Back Analysis of Static Lateral Loading Tests of Pile Foundations in Soft Soils

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ABSTRACT

Pile foundations are used to support structures. In addition to bearing the pile's load, the design's foundation structure must withstand lateral loads. As a result of the pile being exposed to lateral loads, it causes deflection or displacement of the pile. One method of testing foundation capacity is the static lateral loading test. The result of this test is the lateral deflection of the pile, with a certain load given to the pile head due to cyclic loads. The lateral loading test data in the study was tested on seven piles with a diameter of 600 m at the Kapuk Banten project site. The soil investigation results found that the dominance of soft clay soil is quite thick. This research aims to back-analyze the results of static lateral loading tests using LPile 2019 software as a model evaluation in soft soil geotechnical conditions. The back analysis obtained soil parameters that produced deflections close to the results of static lateral loading tests.

Keywords: static lateral loading test; lateral deflection; N-SPT; backa analysis; LPile.

INTRODUCTION

Pile foundations are widely used to support structures when the existing soil has insufficient bearing capacity to use shallow foundations or when settlement is a major design concern (Bowles, 1996). According to (Reese et al., 2006) in addition to withstanding vertical structural loads, pile foundations in the design must also withstand lateral loads. Piles that receive lateral loading are one of the problems in foundation engineering involving soil and structure interaction, while piles with axial loads determine soil interaction (Alvi, 2020). Pile foundations are sensitive to lateral deformation (Luo, 2018). Many studies have been conducted on the behavior of piles that are exposed to lateral loads causing deflection or displacement of the pile (Purwana, 2017).

The design of pile foundations must be calculated based on the characteristics and properties of the soil that are close to the actual conditions. One of the methods of testing foundation capacity is the static lateral loading test. The result of this test is the lateral deflection of the pile, with a certain amount of load applied to the pile head due to cyclic loads. The purpose of this research is a back analysis of static lateral loading tests using LPile 2019 software as a model evaluation in soft soil geotechnical conditions to obtain soil parameters that are suitable or close to the results of static lateral loading tests, namely lateral deflection of the pile. The lateral loading test data was tested on seven piles located in Kapuk Banten. From the results of the soil investigation, soft soil conditions were found in the surface layer, which was quite thick.

RESEARCH METHODS

The research data used is from a project located in Kapuk, Banten. The technical data collection that will be used is borlog soil investigation data, foundation material properties and static lateral loading test results data.

Soil Condition

Kapuk Banten is geographically located in North Jakarta, with land types in rice fields and ponds by the sea. The results of soil investigation drilling, in general, showed that soft soil dominated the soil conditions from the surface layer to a fairly thick depth. The soil investigation was carried out with SPT tests at 3 points, as shown in Figure 1. From the SPT values, information on soft soil with a fairly thick depth was obtained, namely BH-1: 12.5 m, BH-2: 16.5 m, and BH-3: 12,5 m.

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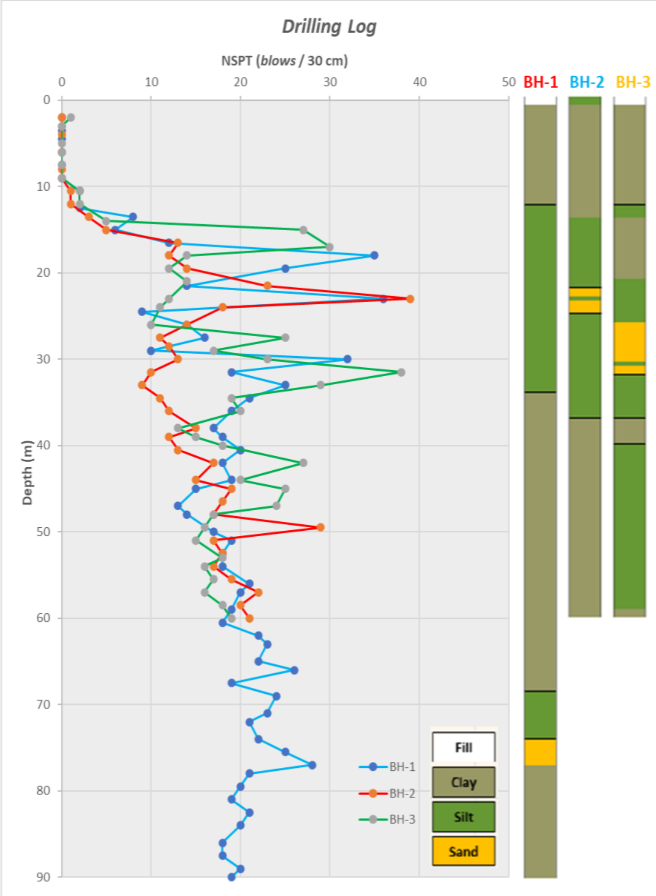

Figure 1. N-SPT Profile vs Depth (m)

In the SPT test at each specific depth, undisturbed soil samples were taken using a sleeve tube for laboratory testing. Tables 1 - 3 show the SPT results in the field whose depth is adjusted to the length of the embedded pile. For the parameters γ, c_u, φ, some are obtained from laboratory testing, and some are correlated. Then, for all parameters, k and ε_{50} using correlation to N-SPT. In Tables 4 - 6, some of the literature used for parameter correlation. These soil parameters are used as input for LPile modeling.

Table 1. BH-1 N-SPT and Soil Parameters

No	Depth (m)	Soil Layer	N-SPT	γ (kN/m^3)	γ' (kN/m^3)	c_u (kn/m^2)	φ (^{o})	k (kN/m^3)	ε_{50}
1	0 - 10.5	Clay	1	14.6	4.6	2.9	1.5	2000	0.02
2	10.5 - 32.0	Silt	19	16.2	6.2	120.0	13.5	60000	0.005
3	32.0 - 66.0	Clay	19	17.7	7.7	106.4	9.5	60000	0.005

Table 2. BH-2 N-SPT and Soil Parameters

No	Depth (m)	Soil Layer	N-SPT	γ (kN/m^3)	γ' (kN/m^3)	c_u (kn/m^2)	φ (^{o})	k (kN/m^3)	ε_{50}
1	0 -14.5	Clay	2.1	15.1	5.1	15.7	7.5	5000	0.02
2	14.5 - 20.0	Silt	16	17	7	105	-	60000	0.005
3	20.0 - 21.0	Sand	39	17	7	-	39	150000	-
4	21.0 - 21.5	Clay	30	17	7	150	-	150000	0.004
5	21.5 - 23.0	Sand	18	17	7	-	38	100000	-
6	23.0 - 35.0	Silt	12	14.9	4.9	36.3	8.5	50000	0.01
7	35.0 - 58.0	Clay	17	17.7	7.7	103.7	11	70000	0.005

Table 3. BH-3 N-SPT and Soil Parameters

No	Depth (m)	Soil Layer	N-SPT	γ (kN/m^3)	γ' (kN/m^3)	c_u (kn/m^2)	φ (^{o})	k (kN/m^3)	ε_{50}
1	0 - 10.5	Clay	1	14.3	4.3	2.9	2	2000	0.02
2	10.5 - 12.0	Silt	5	16	6	25	-	20000	0.02
3	12.0 - 19.0	Clay	19	17	7	100	-	60000	0.005
4	19.0 - 24.0	Silt	11	17	7	80	-	50000	0.01
5	24.0 - 28.5	Sand	22	17	7	-	37	120000	-

Table 4. Correlation of c_u Clay Soil with N-SPT

Consistency	N	C_s (kN/m^2)
Very soft	0-2	<12
Soft	2-4	12-25
Medium	4-8	25-50
Stiff	8-15	50-100
Very Stiff	15-30	100-200
Hard	>30	>200

Source: (Terzaghi et al., 1996)

Table 5. Correlation of Modulus of Subgrade Reaction (ks) by Soil Type

Soil	k_s (MN/m^3)
Dense sandy gravel	220-400
Medium dense coarse sand	157-300
Medium sand	110-280
Fine or silty, fine sand	80-200
Stiff clay (wet)	60-220
Stiff clay (saturated)	30-110
Medium clay (wet)	39-140
Medium clay (saturated)	10-80
Soft clay	2-40

Source: (Bowles, 1996)

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Table 6. Correlation of ε_{50} to Clay Consistency

Consistency of Clay, psf		Undrained Shear Strength, kPa	ε_{50}
Very soft	>250	>12	0.02
Soft	250–500	12–24	0.02
Medium	500–1000	24–48	0.01
Stiff	1000–2000	48–96	0.006
Very stiff	2000–4000	96–192	0.005
Hard	<2000	<192	0.004

Source : (Reese et al., 2006)

Foundation Material

The materials used are 600 mm diameter piles using concrete quality fc' 48.9 MPa, as shown in Table 7 below. Based on the foundation design, varying pile depths are determined, as shown in Table 8 below.

Table 7. Input LPile Properties of Pile

Pile Properties	
Type and Shape Section	Elastic Section
Pile Lengths (m)	According to the depth of the pile
Pile Diameters (mm)	600
Structural Shape	Pipe
Wall Thickness (mm)	100
Pile Cross Sectional Area (mm^2)	282743.34
Moment of Inertia I (mm^4)	6361725124
Elastic Modulus E (kn/m^2)	33167484.08

Table 8. Pile Depth

No. Pile	Pile Depth (m)
TP - 1'	24.7
TP - 2	27.6
TP - 3'	25
TP - 4'	46
TP - 5'	26
TP - 6	28.5
TP - 7	45.5

Pile Lateral Loading Test Data

The static lateral loading test of piles refers to (ASTM D3966/D3966M, 2013) states that the lateral load is applied at the cut-off level at the pile-head. The lateral loading test was conducted in 4 loading cycles: cyclic 1: 50%, cyclic 2: 100%, cyclic 3: 150%, and cyclic 4: 200%. The test load is at a maximum loading of 200% or a working load of 10 tons. Table 9 shows the results of the static lateral loading test of 7 piles obtained from the maximum load of each cyclic, resulting in lateral deflection pile response. Figure 2 shows the deflection graph of 7 piles against the results of the maximum load per cyclic.

Table 9. Lateral Deflection of the Pile

Pile	Lateral Deflection (mm)			
	Cyclic 1	Cyclic 2	Cyclic 3	Cyclic 4
	2.5 ton	5 ton	7.5 ton	10 ton
TP - 1'	1.61	5.15	11.46	21.10
TP - 2	0.92	3.05	6.00	11.51
TP - 3'	4.27	11.41	18.48	27.49
TP - 4'	2.88	8.67	19.13	29.34
TP - 5'	3.66	10.25	20.76	28.48
TP - 6	3.30	7.92	18.33	29.38
TP - 7	3.32	8.87	18.43	30.42

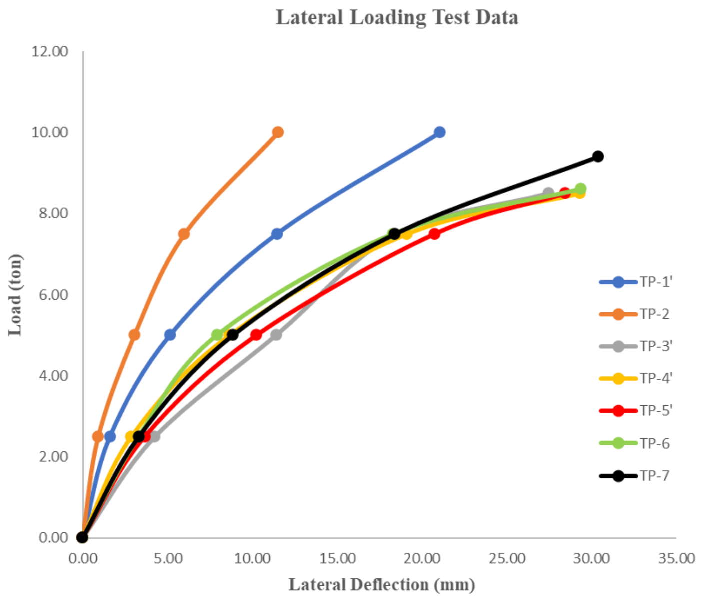

Figure 2. Deflection Curve of 7 Piles of Lateral Loading Test Results

Back Analysis with Lpile 2019 Software

Modeling uses a single pile with a free pile head. For input of soil layers and parameters based on SPT results and correlations listed in Tables 1 - 3. SPT data used is the closest point of 7 test piles. Figure 3 is an example of pile TP-1' for the selection of soil layer type (p-y curve type) by looking at the SPT value. For soft soil, the soft clay model is selected; for medium to hard soil, the stiff clay model is selected; and for the sand soil layer, the sand model is selected. Followed by soil properties as shown in Figure 4, the parameters of soft clay layer 1 are γ', c_u, ε_{50}; for stiff clay, added parameter k; for sand, the parameters are γ', φ, and k.

There are two focuses of evaluation of this modeling, the first is the range of parameter values used, namely the literature in Tables 4 - 6 for parameters c_u, k, and ε_{50}. The second focus is the possibility of not being able to use a soft clay model characterized by deflection results, whether the value is high or low, the value still cannot approach the results of the lateral loading test. So, it is tried to use a stiff clay model with a minimum parameter c_u 23.94 kn/m^2. In the parameter trial process to match the lateral deflection, it is necessary to have an error accuracy level in each cycle or refer to the relative error value calculated as follows:

$$\%U = \frac{|U_P - U_L|}{U_L} \times 100\% \quad (1)$$

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where :
$\%U$: relative error of lateral loading test deflection value with modeling deflection
U_P : modeling deflection
U_L : lateral loading test deflection

It can be said that the smaller the error precision, the closer the accuracy of the parameters and the fit of the lateral deflection results of the loading test.

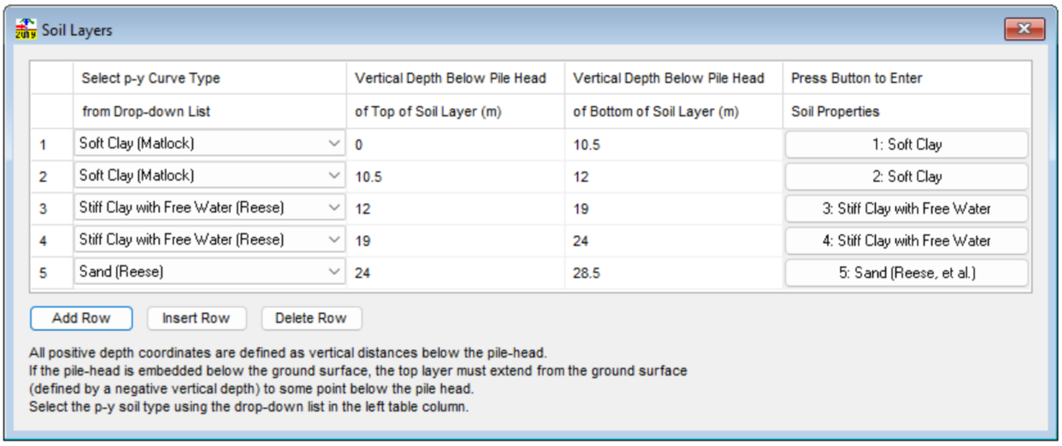

Figure 3. LPile Input of Soil Layer (Example TP-1')

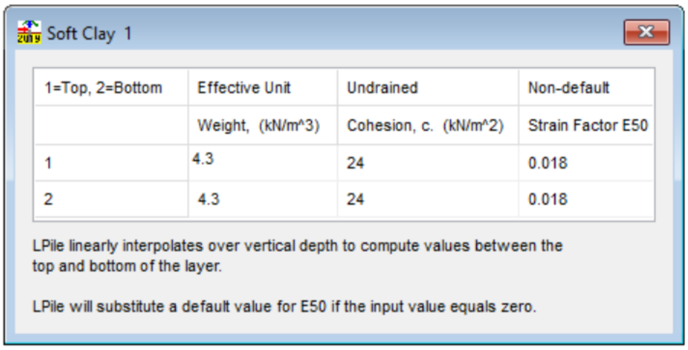

Figure 4 LPile Input of Soil Parameters (Example TP-1')

Furthermore, for the LPile load, Pile-Head Loading Condition (1) Shear [lb or kN] and (2) Moment [in-lb or kN-m] and Condition (1) for loading type can be explained that the load is entered in condition one to get the shift or deflection value. The load used corresponds to the load in the lateral loading test. Please pay careful attention to the use of units as requested by the program. After all the modeling stages have been carried out, the program can perform calculations. The output of the required LPile calculation is the load versus lateral deflection curve. The modeling output is matched against the deflection of the lateral loading test results. If there is a significant deviation, the modeling is repeated by changing the soil parameters until the deflection results match or approach the lateral loading test.

RESULTS AND DISCUSSION

The initial modeling process using the initial soil parameters or original data, as seen in Figure 5, shows a deviation or error rate of more than 100% of the high deflection results from LPile modeling to the lateral loading test results. Therefore, it is necessary to adjust the soil parameters (refer to Table 4 - 6) until the deflection results are suitable or close.

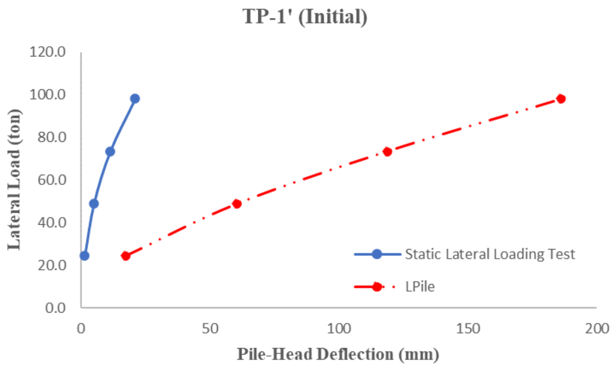

Figure 5. Initial Modeling Process (Example TP-1')

The next process encountered problems in example TP-3' the soft clay model in the first soil layer produced a uniform deflection curve shape and a high deviation or error rate with a range of 29% - 37%, although the parameters were tried to be increased and decreased. The best soft clay model results are shown in Figure 6, with an error of 29%. Then modeling was attempted by replacing the stiff clay model with suitable parameters and an error rate of 15%, as shown in Figure 9 TP-3'. In Figure 7, trying to use the stiff clay model results in a deflection curve that deviates far, and the error rate is more than 100%, so the soft clay model is used, which is considered appropriate, as shown in Figure 9 TP-1' and TP-2 with an error of 10%.

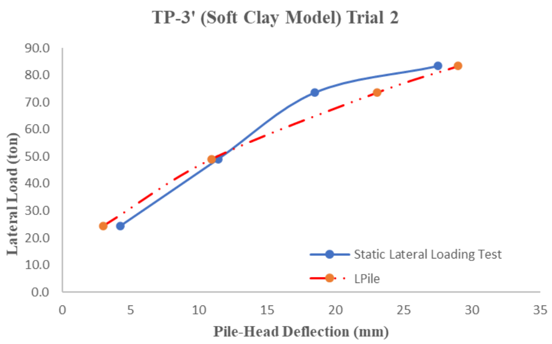

Figure 6. Soft Clay Model (Example TP-3')

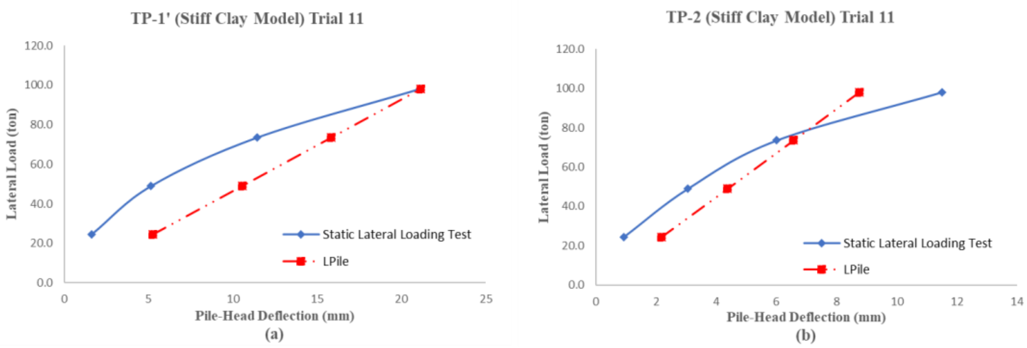

Figure 7. Stiff Clay Model (Example TP-1' and TP-2')

The output obtained in Figure 8, for example, TP-1', shows the deflection and bending moment values that occur from 4 cyclic loading along the pile. The reaction that occurs with the magnitude of the applied load causes an increase in the deflection value at the pile head. The deflection occurred

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only at the depth of the first layer of soft clay, 10.5 m, because at the next depth, no pile reaction occurred. This explanation applies to all piles.

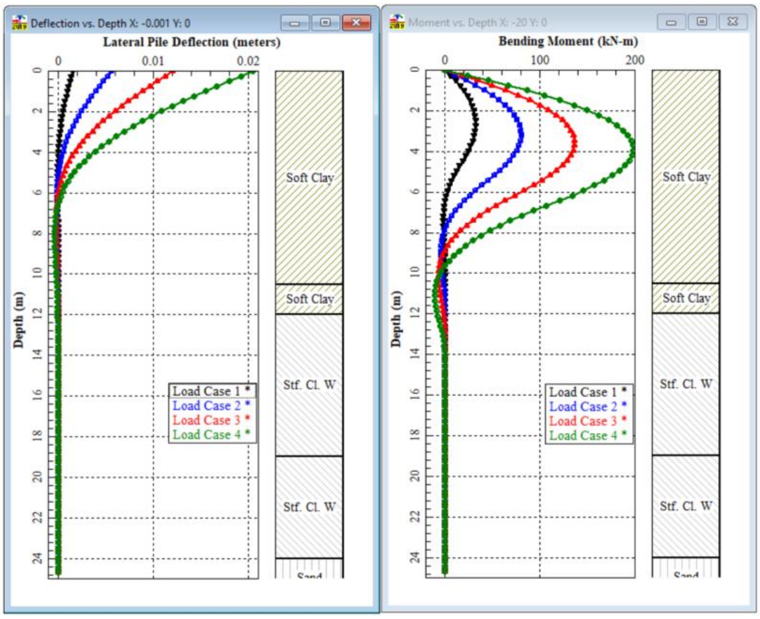

Figure 8. Deflection and Bending Moment (Example TP-1')

Table 10 below shows the parameters that are considered appropriate because they produce deflection values that are close to the same, and the level of deviation is low from several modeling attempts. The influential parameters are the values of c_u and ε_{50} for the soft clay model and the influence of the k value for the stiff clay model. Referring to the literature, the parameter c_u is still within the range of c_u values of 0 - 25 kn/m^2 for very soft to soft soil consistency. Then, the parameter ε_{50} is still within the range of values, except that in TP-3' stiff clay model, the value of ε_{50} decreases. Moreover, for the k parameter, it is still within the range of soft soil 2000 - 40000 kn/m^3.

Table 10. LPile Modeling Soil Parameters

Pile	No. Borlog	Layer Depth (m)	Soil Type	N-SPT	c_u (kn/m^2)	k (kN/m^3)	ε_{50}	Soil Model
TP - 1'	BH-3	0 - 10.5	Clay	1	24.0	-	0.018	*Soft clay*
TP - 2					25.0	-	0.005	
TP - 3'	BH-2	0 - 14.5	Clay	2.1	14.0	-	0.02	*Soft clay*
					25.0	1950	0.0018	*Stiff clay*
TP - 4'					14.0	-	0.018	*Soft clay*
TP - 5'	BH-1	0 - 10.5	Clay	1	14.5	-	0.02	*Soft clay*
TP - 6					15.0	-	0.017	
TP - 7					16.0	-	0.02	

Figure 9 shows the results of 7 piles that were analyzed using LPile to get deflection results close to the same as the static lateral loading test results. The lateral deflection results correspond to 4 cyclic loading given at the head of the pile. From the modeling of 6 piles, the deflection results are more significant than the deflection results of the lateral loading test, there is a significant difference in deflection at TP-4', TP-5' and TP-6. Then, at TP-3' modeling, there is a lower difference in deflection obtained.

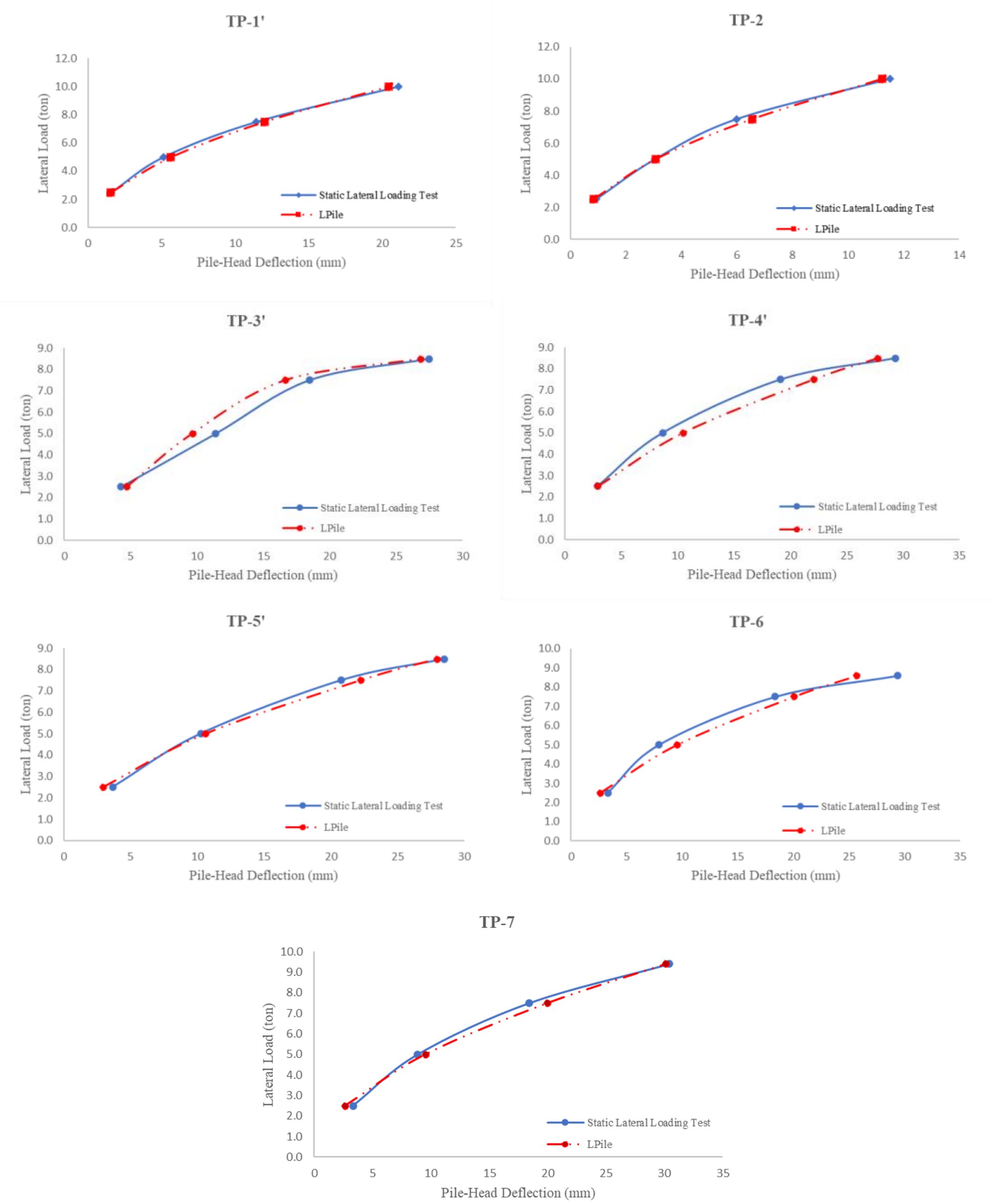

Figure 9. LPile Modeling Static Lateral Loading Test (7 driven pile)

CONCLUSIONS

In this study, SPT boring data, foundation material properties, and lateral loading test results were used without changing the original data, with the exception of soil parameters for modeling input. The initial modeling input parameters show higher deflection values and a high error of more than 100% of the lateral loading test results, so the soil parameters need to be adjusted until they get a deflection value that is close to matching. The greater the lateral load applied, the greater the deflection value produced. The deflection value occurs only in the first layer, thus the parameters that are adjusted or replaced are only the parameters in the first layer. In the Results and Discussion chapter, paragraph 2, it can be concluded that not necessarily the soft clay model or the stiff clay model can be used in every pile, the level of accuracy of the error needs to be considered because

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the smaller the error value means that the deflection value of the LPile is close to the same as the results of the lateral loading test. In soft soil conditions that affect the deflection value, namely the soft clay model parameters c_u and ε_{50}, the greater the value of c_u, the smaller the deflection value, and vice versa, while the greater the value of ε_{50}, the greater the deflection value, and vice versa. In the stiff clay model where the parameter k is the greater the value, the smaller the deflection value, and vice versa. Overall, the parameters used are still within the range of values in the literature.

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