Indonesian Geotechnical Journal, April 2024, Vol 3 (1). Page 49 - 56
DOI: https://doi.org10.56144/igj.v3i1.65
E-ISSN:2829-7520
https://indonesian-geotechnical-journal.org/index.php/JGI/issue/archive

Study on Pile Bearing Capacity Improvement in Soft Soil After Vacuum Consolidation

Adityaputera Wirawan[1,*], Cindarto Lie[2]
[1] Civil Engineering, Faculty of Engineering, Parahyangan Catholic University, Bandung, Indonesia, 40141; adityaputera.wirawan@gmail.com
[2] Civil Engineering, Faculty of Engineering, Parahyangan Catholic University, Bandung, Indonesia, 40141; cindarto@gmail.com
*Correspondence: adityaputera.wirawan@gmail.com

SUBMITTED 10 August 2023 **REVISED** 1 March 2024 **ACCEPTED** 19 April 2024

ABSTRACT: The main problem in developing property over soft soil is significant settlement due to the consolidation process. The soil settlement, which will occur gradually throughout the years, will disrupt existing infrastructures, in this case bridges. To mitigate this issue, the common method is by speeding up the consolidation. The consolidation process must be sped up to avoid the differential settlement problem at the bridge abutments. Due to the limited supply of fill material, a vacuum consolidation method is adopted. In this method, a Prefabricated Vertical Drain (PVD) is installed, and a vacuum is applied to impose pressure as preloading. Because of the consolidation process, theoretically, the effective stress of the consolidated soil increases, and the soil shear strength does as well. Increasing the shear strength of the soils will increases the pile capacity. However, the interesting question is how much the shear strength of the soil can increase and impacts the pile capacity. In this paper, the shear strength improvement of the consolidated soil and the effect on pile bearing capacity is evaluated. This study used a series of in-situ tests that were carried out before and after the vacuum consolidation. A pile loading test using the Pile Dynamic Analyzer (PDA) method was carried out to verify the pile bearing capacity improvements. From the comparison result, it is shown that the theoretical capacity of the piles after consolidation were close to the pile test results.

KEYWORDS Pile Bearing Capacity; Soft Soil; Shear Strength; PVD; Vacuum Consolidation

1 INTRODUCTION

In the development of residential area located in Teluk Naga, Tangerang Regency – Banten, at the North of Jakarta, covering an area of 1000 Ha, 5 bridges as infrastructure support have to be constructed. Project map location and the layout design of the 5 bridges are shown in Figure 1. This study focuses only on Bridge 1 and Bridge 4. According to the geotechnical investigation results, the development area is covered by very soft soil which will undergo consolidation process.

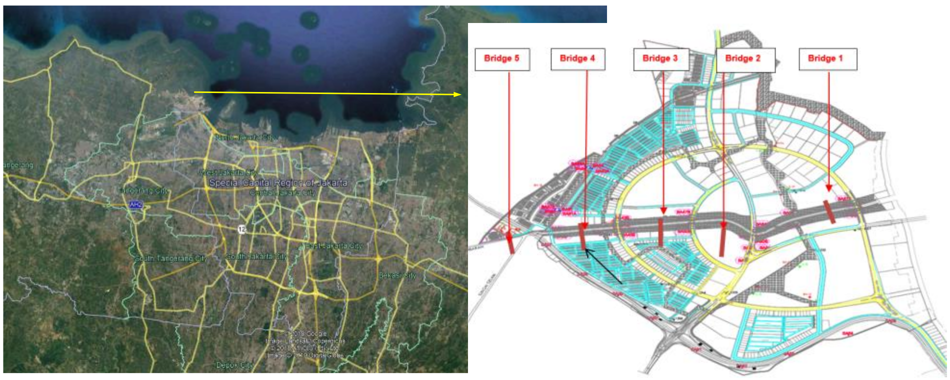

Figure 1. Project map & bridges location.

The bridges are planned to span across the river, with their abutments supported by pile foundations. Prior to the construction of the bridge abutments and embankments, the very soft soil is consolidated by the vacuum consolidation method. Typically, very soft clay soil has low shear strength and limited load carrying capacity for pile foundation. However, as a result of consolidation, there is an increase in shear strength. The increase in shear strength will also affect the load carrying capacity of the pile foundation. This paper studies the effect of increasing the shear strength of the soil base through the consolidation process on the load carrying capacity of the pile foundation. This study focuses on bridge foundation, which has also undergone dynamic testing (PDA) after the consolidation process is complete.

2 SOIL CONDITIONS AT SITE

Reviewing the project location against the geological map sheet of Jakarta and the Thousand Islands (Turkandi et al., 1992) published by the Center for Geological Research and Development, it can be seen that the project location is in an alluvium (sediment) formation area (Qa) consists of clay, silt, sand, gravel, and boulders. This sediment formation spreads evenly along the north coast of Jakarta. The formation process is due to the presence of land deposits and marine deposits. Land deposits originate from rivers that cross Jakarta, while marine deposits occur due to marine activity. The existence of 2 types of sediment also give rise to transitional deposits which are a mixture of marine deposits and land deposits.

General soil stratification is determined based on borehole data conducted for Bridge 1 and Bridge 4. Both bridges have typical soil layer consists of 3 main layers. The first layer is silty clay layer with a very soft consistency, with N-SPT value ranging from 1 to 4. The thickness of this layer is approximately 15 – 18 m. This layer is targeted for the installation of PVD for vacuum consolidation purposes. The second layer is silty clay with a medium to stiff consistency, with N-SPT value ranging from 6 to 15. This layer contains sand lenses with thicknesses of 2 – 5 m. The third layer which is a layer of silty clay with a stiff to hard consistency, with N-SPT value ranging from 15 to 34, can be found after the second layer till the end of drilling. This layer also contains thin and non-continuous sand lenses. Figure 2 shows approximate soil stratification data.

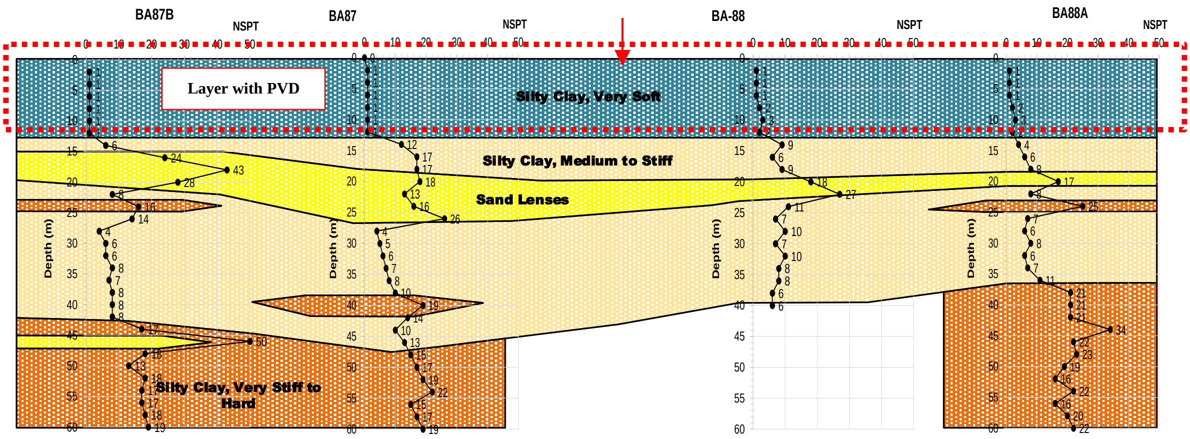

Figure 2. Approximate soil stratification.

3 SOIL SHEAR STRENGTH INCREASE DUE TO CONSOLIDATION

The study on increasing shear strength was carried out based on the results of Vane Shear Test (VST). The VST was also conducted at several project locations, not only at Bridge 1 and Bridge 4. Evaluating data from all project locations has been conducted to understand the characteristics of the very soft clay at the site before and after consolidation process. There are 10 VST points and test results were collected before and after vacuum consolidation. The resume of the vane shear test results before and after consolidation can be seen in Table 1. The mechanism of this study is illustrated in the figure below.

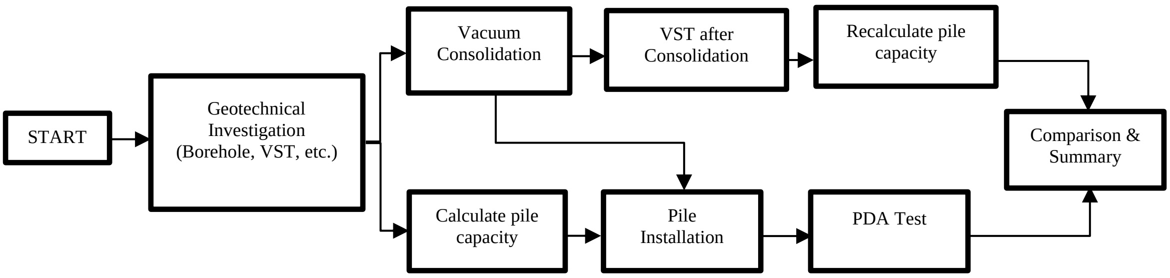

Figure 3. Study flow chart.

Table 1. Summary of VST results, before and after vacuum consolidation

NO	LOCATION	DEPTH OF PVD (m)	Prior to Consolidation ***UNDISTURBED (kPa) (A)***	After Consolidation ***UNDISTURBED (kPa) (B)***	Shear Strength Improvement Factor (C = B/A)
1	Section 8 Zone 1	14.5	16.2	31.7	2.0
			13.3	35.0	2.6
			17.6	41.2	2.3
			19.5	38.4	2.0
3	Section 8 Zone 4	18.0	10	46.2	4.6
			8.6	44.4	5.2
			12.1	50.9	4.2
			17.4	52.1	3.0
4	Section 3 Zone 3	13.5	10.7	48.6	4.5
			7.6	43.2	5.7
			17.1	31.8	1.9
			20.2	53.3	2.6
5	Section 11 Zone 1S	14.0	17.5	27.5	1.6
			12.8	58.1	4.5
			38.5	43.1	1.1
			38.2	43.6	1.1
6	Section 5 Zone 4B	12.5	16.6	58.8	3.5
			14.1	64.3	4.6
			17.4	61.3	3.5
			15.5	48.4	3.1
7	Section 5 Zone 5	12.5	12.1	42.5	3.5
			18.4	67.2	3.7
			17.2	64.0	3.7
			18.6	52.3	2.8
			12.6	39.6	3.1
8	Section 5 Zone 6	13.0	11.1	27.5	2.5
			8.6	66.2	7.7
			15.5	54.2	3.5
			10.6	27.3	2.6
			8.1	41.6	5.1
			14.9	41.7	2.8

From Table 1, it can be observed that the increase in shear strength varies from 1.1 to 7.7 times the original shear strength. Upon closer examination of the results, the multiplier increase in shear strength improvement factor depends on the initial soil shear strength. A higher initial shear strength has a lower shear strength improvement factor compared to soil with lower initial shear strength. This may lead to a situation in which the clay material may reach a compression limit and an increment limit of shear strength due to the consolidation process. Additionally, the increment of the shear strength is not linear based on overburden pressure that was given to the clay soil. To see the trend of shear strength improvement factor, the data results were plotted in Figure 4.

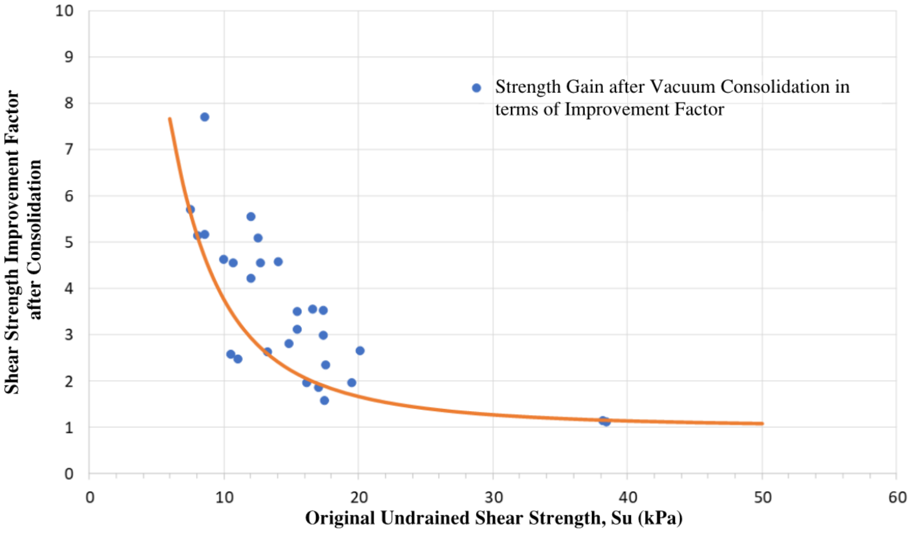

Figure 4. Relation between initial shear strength versus shear strength improvement factor.

4 THEORETICAL PILE CAPACITY

To estimate pile capacity for the foundation, the theoretical pile capacity method by Coyle and Castello (1981) for sandy soil and Tomlinson Method (1970) for clayey soil, along with a safety factor of 2.5 (refer to SNI 8460:2017) for compression capacity were used. The pile capacity after consolidation takes into account the increase in soil shear strength due to the consolidation of very soft clay soils in the surface layer as deep as 10 m, based on the VST results shown in Figure 4.

By using that assumption and method, the pile capacity profiles can be made to determine the length of the pile according to load requirements. The calculated pile capacity profiles are for spun piles with a diameter of 600 mm. The estimated pile length is 40 to 45 m with an allowable capacity of 1300 kN. The calculation shows that increasing the shear strength of soft soil layer due to vacuum consolidation also increases the pile capacity by about 20% and eliminate potential for negative skin friction. The example of pile capacity profile based on N-SPT data can be seen in Figure 5.

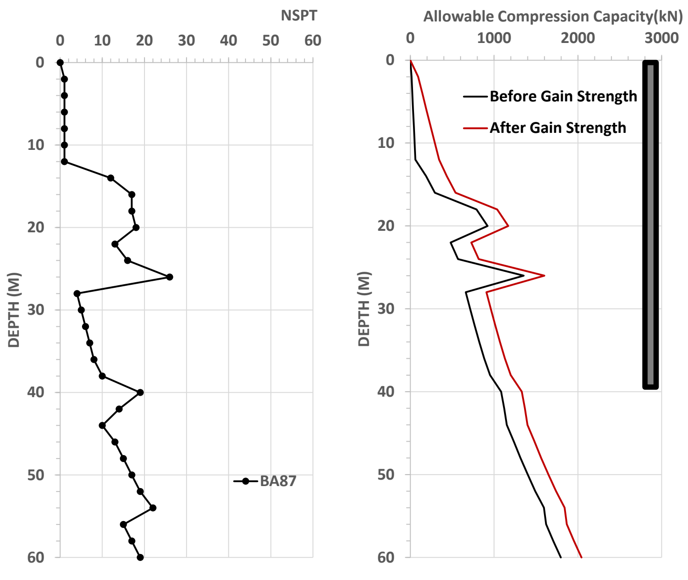

Figure 5. Theoretical pile capacity profile for spun pile with a diameter of 600 mm.

5 ACTUAL PILE CAPACITY

Dynamic pile testing (PDA) was carried out on Bridge 1 and Bridge 4. Each bridge consists of 4 piers and 2 abutments. Pile driving is carried out after the soil has been consolidated, thus all PDA test results reflect the load carrying capacity after an increase in soil shear strength. Unfortunately, there is no pile testing data on the original soil condition, so the theoretical original pile capacity cannot be compared with the pile capacity on the original soil (before consolidation process).

On Bridge 1, 6 points of PDA for pile foundation were carried out, 2 points at Abutment 2, 2 points at Pier 1, and 2 points at Pier 2. Detailed typical of bridge design can be seen on Figure 6. A summary of pile test results on bridge 1 can be seen in Table 2. Based on the test results using a safety factor of 2.5 (refer to SNI 8460:2017), the allowable capacity of the D600 spun pile with a length of 38.75 – 47.5 m is in the range of 1360 – 1800 kN, with an average of 1500 kN.

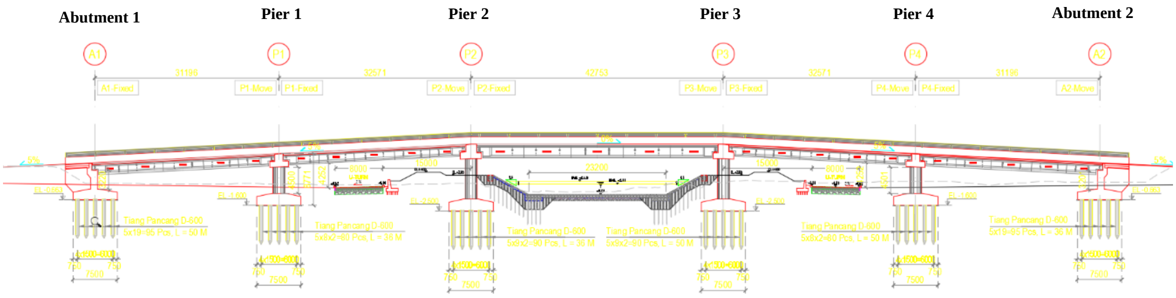

Figure 6. Typical longitudinal section of Bridge 1 & Bridge 4.

Table 2. Summary of PDA test at Bridge 1

No	Location	Pile Name	Date of Finish	Pile Dimension	Length of Pile (m)	PDA Ultimate Capacity (kN)			Allowable Capacity, SF = 2.5 (kN)
						15 min	1 hr	1 day	
1	Abutment 2 - Bridge 1	L01	26-Mar-18	Spun D60 cm	40.25	4230	4320	3500	1400
2	Abutment 2 - Bridge 1	L05	28-Mar-18	Spun D60 cm	38.75	3560	4510	4500	1800
3	Pier 1 - Bridge 1	H43	24-Apr-18	Spun D60 cm	47.5	3670	3830	3760	1504
4	Pier 1 - Bridge 1	H05	25-Apr-18	Spun D60 cm	44	4190	4260	3910	1564
5	Pier 2 - Bridge 1	I48	16-Apr-18	Spun D60 cm	45.75	3290	3400	3400	1360
6	Pier 2 - Bridge 1	I05	17-Apr-18	Spun D60 cm	44.7	4030	3750	3970	1588
Average									1500

On Bridge 4, 8 points of PDA for pile foundation were carried out, 2 points at Abutment 2, 2 points at Pier 2, 2 points at Pier 3, and 2 points at Pier 4. Summary pile test results for bridge 4 can be seen in Table 3. Based on the test results using a safety factor of 2.5, the allowable capacity of the D600 spun pile with a length of 19.25– 35.25 m is in the range of 1312 – 1944 kN, with an average of 1660 kN.

Table 3 Summary of PDA test at Bridge 4

No	Location	Pile Name	Date of Finish	Pile Dimension	Length of Pile (m)	PDA Ultimate Capacity (kN)			Allowable Capacity, SF = 2.5 (kN)
						15 min	1 hr	1 day	
1	Abutment 2 - Bridge 4	F48	01-Feb-18	Spun D60 cm	19.25	3480	3750	4500	1800
2	Abutment 2 - Bridge 4	F95	02-Feb-18	Spun D60 cm	20.4	3470	3790	4080	1632
3	Pier 2 - Bridge 4	C86	08-Dec-17	Spun D60 cm	30.8	3230	4140	4410	1724
4	Pier 2 - Bridge 4	C5	11-Dec-17	Spun D60 cm	34.15	-	3760	3918	1567.2
5	Pier 3 - Bridge 4	D43	29-Jan-18	Spun D60 cm	34.05	4140	4270	4300	1720
6	Pier 3 - Bridge 4	D86	30-Jan-18	Spun D60 cm	32.5	4340	4740	4860	1944

No	Location	Pile Name	Date of Finish	Pile Dimension	Length of Pile (m)	PDA Ultimate Capacity (kN)			Allowable Capacity, SF = 2.5 (kN)
						15 min	1 hr	1 day	
7	Pier 4 - Bridge 4	E38	06-Feb-18	Spun D60 cm	35.26	3940	3920	-	1568
8	Pier 4 - Bridge 4	E76	08-Feb-18	Spun D60 cm	35.25	3520	3670	3280	1312
Average									1660

6 COMPARISON OF PILE CAPACITY

To confirm that the increase in bearing capacity on the pile foundation also occurs along with the increase in soil shear strength due to the completion of the consolidation process, a comparison of the theoretical carrying capacity with the PDA test results is summarized. Unfortunately, PDA test results only reflect the carrying capacity after consolidation, while the carrying capacity in original soil conditions has no test results and only based on theoretically. Nevertheless, the comparison can still be made by seeing the results of theoretical pile capacity, considering the increased shear strength of clay soil due to consolidation process, versus the actual pile capacity from PDA test for pile installed after consolidation completed. The comparison results can be seen in Table 4. The comparison results indicate that the theoretical carrying capacity, that has taken into account the increase in soil shear strength, closely matches the results of PDA testing.

Table 4. Comparison between theoretical pile carrying capacity versus PDA test

Location	Pile	Length (m)	Normal Allowable capacity (kN)	Allowable capacity after gain strength (kN)	Allowable Capacity from PDA (kN)
Bridge 1	Spun D600	38.75 – 47.5	800 – 1400	1000 – 1600	1360 – 1800
Bridge 4	Spun D600	19.25 – 35.25	1050 – 1650	1300 - 1950	1310 - 1940

7 CONCLUSION

The shear strength of the soft soil in North Jakarta can increase from 1.1 to 7.7 times from the original shear strength after consolidation. The shear strength improvement factor depends on the initial soil shear strength. Higher initial shear strength has a lower shear strength improvement factor compared to soil with lower initial shear strength. It is suspected to be due to higher stiffness in soil with higher shear strength, resulting in a lower impact of compression from vacuum loading compared to softer soil. This may lead to a situation in which the clay material may reach a compression limit and an increment limit of shear strength due to the consolidation process. Moreover, the increment of the shear strength is not linear based on overburden pressure that was given to the clay soil.

By carrying out vacuum consolidation on soft soil in the bridge area as deep as approximately 10 m can increase the axial carrying capacity of the foundation by about 20% compared to normal condition (without consolidation). The comparison results, indicate that the theoretical carrying capacity, that has taken into account the increase in soil shear strength, closely matches the results of PDA testing.

DISCLAIMER

This paper does not constitute professional advice. Readers are encouraged to seek guidance from qualified experts or professionals before making decisions based on the content of this paper. The authors and their affiliated institutions disclaim any liability for actions taken by individuals or entities based on the information presented in this paper.

ACKNOWLEDGMENTS

Lastly, we want to acknowledge our families and friends for their patience, encouragement, and understanding during the often-demanding phases of this project. Their unwavering support was a driving force behind our efforts.

REFERENCES

Bowles, J. E. and Guo, Y., 1996. *Foundation analysis and design*, Vol. 5, p. 127. New York: McGraw-hill.

Standar Nasional Indonesia, 2017. *Persyaratan Perancangan Geoteknik* (SNI 8460:2017). Badan Standardisasi Nasional.

Casagrande, A., 1936. *The Determination of the Pre-Consolidation Load and Its Practical Significance*. In Proc. 1st Int. Conf. Soil Mech. pp. 3-60.

Coyle, H. M. and Castello, R. R., 1981. New Design Correlations for Piles in Sand. *Journal of the Geotechnical Engineering Division*, 107(7), pp.965-986.

Ladd, C. C., Foott, R., Ishihara, K. and Schlosser, F., 1977. Stress-deformation and Strength Characteristics.

PT CND Geoteknika, 2020. *Engineering Report - Review Daya Dukung Tiang Pancang Jembatan Tahang 1 dan Jembatan Tahang 4, PIK-2 Terhadap Kenaikan Kuat Geser Tanah Akibat Vakum Konsolidasi*, Bandung, Indonesia

PT Geotekindo, 2017. *Engineering Report - Post VST Result at South Part of Ring Road and Sea Dike Section 1 & 2 & 3 & 4 & 5A*, Jakarta, Indonesia

Rahardjo, P. P., 2013. *Manual Pondasi Tiang*, 4th edition. Bandung: Publikasi GEC, Universitas Katolik Parahyangan.

Tomlinson, M. J., 1970. *Construction Industry Research and Information Association Research Report no.26 - The Adhesion of Piles in Stiff Clay*, London.

Tomlinson, M. J., 1977. *Pile Design and Construction Practice*, 1st edition. London: Viewpoint Publication.

Tomlinson, M. J., 1986. *Foundation Design and Construction*, 5th edition. Essex: Longman Scientific & Technical.

Turkandi, T., Sidarto, Agustiyanto, D. A., Hadiwidjoyo, M., Purbo, M., 1992. *Peta Geologi Lembar Jakarta dan Kepulauan Seribu*. Bandung: Pusat Penelitian dan Pengembangan Geologi.

- This page is intentionally left blank -