

UNCERTAINTY OF p-y CURVE PARAMETERS FOR LATERALLY LOADED DRIVEN PILES IN SOFT CLAYS

Widjojo A. Prakoso

Civil Engineering Department, Universitas Indonesia, Indonesia. E-mail: wprakoso@eng.ui.ac.id

Miranti

PT Eskapindo Matra, Indonesia. E-mail: miranti.me92@gmail.com

Helen Fransisca, Putri S. Gandina, Dolok H. Panjaitan, and A. Magfirah Fitrah

PT DSP Consulting Engineers, Indonesia. E-mail: helen@davysukamta.com, putri@davysukamta.com,
dolok@davysukamta.com, firah@davysukamta.com

One of the design checks for driven piles is the pile lateral deflection due to lateral forces and moments. In the Indonesian practice, the pile lateral deflection is limited to 25mm to minimize the pile structural demands during strong earthquakes. This paper evaluates the field performance of laterally loaded driven piles, and is a continuation of previous studies by the authors. Twenty-nine driven concrete spun piles from three projects were laterally loaded according to ASTM D 3966-07, and the maximum lateral load was gradually applied in four cycles to 200% of the design lateral capacity. Subsequently, the test results were back-analyzed using the computer program LPILE. For each case, a trial-and-error process was conducted using a set of LPILE p-y curve input parameters to match the LPILE results with the actual pile load versus lateral deflection data. The required LPILE p-y curve input parameters were then evaluated. The first finding was that soft clays not subjected to any ground improvement measures appeared to be modelled better using the p-y curves for soft clays, while soft clays subjected to ground improvement measures appeared to be modelled better using the p-y curves for stiff clays with free water. New S_{u-Sug} based correlations for estimating the strain level ϵ_{50} and the initial stiffness K_{Sug} are proposed. The uncertainty of these correlations was also examined.

Keywords: Driven piles, laterally loaded piles, pile load tests, soft clays, p-y curves, preloading, uncertainty.

1. Introduction

The lateral deflection of driven piles is one of the design checks, as the piles may be subjected to significant lateral forces, including those induced by earthquakes. In fact, based on the Indonesian geotechnical code SNI 8460:2017 (BSN 2017), the allowable lateral resistance is to be determined by the lateral deflection limit criteria. These limit criteria include the 25mm limit for significant earthquake lateral load conditions. Therefore, it is of interest to understand the lateral deflection of piles subjected to significant lateral load.

The pile lateral deflection and bending moments are primarily controlled by the upper soil layers. Where these layers are soft clays, the pile lateral deflection and bending moment could be relatively significant. In some cases, these soft clays are subjected to ground improvement measures, such as vacuum and fill preloading, and subsequently, driven piles are installed through these improved soils.

This paper evaluates cases of laterally loaded driven piles in both soft clays in their relatively original conditions and similar clays subjected to either vacuum or fill preloading. These cases are subsequently evaluated using the typical models employed in geotechnical engineering practices. This paper is a continuation of that previously published by the authors (Prakoso et al. 2024).

2. Data

The case database consisted of 28 load test data sets of 0.6 m in diameter (wall thickness = 0.10 m) and one load test data set (Case No. 29) of 0.5 m in diameter (wall thickness = 0.09m) driven prestressed concrete spun piles. These 29 piles were taken from three projects (P1, P2, and P3). The upper soft clays of P1 were not improved. The upper soft clays of P2 and P3 were improved by way of vacuum preloading and by way of fill preloading, respectively. In each project location, a series of borings consisting of N-SPT values were available; due to space limitation, only the summary of N-SPT values of the upper soft clays is provided. For P1, the mean N-SPT to depths of 10.5 m to 14.5 m is 1 – 2 blow/0.3m, and for P2, the mean N-SPT to depths of 10.0m to 11.0m is 1 – 3 blow/0.3m. For P3, the mean N-SPT to depths of 5.0 m to 7.0 m is 5 – 7 blow/0.3m.

All the laterally loaded pile tests were performed based on ASTM D 3966-07 (ASTM 2007) using two-pile setting. The test condition was the free-head condition, and lateral test load was applied at approximately pile cut-off elevation. Each load test was conducted in four cycles: 50%, 100%, 150%, and 200% of design lateral capacity. The lateral deflection was measured at the elevation as the applied load. The cases considered are summarized in Table 1, and their “back-bone” load versus lateral deflection curves are shown in Fig. 1.

Table 1. Data of laterally loaded pile tests in soft clay-silt soils.

No	Project	Pile ID	Pile Embedded Length (m)	Depth of Evaluated Soil Layer (m)	p-y Curve Parameters			
					Soil Model	Observed Strength, S_{u-Sug} (kPa)	ϵ_{50-Sug}	k_{Sug} (MN/m ³)
1	P1	TP - 1'	24.7	0 - 10.5	Soft clay	24.0	0.018	-
2	P1	RP-1	24.7	0 - 10.5	Soft clay	21.0	0.020	-
3	P1	TP - 2	27.6	0 - 10.5	Soft clay	39.0	0.018	-
4	P1	RP-2	27.6	0 - 10.5	Soft clay	38.0	0.018	-
5	P1	TP - 3'	25.0	0 - 14.5	Soft clay	14.0	0.018	-
6	P1	RP-3	25.0	0 - 14.5	Soft clay	14.0	0.020	-
7	P1	TP - 4'	46.0	0 - 14.5	Soft clay	16.0	0.022	-
8	P1	RP-4	46.0	0 - 14.5	Stiff clay w. free water	35.0	0.200	5
9	P1	TP - 5'	26.0	0 - 10.5	Soft clay	14.5	0.021	-
10	P1	RP-5	26.0	0 - 10.5	Soft clay	14.0	0.020	-
11	P1	TP - 6	28.5	0 - 10.5	Soft clay	15.0	0.017	-
12	P1	RP-6	28.5	0 - 10.5	Soft clay	13.0	0.020	-
13	P1	TP - 7	45.5	0 - 10.5	Soft clay	16.0	0.020	-
14	P1	RP-7	45.5	0 - 10.5	Soft clay	16.0	0.020	-
15	P1	P711	27.2	0 - 10.5	Soft clay	18.0	0.018	-
16	P1	P544	27.5	0 - 14.5	Soft clay	16.0	0.020	-
17	P1	P592	28.1	0 - 10.5	Soft clay	25.0	0.015	-
18	P1	T 645	29.0	0 - 14.5	Soft clay	20.0	0.026	-
19	P1	T 1064	29.0	0 - 14.5	Soft clay	14.8	0.020	-
20	P1	T 470	29.0	0 - 14.5	Soft clay	12.0	0.018	-
21	P1	T 688	30.0	0 - 14.5	Soft clay	14.0	0.020	-
22	P1	T 1304	30.0	0 - 14.5	Soft clay	14.0	0.020	-
23	P1	T 674	28.5	0 - 14.5	Soft clay	10.0	0.020	-
24	P1	T671	28.5	0 - 14.5	Soft clay	12.0	0.023	-
25	P2	P 1459	33.4	0 - 10.0	Stiff clay w. free water	35.0	0.015	55
26	P2	P 828	36.5	0 - 10.0	Stiff clay w. free water	50.0	0.009	130
27	P2	P 1387	33.1	0 - 11.0	Stiff clay w. free water	40.0	0.010	96
28	P3	SP 54	30.0	0 - 7.0	Stiff clay w. free water	40.0	0.015	70
29	P3	SP 75*	30.5	0 - 5.0	Stiff clay w. free water	59.0	0.008	150

For Project P1, Case No. 23 was the case with the largest pile lateral deflection; at a lateral load of about 75kN, the deflection was about 36.6mm. Cases No. 3 and 4 were the cases with the smallest lateral deflection; at the same load, the deflection was about 6.0mm and 6.8mm, respectively. For Project P2, at a lateral load of about 80kN, the pile lateral deflection varied from 2.9mm to 6.4mm. For Project P3 for the pile with same diameter, at a lateral load of about 90kN, the pile lateral deflection was 4.6 mm.

3. Research Method

The extensive back analyses of laterally loaded pile tests were performed using the computer program LPILE (Reese and Wang 2016) to match the LPILE results with the actual load versus lateral deflection data. Four load points were considered in the back-analyses: 50%, 100%, 150%, and 200% of design lateral capacity. The p-y curves for soft clays were computed using the model developed by Matlock (1970), and the parameters evaluated were the undrained shear strength S_u and the strain level at 50% of the ultimate pressure ϵ_{50} . The p-y curves for stiff clays with free water were computed using the model developed by Reese et al. (1975), and the parameters evaluated were the initial stiffness K and the strain level ϵ_{50} . The p-y curves for sands were computed using the model developed by Reese et al. (1974). All the parameters assumed static loading conditions. The soil model, S_u , ϵ_{50} , and K were the p-y curve parameters to be evaluated.

The set of LPILE input parameters was considered to be final if it gave the minimum overall difference in lateral deflection for the above load points. The required parameters in LPILE models to match the test and model results are denoted as S_{u-Sug} , ϵ_{50-Sug} , and K_{Sug} . The results reported herein are based on the processes performed to the upper soft clays previously described. The parameters from the three projects were subsequently evaluated using the linear regression approach, and the associated uncertainty was also evaluated.

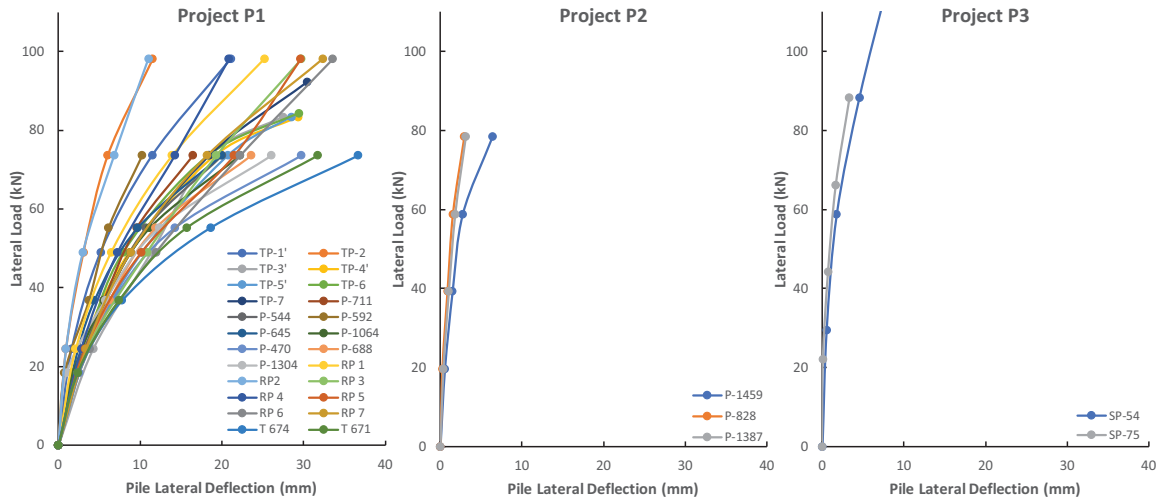


Fig. 1. Pile lateral load versus lateral deflection curves.

3. Results

3.1. General observations

All the back-analysis results are summarized in Table 1 (“p-y Curve Parameters” consisting of soil model, S_{u-Sug} , ϵ_{50-Sug} , and K_{Sug}). The upper clays of the cases in P1 (no ground improvement) could be modelled using either the p-y curves for soft clays (23 of 24 cases) and the p-y curves for stiff clays (1 of 24 cases). The upper clays of all the three cases in P2 (vacuum preloading) and those of the two cases in P3 (fill preloading) could also be modelled using the p-y curves for stiff clays. Based on these observations, soft clays not subjected to any improvement measures appear to be modelled more appropriately using the p-y curves for soft clays. On the other hand, soft clays subjected to ground improvement measures appear to be better modelled using the p-y curves for stiff clays with free water. There is no clear difference between the effect of vacuum preloading and that of fill preloading on the suggested models and parameters.

3.2. Suggested ϵ_{50}

Reese et al. (2006) propose that the strain level ϵ_{50} for very soft to soft clays having $S_u < 24$ kPa and for medium clays $S_u = 24$ kPa – 48 kPa are 0.02 and 0.01, respectively. The strain level ϵ_{50} for stiff clays having $S_u = 48$ kPa – 96 kPa are 0.006. These values are shown in Fig. 2a.

S_{u-Sug} varied from 10 kPa to 39 kPa (mean = 17.8 kPa) for the p-y curves for soft clays of P1, and it varied from 35 kPa to 59 kPa (mean = 44.8 kPa) for the p-y curves for stiff clays of P2 and P3. ϵ_{50-Sug} varied from 0.015 to 0.026 (mean = 0.0197) for the p-y curves for soft clays of P1, and it varied from 0.008 to 0.015 (mean = 0.0114) for the p-y curves for stiff clays of P2 and P3. These ϵ_{50-Sug} values are plotted against the suggested S_{u-Sug} in Fig. 2a, and ϵ_{50-Sug} decreases with S_{u-Sug} . This trend is consistent with that proposed by Reese et al. (2006), but ϵ_{50-Sug} for higher S_{u-Sug} appears to be somewhat greater than that proposed by Reese et al. (2006). The linear regression of ϵ_{50-Sug} to S_{u-Sug} as shown in Fig. 2a is as follows:

$$\epsilon_{50-Sug} = (-0.00025 \cdot S_{u-Sug} + 0.024) \quad (1)$$

S_{u-Sug} is in kPa. The standard deviation of the ϵ_{50-Sug} regression equation is 0.00235. Note that Case No. 8 was not included in the regression due to data inconsistency. It is highlighted that this equation was developed based on more data sets with lower S_{u-Sug} and less data sets with higher S_{u-Sug} .

3.3. Suggested K_{Sug}

Reese et al. (2006) propose that the static initial stiffness for clays having $S_u = 50$ kPa – 100 kPa is 135 MN/m³. This value is shown in Fig. 2b.

K_{Sug} for the p-y curves for stiff clays varied from 55 MN/m³ to 150 MN/m³ (mean = 100.2 MN/m³). However, K_{Sug} for the same S_{u-Sug} range of Reese et al. (2006) were 130 MN/m³ and 150 MN/m³. As previously stated, the upper layers of clays subjected to ground improvement could be modelled using the p-y curves for stiff clays, and therefore the range of K_{Sug} is extended to lower S_{u-Sug} as shown in Fig. 2b. It can be observed that K_{Sug} increases with increasing S_{u-Sug} . The linear regression of K_{Sug} to S_{u-Sug} as shown in Fig. 2b is simplified to the following:

$$K_{Sug} = (4,000 \cdot S_{u-Sug} - 78,000) \quad (2)$$

K_{Sug} and S_{u-Sug} are in kN/m^3 and kPa , respectively. The standard deviation of the simplified K_{Sug} regression equation is $11,314 \text{ kN/m}^3$. Note that Case No. 8 was not included in the regression due to data inconsistency. It is highlighted that this equation was developed based on only five data sets.

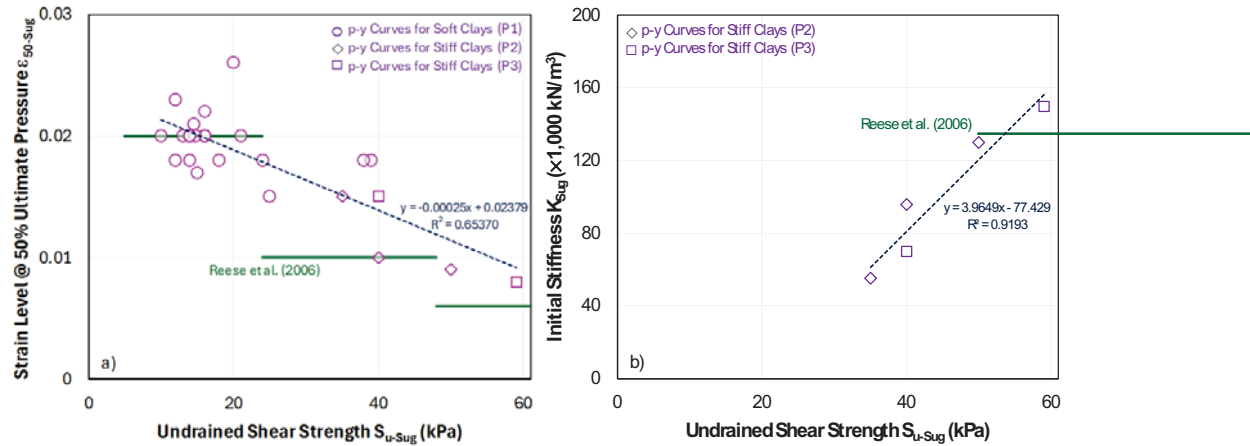


Fig. 2.a) ϵ_{50-Sug} for different S_{u-Sug} , and b) K_{Sug} for different S_{u-Sug} of "Stiff Clays".

4. Conclusions

The lateral deflection of laterally loaded piles is primarily controlled by the upper clays, and the deflection could be significant where these layers are soft clays. This paper evaluated cases of laterally loaded driven concrete spun piles in both soft clays in their relatively original conditions and similar clays subjected to either vacuum or fill preloading, and it evaluated 29 load test data sets from three projects. These cases were back-analyzed using the widely used LPILE models, and extensive trials were performed to obtain the input parameters giving the minimum differences in results. The first result was that soft clays not subjected to any ground improvement measures appeared to be modelled better using the p-y curves for soft clays, while soft clays subjected to ground improvement measures appeared to be modelled better using the p-y curves for stiff clays with free water. Subsequently, new S_{u-Sug} based correlations for estimating the strain level at 50% of the ultimate pressure ϵ_{50} and the initial stiffness K_{Sug} are proposed; for a higher S_{u-Sug} , ϵ_{50-Sug} is lower, and K_{Sug} is higher. These correlations were to complement those widely used in the geotechnical engineering practices. The uncertainty of these correlations was also examined.

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