load test was determined through the finite element method program, PLAXIS 2D. This finite element method (FEM) is a numerical strategy for solving accurate and precise solutions of partial differential and integral equations. The geometry of the generated mesh was parametrically delineated to grant the probability of geometrical variations when needed. This study used a model consisting of a 600 mm diameter pile with an embedded length of 44.5 m to determine the simulation of the single pile loaded with axial load until the load-settlement curve indicates failure.

The two-dimensional finite element geometry model between the soil-pile interaction systems is displayed in Figure 5(a). Meanwhile, Figure 5(b) portrays the finite difference mesh utilized in the pile test analysis consisting of 1359 elements and 11632 nodes. The soil was modeled using triangular elements with 15 nodes, with a total geometry of 12 m width and 80 m depth. Furthermore, the standard fixities were used to determine the boundaries condition, where both

sides of geometry used the roller conditions, and bottom boundaries were fixed.

The material behavior of the soil layers was used to simulate the perfectly elastic-plastic Mohr-Coulomb constitutive law. Afterward, the interaction between the pile structures with surrounding soil was determined using the interface factor (R_{int}) along the pile's shaft. Interfaces are joined elements added to plates or geo-grids to allow proper modeling of soil-structure interaction. It is also used to simulate the thin zone of intensely sharing material at the contact between a plate and the surrounding soil (Dandagawhal, 2018).

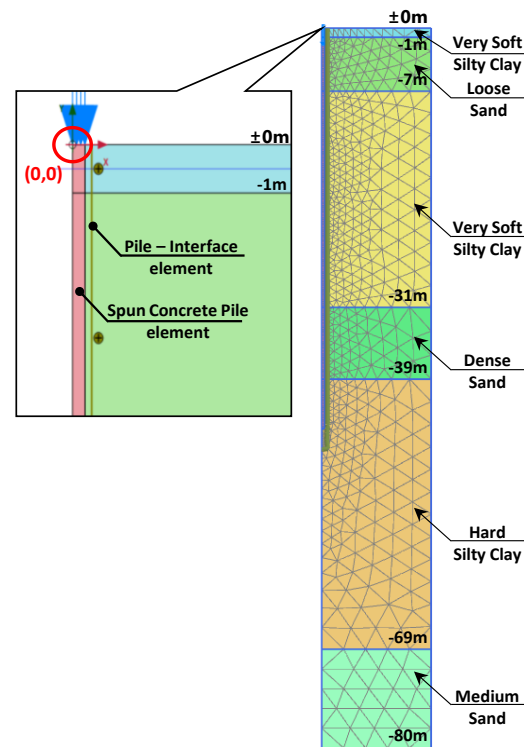


Figure 5. Finite Element Model for analysis (PLAXIS 2D 2019) Stage Construction

This project's finite element model simulation stage started with calculating the soil's initial stress to determine the K_0 condition. This process was carried out using Jaky's formula, where K_0 equals $1 - \sin \phi'$, then installed and activated the single pile at a groundwater level of 0.5 m below the ground. Furthermore, the initial displacements were reset to zero because the measured data were obtained without considering the installation effects. Lastly, the

interface element was activated, and additional axial loads were given until the pile failed with a total load of 5655 kN. The detailed construction stages are shown in Table 3.

Table 3. Finite Element Method stage construction activities of the tested spun pile

Orders	Stage Construction Activities
1	Initial phase
2	Installation of the prestressed tested spun pile
3	Reset displacement to zero activation
4	Activate of interface and apply maximum loads of 5655 kN

2.5 Soil Constitutive Model

The spun pile is considered a linear–elastic material, where the model represents Hooke's law of isotropic linear elasticity. According to the geotechnical field investigation, the groundwater table was located -0.5 m below the ground level, while the spun pile used for this study was classified as class A1 concrete. Furthermore, the pile was modeled using a cluster, and the linear elastic material was applied to determine the rigidity of the concrete material, such as modulus of elasticity (E), Poisson's ratio (ν), and the unit weight of concrete (γ_c). Table 4 summarizes the input parameters for the tested spun pile elements.

The Mohr-Coulomb model, a commonly linear elastic perfectly plastic model as a first approximation of soil behavior, with a constant average stiffness was used to predict the soil layer. This model involves 4 main input soil parameters, namely Elastic modulus (E),

Poisson's ratio (ν), friction angle (ϕ), and cohesion (c). The clays and the sands were simulated following undrained and drained behavior, respectively. The main difference between those two behaviors was the generation of excess pore pressure due to loading. In the undrained condition, the excess pore pressure is generated, while in the drained condition, it remains zero.

In this analysis, the clay and silt adopted the Undrained B model consisting of effective stiffness parameters and undrained shear strength (S_u). During this process, the consolidation analysis does not need to be performed after undrained calculation due to excess pore pressure generation. A more detailed explanation is shown in the Plaxis 2D 2019 manual. The detailed type of materials for the soil and structural element in this study is shown in Table 5. Meanwhile, the complete soil stratification and parameter input of the Finite Element Method (PLAXIS 2D, 2019) are summarized in Table 6.

Table 4. Prestressed Concrete Spun Pile Input Materials

Properties	Value
Unit Weight (γ)	24 kN/m ³
Modulus of Elasticity (E)	3E+07 kN/m ²
Poisson Ratio (ν)	0.2

Table 5. Type of Material Model in PLAXIS 2D 2019

Material	Material Model	Type of Material
Concrete	Linear Elastic	Non-porous
Clay	Mohr-Coulomb	Undrained (B)
Silt	Mohr-Coulomb	Undrained (B)
Sand	Mohr-Coulomb	Drained

Table 6. Input parameters for Mohr-Coulomb Model in PLAXIS 2D 2019

Layer	Depth (m)	Soil Type	N _{SPT}	USCS Symbol	ϕ (°)	γ (kN/m ²)	γ_{sat} (kN/m ²)	S_u (kN/m ²)	E' (kN/m ²)	ν'	R_{int}
1	0.0 – 1.0	Very Soft – Silty Clay	2	CL	0	16	17	11	2700	0.35	1
2	1.0 – 7.0	Loose – Sand	8	SW	30	16	18	0	21000	0.25	1
3	7.0 – 31.0	Very Soft – Silty Clay	2	CL	0	16	17	11	3250	0.35	1
4	31.0 – 39.0	Dense – Sand	32	SW	37	19	21	0	50000	0.30	1
5	39.0 – 69.0	Hard – Silty Clay	26	CL	0	18	20	156	40000	0.30	1
6	69.0 – 80.0	Medium – Sand	27	SW	36	19	21	0	45000	0.30	1

3 RESULTS AND DISCUSSION

3.1 Soil Modulus and Shear Strength Properties Correlation

Several trial-error processes were used to determine the correct input parameters for the curve-fitting process. This technique is known as the back analysis and consists of soil parameters with considerable effects on the load-settlement curve results, such as the Undrained Soil Strength (S_u) and Effective Young's Modulus (E'). Several iterations changed those 2 soil parameters based on back analysis until the computed results were close to the field measurement.

The clay's undrained shear strength (S_u) was achieved from empirical correlation through back analysis, which correlates S_u with the N_{SPT} , as described in Equation (1) and (2).

$$S_u = 5.5 N_{SPT} (kPa) \tag{1}$$

$$S_u = 6 N_{SPT} (kPa) \tag{2}$$

The empirical equations (1) and (2) are used to forecast the S_u of the clay with very soft and stiff to hard clay consistencies. Figure 6 compares the S_u profile calculated from the above equation and actual soil profile depth. The S_u obtained from these 2 equations depends on the SPT-N value of each soil layer.

The effective soil modulus (E') is also a fundamental soil property for predicting its deformation characteristics. Due to the back analyses, the effective soil modulus for clay was estimated as $E'=1350$ N (kPa) and $E'=2625$ N (kPa) for sand. Figure 7 shows the comparison between the E' values with the actual soil profile stratification depth. Like the S_u values determination, the effective soil modulus (E') also relies on each layer's SPT-N value. For practical purposes, the suggested correlations equations between SPT-N values with Undrained Soil Strength (S_u) and Effective Young's Modulus (E') used in the Mohr-Coulomb model are summarized in Table 7. This correlation could be used for future projects near the area, assuming the soil stratification is similar.

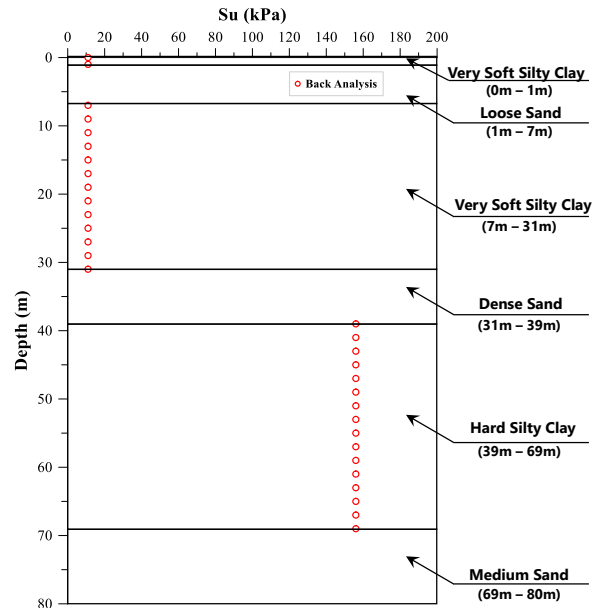


Figure 6. The profile of undrained shear strength with depth

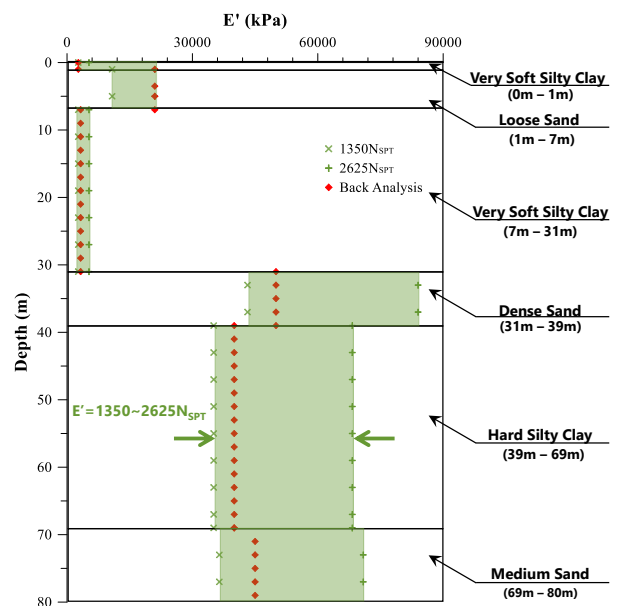


Figure 7. The profile of Effective Young's modulus with depth

Table 7. S_u and E' Correlation based on SPT-N Data Borehole 01

Layer	Soil Type	S_u (kN/m ²)	E' (kN/m ²)
1.	Very Soft – Silty Clay	$5.5 \times N_{SPT}$	$1350.0 \times N_{SPT}$
2.	Loose – Sand	-	$2625.0 \times N_{SPT}$
3.	Very Soft – Silty Clay	$5.5 \times N_{SPT}$	$1625.0 \times N_{SPT}$
4.	Dense – Sand	-	$1562.5 \times N_{SPT}$
5.	Hard – Silty Clay	$6 \times N_{SPT}$	$1538.5 \times N_{SPT}$
6.	Medium – Sand	-	$1666.7 \times N_{SPT}$

3.2 Load-Settlement Curve

The test results indicated that the spun pile was not tested until failure, while the finite element analysis was utilized to extrapolate the load-settlement curve to assess the maximum capacity of the tested pile. The pile is not tested until 200% of the design load is achieved because the cost of static pile testing is expensive, hence non-failure pile testing becomes common practice in the field. The load-settlement curve of the determined and computed finite element method analyses is shown in Figure 8. The results showed that the computed curve fitted properly with the measured data. Therefore, it can be concluded that the FE model and input parameters were valid and verified. According to Mazurkiewicz's theory, the ultimate pile capacity was 4110 kN.

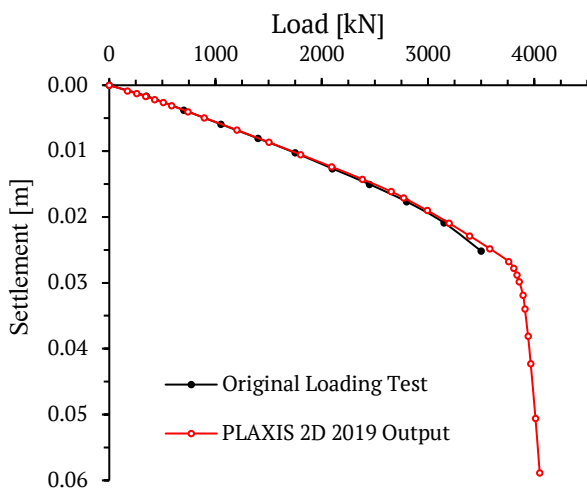
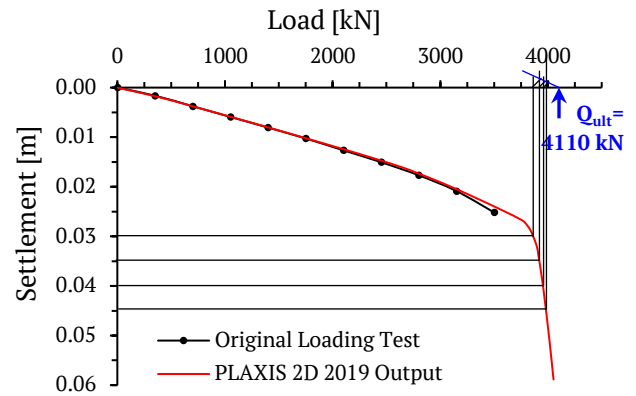
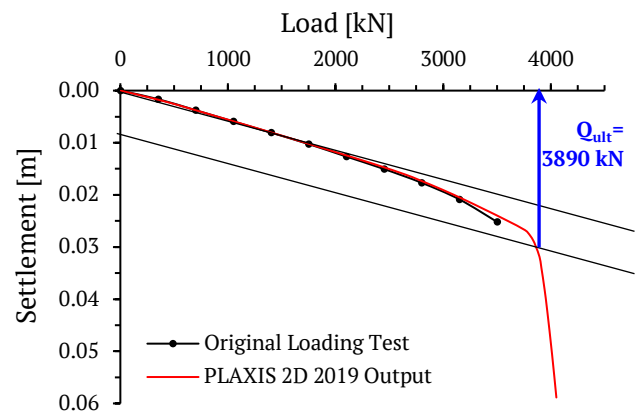


Figure 8. Comparison of measured and computed load-settlement curves

The interpretation of the pile ultimate capacity ($R_{inter} = 1$) was carried out with Mazurkiewicz's and Davisson's Method after obtaining the extrapolated load-settlement curve with the PLAXIS 2D 2019 program. The calculation and determination of the ultimate capacity are shown in Figure 9. Davisson's method yields a smaller ultimate capacity than Mazurkiewicz, with a difference of approximately 5%.



a)



b)

Figure 9. Comparison of measured ultimate capacity value based on a different method: a). Mazurkiewicz's Method ($Q_{ult} = 4110$ kN), b) Davisson's Method ($Q_{ult} = 3890$ kN)

3.3 Influence of the Interface Coefficient (R_{inter})

To study the influence of the interface values, the axially loaded single pile was modeled by various R_{inter} values, varying from 0.7 to 1. Therefore, the interface value is used to reduce the friction between the structure (pile foundation) and the adjacent soil was used to reduce the friction between the structures with sand or clay soil, according to Gouw (2014). Figure 10 shows experimental (trial and error) load-settlement curves with different R_{inter} values used to produce several forms of load-settlement curves. It shows that the variation of the soil-pile interface (R_{inter}) influenced the changes and decreased the pile capacity before reaching failure conditions.

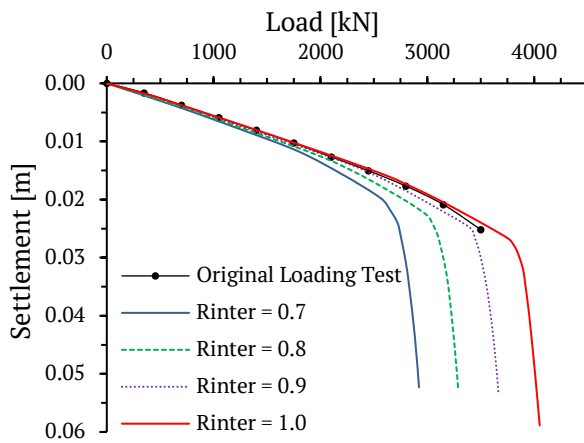


Figure 10. Load-Settlement Curves for A1204 pile with variations of R_{inter} values

3.4 Influence of the Pile Embedded Length

Another parametric study was also performed with the different lengths of embedment piles, such as 35 m and 47.50 m, with the load-settlement curve result shown in Figure 11. The ultimate capacity of the driven pile with an embedded length of 35 m is smaller by 47.5 m due to skin friction.

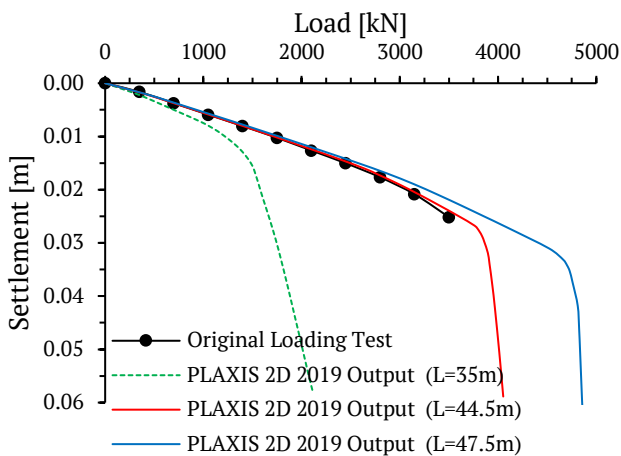


Figure 11. Load-Settlement Curves for A1204 pile with variations of pile length.

4 CONCLUSION

This study used a 2D finite element to analyze the pile foundation located in the Northern Jakarta Coastal Area, Indonesia. Furthermore, several geotechnical engineering parameters of soil, such as undrained shear strength and effective modulus, were achieved using data from an in-situ soil site investigation and empirical correlations with SPT-N. The simulation of the 2D

Finite Element model for forecasting the ultimate pile capacity was validated in this study. The results shows that the pile load test is successfully simulated using finite element analysis. The computed load settlement curve is generally close to the measured data. Furthermore, the empirical correlation according to SPT-N values is developed to obtain the Undrained Shear Strength and Effective Young's modulus. The effective soil modulus for clay was estimated as $E' = 1350 N_{SPT}$ (kPa) and $E' = 2625 N_{SPT}$ (kPa) for sand, while the Undrained Shear Strength (S_u) was estimated at $5.5 N_{SPT}$ and $6 N_{SPT}$. This empirical correlation is valid for the soil near the project. Meanwhile, further study needs to be carried out for other locations. The interpretation of ultimate pile capacity by Mazurkiewicz and Davisson's methods yielded a close result, with a 5% difference. Numerical results showed that reducing R_{inter} values leads to a smaller load-settlement curve with a decrease in load.

DISCLAIMER

The authors declared no conflict of interest.

AVAILABILITY OF DATA AND MATERIALS

All data are available from the author.

AUTHOR CONTRIBUTION STATEMENTS

Aswin L contributes in conceptualization, writing-original draft, writing-review and editing, and supervision. Varian H. B carried out the FEM analysis, wrote- review and edited the manuscript, collected the field data, and plot figures. Yiska V. C. W performed the FEM analysis, wrote- review and edited the manuscript, and plot figures.

ACKNOWLEDGMENTS

The authors are grateful to PT. Pakubumi Semesta, for providing detailed geotechnical information on this case study.

REFERENCES

ASTM D1586-67, 1978. *Standard Method for Penetration Test and Split-Barrel Sampling of Soils*. United States of America: American Society for Testing and Materials.

- ASTM D1143, 2007. *Standard Test Methods for Deep Foundations Under Static Axial Compressive Load*. United States of America: American Society for Testing and Materials.
- Bruno, D., & Randolph, M., 1999. Dynamic and Static Load Testing of Model Piles Driven into Dense Sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 125(11), pp. 988-998.
- Coduto, D.P., 2001. *Foundation Design Principles and Practices 2nd ed.* New Jersey: Prentice-Hall, Inc.
- Crispin, J., Leahy, C., & Mylonakis, G., 2018. Winkler Model for Axially-Loaded Piles in Inhomogeneous Soil. *Géotechnique Letters*, 8(4), pp. 290-297.
- Dandagawhal, S., 2018. Settlement Analysis of Pile Foundation using Plaxis 2D. *International Journal of Science and Research*, 8(9) pp. 1706-1714.
- Das, B.M., 2016. *Principles of Foundation Engineering*. Boston: Cengage Learning.
- Dias, T.G.S. & Bezuijen, A., 2018. Load-Transfer Method for Piles under Axial Loading and Unloading. *J. Geotech. Geoenviron. Eng.*, 144(1):04017096.
- Dijkstra, J., Broere, W., & Heeres, O.M., 2011. Numerical Simulation of Pile Installation. *Computers and Geotechnics*, 38 (5), pp. 612-622.
- Gouw, T.L., 2014. Common Mistakes on the Application of Plaxis 2D in Analyzing Excavation Problems. *International Journal of Applied Engineering Research*, 9(21) pp. 8291-8311.
- Hutabarat, L.E., Rainaldo, D., Ilyas, T., & Prakoso, W.A., 2019. Site Characterization of Marine Clay Consolidation Ratio on Kamal Muara Area, Northern Jakarta. *South Lampung: International Conference on Science, Infrastructure Technology and Regional Development*.
- Karlsruud, K., 2014. Ultimate Shaft Friction and Load-Displacement Response of Axially Loaded Piles in Clay Based on Instrumented Pile Tests. *Journal of Geotechnical and Geo-environmental Engineering*, 140 (12) : 04014074.
- Kitiyodom, P., Matsumoto, T., & Kanefusa, N., 2004. Influence of Reaction Piles on The Behaviour of a Test Pile in Static Load Testing. *Canadian Geotechnical Journal*, 41(3), pp. 408-420.
- Li, J., Tan, Y. & Liang, F., 2012. A Modified Analysis Method for the Nonlinear Load Transfer Behaviour of Axially Loaded Piles. *KSCE J. Civ. Eng*, 16 (3), 325-333.
- Lu, X., Li, P., Chen, B., & Chen, Y., 2005. Computer Simulation of The Dynamic Layered Soil-Pile-Structure Interaction System. *Canadian Geotechnical Journal*, 42(3), pp. 742-751.
- Mahmoud, H.N., Tetsuo, T., Susumu, I., & Mourad, K., 2014. On the Influence of Vertical Loads on the Lateral Response of Pile Foundation. *Computers and Geotechnics*, 55, pp. 392-403.
- Nasrollahzadeh, E. & Hataf, N., 2019. Experimental and Numerical Study on The Bearing Capacity of Single and Groups of Tapered and Cylindrical Piles in Sand. *International Journal of Geotechnical Engineering*. pp. 1-12.
- PLAXIS. 2019. *Manual Tutorial Plaxis 2D 2019*. Netherlands: Delft University of Technology & PLAXIS.
- Randolph, M.F., 2003. Science and Empiricism in Pile Foundation Design. *Geotechnique*, 53(10), pp. 847-875.
- Rojas, E., Valle, C., & Romo, M. P., 1999. Soil-pile Interface Model for Axially Loaded Single Piles. *Soils and Foundations*, 39(4), pp. 35-45.
- Said, I., Gennaro, V.D., & Frank, R., 2009. Axisymmetric Finite Element Analysis of Pile Loading Tests. *Computers and Geotechnics*, 36 (1-2), pp. 6-19.
- Taqwa, F.M.L, Hutabarat, L.E., Ilyas, T., & Prakoso, W.A., 2019. *Estimation of Settlement Induced Land Subsidence of Marine Clay on Kamal Muara Area, Northern Jakarta, Based on the Change of Pore Water Pressure. Lampung: 2018*

International Conference on Engineering, Technologies, and Applied Sciences.

Tomlinson, M., 1994. *Pile Design and Construction Practice*. Fourth Edition. London: E & F N Spon.

Zhou, J.J., Wang, K.H., Gong, X.N., & Zhang, R.H., 2013. Bearing Capacity and Load Transfer Mechanism of a Static Drill Rooted Nodular Pile in Soft Soil Areas. *Journal of Zhejiang University-Science A.*, 14, pp. 705–719.