EASR

Engineering and Applied Science Research

https://www.tci-thaijo.org/index.php/easr/index

Published by the Faculty of Engineering, Khon Kaen University, Thailand

Experimental study of pile set-up of driven piles in Bangkok Clay

Phitsanu Pholkainuwatra[1)], Sitthiphat Eua-apiwatch*[1)] and Siam Yimsiri[2)]

[1)]Department of Civil Engineering, Faculty of Engineering, Burapha University, Chonburi 20131, Thailand
[2)]Sustainable Civil Engineering and Infrastructure Research Unit, Department of Civil Engineering, Burapha University, Chonburi 20131, Thailand

Received 19 March 2021
Revised 29 April 2021
Accepted 19 May 2021

Abstract

Experimental study of pile set-up of driven piles in Bangkok Clay was conducted on seven I-shape prestressed concrete piles with their pile tips varied between 8-21 meters below ground level. The study site was selected at State Railway of Thailand (SRT) Eastern line between Hua Takhe station and Chachoengsao junction. The soil condition of the site consisted of high plasticity soft clay approximately 12 meters in thickness and the second layer is 6 meters of high plasticity medium clay, and the third layer is 4 meters of high plasticity stiff clay. Three periods of dynamic pile load test were carried out, including the end of drive (EOD), 11 days, and 32 days after pile installation to observe the pile resistance set-up behavior. After 32 days, it was found that the overall average side resistance set-up ratio is 5.4, the overall average tip resistance set-up ratio is 1.5, and the total pile resistance set-up ratio is 2.7. The increase in side resistance with time is more significant than that of tip resistance. The increase in side and tip resistances of stiff clay are smaller than those of soft and medium clays. To predict pile set-up in Bangkok Clay, the pile set-up parameter of 1.065 is recommended for Skov and Denver [1] pile resistance prediction equation.

Keywords: Pile set-up, Dynamic pile load test, Driven pile, Pile capacity, Bangkok Clay

1. Introduction

Bangkok is located on the low-lying Chao Phraya plain covered by a thick series of alluvial and marine soil deposits, and the engineering properties of Bangkok Clay have been investigated by many researchers [2-4]. It is widely known that soft Bangkok Clay is of low strength and highly compressible material [3]. Due to this reason, most structures in this area rest on pile foundations. The ultimate carrying capacity of pile is derived from soil resistance from its tip (end bearing) and side (skin friction). The ultimate capacity of a single pile shows the maximum load that a pile can withstand under a different mode of loading, such as tension, compression, lateral, etc. Driven pile is normally installed into the ground using an impact or vibratory hammer, which leads to disturbance and displacement of soil surrounding it. This technique generates soil displacement at different levels depending on ground conditions. When a pile is driven into fine-grained soil, its capacity, both tip and side resistances, usually increase after its installation.

Many researchers have studied an increase of pile capacity with time after installation which is known as pile set-up, [5-7]. Some experimental studies have been conducted on full-scale load tests of driven piles in cohesive and cohesionless soils, in which they reported effects of set-up with time. Hosseini and Rayhani [8] studied the evolution of side resistance in different types of piles over elapsed times and effects of excess pore water pressure in sensitive marine clay in Ontario, Canada. They found that the average side resistance set-up ratios were approximately 4.5-5.5 times after 30 days from the end of driving. Haque et al. [9] developed an analytical model to estimate the pile set-up parameter from layered soil to predict pile resistances used in pile design based on available soil properties (e.g. undrained shear strength, plasticity index, soil sensitivity). Unfortunately, few researchers conducted studies of pile set-up of driven piles in Bangkok Clay [10]; therefore, this research aims to investigate the behavior of pile set-up of Bangkok Clay.

2. Pile set-up

Pile set-up has been studied extensively in the past by many researchers. This phenomenon is an increase in pile capacity with time after its installation. The mechanisms of pile set-up are mainly divided into three phases [7] as presented in Figure 1.

Phase I: Dissipation of logarithmically nonlinear rate of excess pore water pressure which is the function of soil (permeability and sensitivity) and pile (type and size) properties.

Phase II: Dissipation of logarithmically linear rate of excess pore water pressure which is due to the effects of effective stress increase, consolidation, and gain of shear strength.

Phase III: Thixotropic and aging effects.

*Corresponding author. Tel.: +669 4792 9982
Email address: sitthiphat@eng.buu.ac.th
doi: 10.14456/easr.2022.11

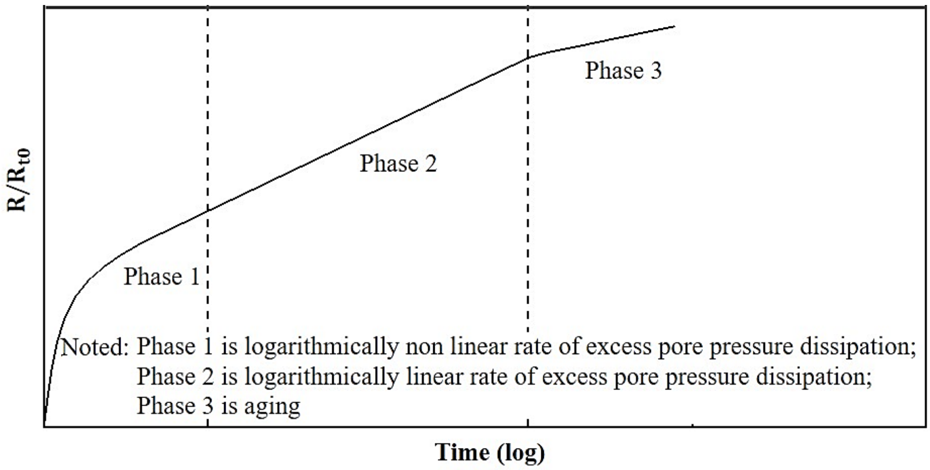

Figure 1 Phase of pile set-up (after Komurka et al. [6])

During pile driving, the installation induces large displacement on the shaft. The surrounding soil is displaced predominately radially along the shaft and beneath the tip, thus generating a significantly increase of excess pore water pressure [11, 12]. During the first phase, the excess pore water pressure is developed by the disturbance and remolding of soil surrounding the pile. The dissipation rate is a nonlinear trend after driving. During the second phase, for some time after pile driving, the dissipation of excess pore water pressure becomes constant with respect to the log of time. This process is accompanied by changes in the stress of soil surrounding the pile, which causes increase of effective stress, and reconsolidation of soil and its strength increases [6]. The duration of this reconsolidation depends on the permeability of soil. The time frame for set-up can be evaluated using conventional consolidation theory. It may range from days in coarse-grained soils to weeks or years in fine-grained soils [13-15]. The last phase of pile set-up, aging of soil, refers to a time-dependent change in soil properties at constant effective stress, which could be related to thixotropy, secondary compression, particle interference, clay dispersion [14, 16], and biological and chemical cementation processes [17].

Several empirical relationships have been proposed to predict driven pile resistance capacity after the end of drive (EOD) period. Skov and Denver [1] proposed the relationship of pile resistance capacity increasing with the logarithm of time as shown in Eq. (1).

$$R_t = R_{t0}\left[A\ log\left(\frac{t}{t0}\right) + 1\right] \tag{1}$$

Where R_t is total pile resistance at a certain time after the installation. R_{t0} is total pile resistance at the initial time. t and $t0$ are time elapsed since the end of initial pile driving and a reference time after pile installation and A is the setup parameter, which was presented by 0.2 for sand and 0.6 for clay.

Svinkin [15] proposed the empirical relationship of pile set-up in silty sands and dense soil based on load test data as shown in Eqs. (2) and (3).

$$R_t = 1.4R_{EOD}t^{0.1} \text{ upper bound} \tag{2}$$

$$R_t = 1.025R_{EOD}t^{0.1} \text{lower bound} \tag{3}$$

where, R_{EOD} is total pile resistance at EOD.

3. Experimental procedures

The study site is located in Lat Krabang district in the Eastern part of Bangkok. Test piles were installed next to the railway track as part of the State Railway of Thailand (SRT) Eastern line between Hua Takhe station and Chachoengsao junction. The location of the study site is presented in Figure 2. Seven I-22 prestressed concrete piles were installed at various depths of pile tips ranging from 8 to 21 meters using a drop hammer weight of three tons and a drop height of 900 mm to cover the three layers, including soft clay, medium clay, and stiff clay. Detail of the test pile is shown in Figure 3. To prevent the disturbance among test piles, an appropriate pile spacing should not less than 30 inches or 2.5 pile diameters as recommended by AASHTO [18] design specifications. Therefore, the tested piles were installed two meters away from each other.

4. Subsurface conditions

Two soil borings down to 30 meters in depth were conducted to obtain the subsurface condition. These boreholes are approximately 130 meters apart to confirm the uniformity of the subsurface. The first layer of soil consisted of high plasticity soft clay with a thickness of 12 meters and the second layer can be classified as high plasticity medium clay with a thickness of 6 meters, and the third layer is 4 meters of high plasticity stiff clay. The dense sand layer was encountered at a depth of 22 meters with a thickness of 8 meters (end of boring). The Shelby tube obtained soft and medium clay samples then sent to the laboratory for fundamental engineering property tested. In stiff clay and dense sand layer, a standard penetration test (SPT) was conducted to obtain the SPT-N value. Laboratory tests of the soil samples following the ASTM consisted of natural water content, Atterberg limits, total unit weight, and unconfined compression tests. The subsurface condition of the study site is shown in Figure 4

Figure 2 Location of study site

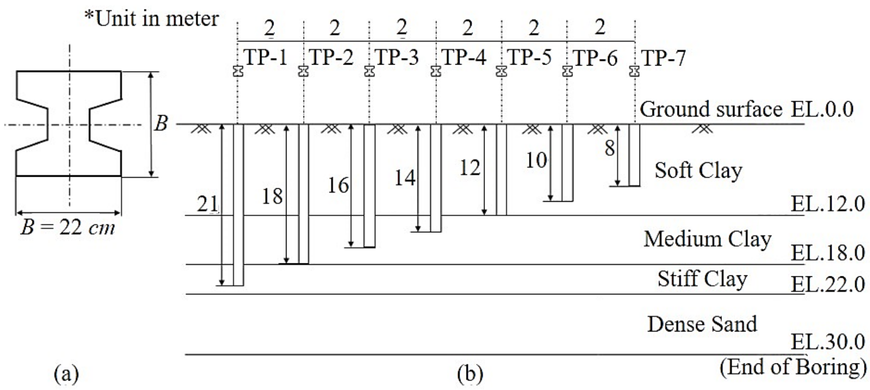

Figure 3 Detail of test piles (a) cross-section of test pile (b) pile installation detail

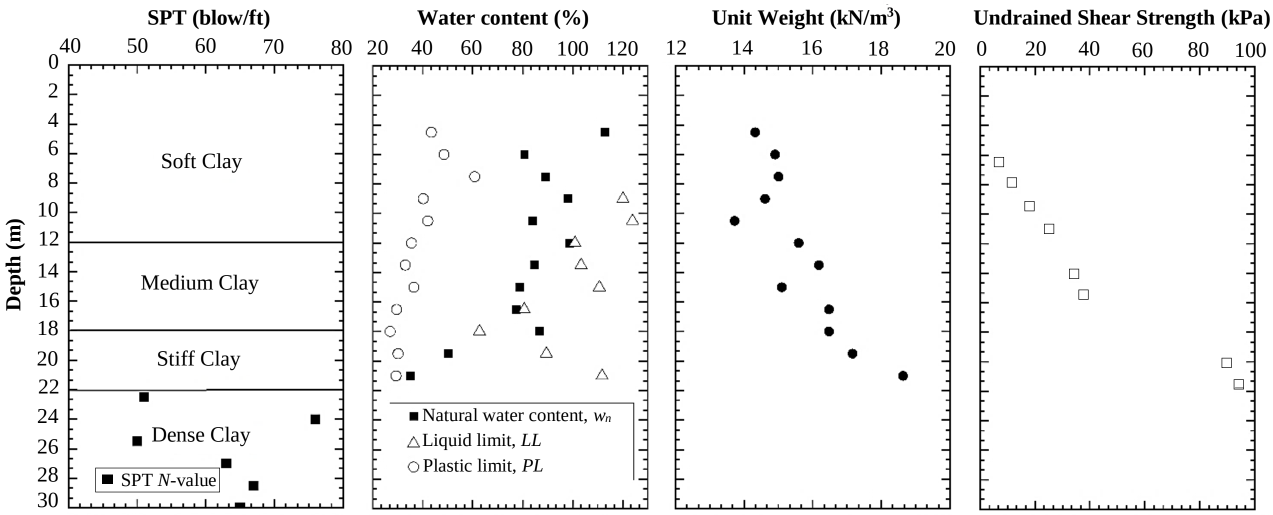

Figure 4 Subsurface condition of the study site

5. Dynamic pile load test

Dynamic Pile Load Test (DLT) following the ASTM D4945 was performed in all tested piles to obtain the ultimate pile capacity. All piles were tested at three periods, including End of Drive (EOD), 11 days, and 32 days after the pile installation. Two pairs of strain transducers and accelerometers were attached at the tested pile surface to measure strain and acceleration signals and three tons drop hammer with drop height of 900 mm was used in the test. The dynamic measurements from strain transducers and accelerometers were acquired with Pile Driving Analyzer (PDA) during driving and restrike. The data obtained from PDA includes stresses, integrity, and estimated ultimate pile capacity. The Case Pile Wave Analysis Program (CAPWAP) was used to determine the side resistance and end bearing of piles.

6. Results and discussions

Table 1 shows skin resistance, tip resistance, and total resistance of piles from dynamic pile load test. Due to the fact that pipe lengths were varied and pile capacity can be separated into side and tip resistances, the analysis can consider the development of individual resistance of specific soil layer.

Table 1 Dynamic pile load test results

Test pile ID.	Events	Time of DLT (day)	R_s (kN)	R_{tip} (kN)	R_t (kN)
TP-1 (21 m)	1st DLT	EOD	336	111	447
	2nd DLT	11	767	127	894
	3rd DLT	32	1044	133	1178
TP-2 (18 m)	1st DLT	EOD	308	95	403
	2nd DLT	11	705	119	824
	3rd DLT	32	933	133	1066
TP-3 (16 m)	1st DLT	EOD	249	82	331
	2nd DLT	11	442	91	533
	3rd DLT	32	658	106	764
TP-4 (14 m)	1st DLT	EOD	107	50	157
	2nd DLT	11	364	65	429
	3rd DLT	32	498	87	585
TP-5 (12 m)	1st DLT	EOD	95	39	134
	2nd DLT	11	277	57	333
	3rd DLT	32	375	76	451
TP-6 (10 m)	1st DLT	EOD	77	32	110
	2nd DLT	11	119	38	157
	3rd DLT	32	188	62	250
TP-7 (8 m)	1st DLT	EOD	65	36	101
	2nd DLT	11	96	40	136
	3rd DLT	32	112	46	158

Remarks: R_s = side resistance; R_{tip} = tip resistance; R_t = total resistance

6.1 Side resistance

Table 2 shows side resistance and unit side resistance of tested piles. The unit side resistance (unit in kN/m) was calculated based on superposition concept by which the side resistances at various depths were subtractions of the side resistances at sequential orders as explained in Eq. (4). The unit side resistances at the EOD were used as reference values in calculating the side resistance set-up ratios at 11 days and 32 days. Table 3 shows side resistance set-up ratios of various conditions.

$$\text{Unit side resistance 10 to 12 m} = \frac{(\text{side resistance 12 m}) - (\text{side resistance 10 m})}{(\text{length 12 m}) - (\text{length 10 m})} \tag{4}$$

Table 2 Unit side resistance

Soil type	Depth of pile tip (m)	Side resistance (kN)			Unit side resistance (kN/m)		
		EOD	11 days	32 days	EOD	11 days	32 days
Soft clay	8	65	96	112	8.1	12.0	14.0
	10	77	119	188	6.0	11.5	38.0
	12	95	277	375	9.0	79.0	93.5
Medium clay	14	107	364	498	6.0	43.5	61.5
	16	249	442	658	71.0	39.0	80.0
Stiff clay	18	308	705	933	29.5	131.5	137.5
	21	336	767	1044	9.3	20.7	37.0

Table 3 Side resistance set-up ratios

Time of DLT (days)	Depth of pile tip (m)										Overall average
	Stiff clay			Medium clay			Soft clay				
	21	18	Avg	16	14	Avg	12	10	8	Avg	
EOD	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
11	2.2	4.5	3.3	0.6	7.3	3.9	8.8	1.9	1.5	4.1	3.8
32	4.0	4.7	4.3	1.1	10.3	5.7	10.4	6.3	1.7	6.2	5.4

Figure 5 shows average side resistance ratio of each soil layer. It can be seen that all soils give quite consistent value with stiff clay gives somewhat smaller values. On average, if considering the dynamic pile load test at 32 days after pile installation, the overall average side resistance set-up ratio is 5.4. This phenomenon can be attributed to pile driving where high excess pore water pressure is developed in the surrounding soil near the pile. This excess pore water pressure causes a reduction in the effective stresses and, hence, the reduction in shear strength after driving. The amount of excess pore water pressure can approach up to twice the in-situ vertical effective stress and there is much higher pore water pressure at the toe of the pile [19]. Stiff clay, due to its larger strength, should develop less excess pore water pressure. This resulting in less dissipation afterward and lower increase in side resistance.

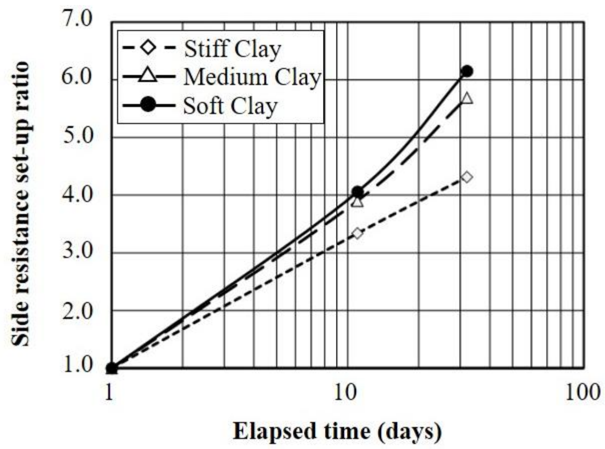

Figure 5 Side resistance set-up ratios

6.2 Tip resistance

Table 4 shows results of tip resistance set-up ratios. Tip resistances at the EOD were used as reference values in calculating the tip resistance set-up ratios at 11 days and 32 days. The overall average tip resistance set-up ratio is 1.5 at 32 days after piles installation. After, 32 days, the average tip resistance set-up ratios of soft clay, medium clay, and stiff clay are 1.6, 1.5, and 1.3, respectively.

Table 4 Tip resistance set-up ratios.

Time of DLT (days)	Depth of pile tip (m)										Overall average
	Stiff clay			Medium clay			Soft clay				
	21	18	Avg	16	14	Avg	12	10	8	Avg	
EOD	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
11	1.1	1.2	1.2	1.1	1.3	1.2	1.5	1.2	1.1	1.3	1.2
32	1.2	1.4	1.3	1.3	1.7	1.5	2.0	1.9	1.3	1.6	1.5

Figure 6 shows the average tip resistance set-up ratio of each clay layer. It can be seen that all soils give quite consistent value with stiff clay gives somewhat smaller values. Moreover, set-up of tip resistance is found to be much smaller than those of skin resistance.

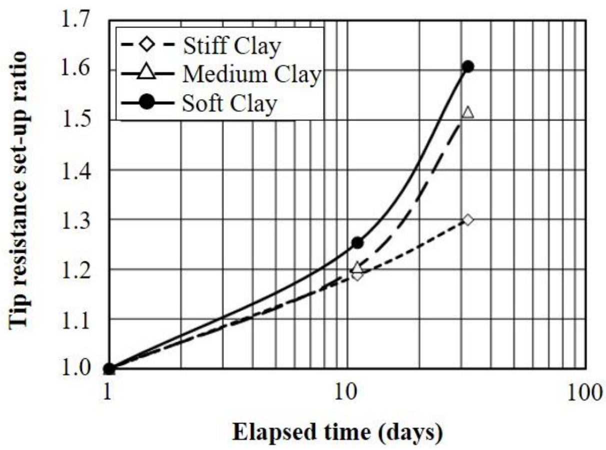

Figure 6 Tip resistance set-up ratios

6.3 Total pile resistance

Table 5 and Figure 7 shows the total pile resistance set-up ratios. After elapsed time of 32 days, the overall average total pile resistance set-up ratio is 2.7, and the average total pile resistance set-up ratios in soft clay, medium clay, and stiff clay are 2.4, 3.0, and 2.6, respectively. Kuntiwattanakul [10] conducted the experiment of pile set-up in Bangkok Clay and found that overall average pile resistance ratio of 24 meters I-shape pile at 31 days after installation is 3.9, which is greater than the result obtained from 21-meter I-Shape in this study (2.6). Due to the limited number of tested piles used in the study, further investigation is needed to confirm the pile set-up behavior of pile installed in Bangkok Clay.

The pile resistance set-up ratio gives unsatisfactory results against the prediction of pile set-up from Skov and Denver [18] (1.9) and Svinkin [15] (1.5-2.0). The significant parameter in the pile resistance prediction is the set-up parameter (A). Skov and Denver [1] suggested using A = 0.60 for clay in the pile resistance prediction equation. This study recommends using A = 1.065 in Skov and Denver [1] pile resistance prediction equation. Pile resistance set-up ratios for all tested piles are plotted with time after installation and presented in Figure 8.

Figure 9 shows the development of side, tip, and total resistances of piles with time. As discussed earlier, it can be seen that side resistance increase at much larger rate than that of tip resistance. After 32 days, the overall average tip resistance set-up ratio is 1.5, whereas the overall average side resistance set-up ratio is 5.4. This finding is consistent with several studies who reported that no set-up observed for tip resistance [6, 7, 16, 20]. Moreover, Haque and Abu-Farsakh [9] did not consider set-up of tip resistance to estimate the total pile resistance in their study.

Table 5 Total pile resistance set-up ratios.

Time of DLT (days)	Depth of pile tip (m)										Overall average
	Stiff clay			Medium clay			Soft clay				
	21	18	Avg	16	14	Avg	12	10	8	Avg	
EOD	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
11	2.0	2.1	2.0	1.6	2.7	2.2	2.5	1.4	1.4	1.8	2.0
32	2.6	2.7	2.6	2.3	3.7	3.0	3.4	2.3	1.6	2.4	2.7

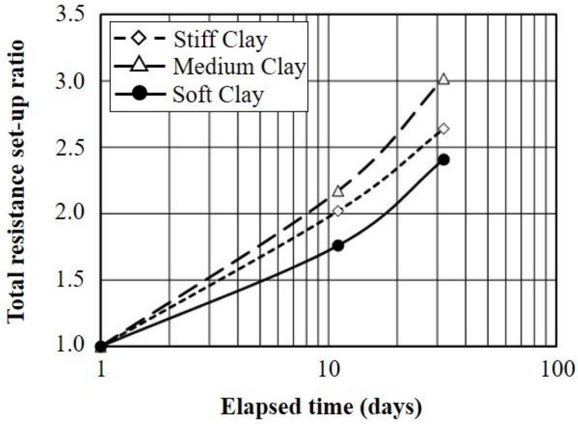

Figure 7 Total pile resistance set-up ratios

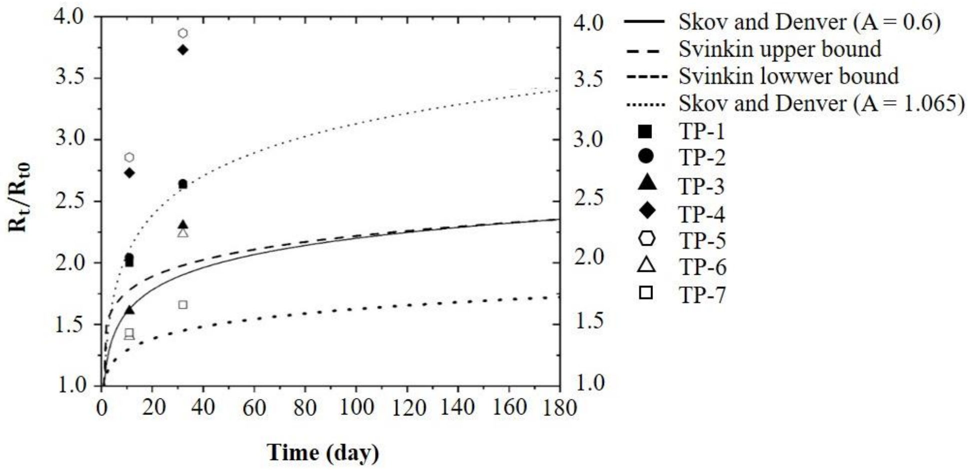

Figure 8 Pile resistance set-up ratio for all test piles

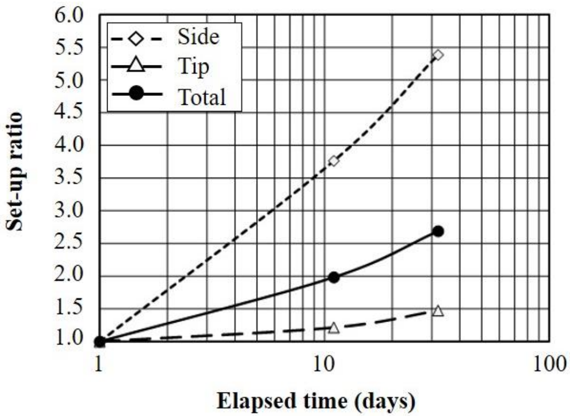

Figure 9 Development of resistance of pile with time

7. Conclusions

Experimental study of pile set-up of driven piles in Bangkok Clay was conducted on seven test piles with pile tips varied from 8-21 meters belowground. The subsurface condition of the site consisted of soft clay approximately 12 meters in thickness and the second layer is 6 meters of medium clay, and the third layer is 4 meters of stiff clay. Three periods of dynamic pile load test were carried out, including the end of drive (EOD), 11 days, and 32 days to observe the pile resistance set-up behavior. Due to that fact that pipe lengths were varied and pile capacity can be separated into side and tip resistances, the analysis can consider the development of individual resistance in specific soil layer. The following conclusions can be drawn:

- For I-22 piles in Bangkok Clay, their total resistance set-up ratios are 2.4, 3.0, and 2.6 when their tips are in stiff, medium, and soft clay layers, respectively, after 32 days. On average, the set-up ratio is found to be 2.7 after 32 days.
- The increase in pile capacity with time is mainly due to the increase in skin resistance.
- The average side resistance set-up ratios are 4.3, 5.7, and 6.2 for stiff, medium, and soft clays, respectively, after 32 days.
- The average tip resistance set-up ratios are 1.3, 1.5, and 1.6 for stiff, medium, and soft clays, respectively, after 32 days.
- Pile set-up parameter of 1.065 is recommended in Skov and Denver [1] pile resistance prediction equation.

8. Acknowledgement

This research is partly supported by the Research and Development Fund of Burapha University to the Sustainable Civil Engineering and Infrastructure Research Unit and by the Research Grant of Thailand Science Research and Innovation through Burapha University. The authors would like to thank the Mega Pi Company Limited for providing sufficient and accurate dynamic load test results.

9. References

[1] Skov R, Denver H. Time dependence of bearing capacity of piles. Proceedings of the 3rd International Conference on the Application of Stress-Wave Theory to Piles; 1988 May 25-27. Ottawa, Canada. Vancouver: BiTech Publishers; 1988. p. 879-88.

[2] Ratananikom W, Likitlersuang S, Yimsiri S. An investigation of anisotropic elastic parameters of Bangkok Clay from vertical and horizontal cut specimens. Geomech Geoeng. 2013;8(1):15-27.

[3] Ratananikom W, Yimsiri S, Likitlersuang S. Undrained shear strength of very soft to medium stiff Bangkok Clay from various laboratory tests. Geotech Eng. 2015;46(1):64-75.

[4] Yimsiri S, Ratananikom W, Fukuda F, Likitlersuang S. Undrained strength-deformation characteristics of Bangkok Clay under general stress condition. Geomech Eng. 2013;5(5):419-45.

[5] Haque MN, Abu-Farsakh M. Estimation of pile setup and incorporation of resistance factor in load resistance factor design framework. J Geotech Geoenviron Eng. 2018;144(11).

[6] Komurka VE, Wagner AB, Edil TB. Estimating soil/pile set-up. Final report. Wisconsin: the Wisconsin Department of Transportation; 2003.

[7] Ng KW, Roling M, AbdelSalam SS, Suleiman MT, Sritharan S. Pile setup in cohesive soil. I: experimental investigation. J Geotech Geoenviron Eng. 2013;139(2):199-209.

[8] Hosseini MA, Rayhani M. Evolution of pile shaft capacity over time in marine soils. Int J Geo Eng. 2017;8(12):1-15.

[9] Haque M, Abu-Farsakh M, Tsai C. Field investigation to evaluate the effects of pile installation sequence on pile setup behavior for instrumented test piles. Geotech Test J. 2016;39(5):769-85.

[10] Kuntiwattanakul P. Pile set-up in Bangkok subsoil. Proceedings of the 2nd RMUTR Conference; 2017 Jun 20-21; Nakorn Pathom, Thailand. Nakorn Pathom: Rajamangala University of Technology Rattanakosin; 2017. p. 32-9. (In Thai)

[11] Abu-Farsakh M, Haque MN, Tsai C. A full-scale field study for performance evaluation of axially loaded large-diameter cylinder piles with pipe piles and PSC piles. Acta Geotechnica. 2017;12(4):753-72.

[12] Ng KW, Sritharan S. A procedure for incorporating setup into load and resistance factor design of driven piles. Acta Geotechnica. 2016;11:347-58.

[13] Fellenius B. Discussion of "pile aging in cohesive soils" by Paul Doherty and Kenneth Gavin. J Geotech Geoenviron Eng. 2014;141(4):07014039.

[14] Rausche F, Robinson B, Likins G. On the prediction of long term pile capacity from end-of-driving information. In: DiMaggio JA, Hussein MH, editor. Proceedings of the Current Practices and Future Trends in Deep Foundation; 2004 Jul 27-31; Los Angeles, USA. Reston: ASCE; 2004. p. 77-95.

[15] Svinkin MR. Setup and relaxation in glacial sand-discussion. J Geotech Eng. 1996;122(4):319-21.

[16] Long JH, Kerrigan JA, Wysockey MH. Measured time effects for axial capacity of driven piling. Transp Res Rec. 1999;1663(1):8-15.

[17] Bowman ET, Soga K. Mechanisms of setup of displacement piles in sand: laboratory creep tests. Can Geotech J. 2005;42(5):1391-407.

[18] American Association of State Highway and Transportation Officials (AASHTO). AASHTO LRFD Bridge design specifications. 7th ed. Washington: AASHTO; 2014.

[19] Randolph MF, Carter JP, Wroth CP. Driven piles in clay-the effects of installation and subsequent consolidation. Geotechnique. 1979;29(4):361-93.

[20] Bullock PJ, Schmertmann J, McVay MC, Townsend FC. Side shear setup. II: results from Florida test piles. J Geotech Geoenviron Eng. 2005;131(3):301-10.