Time-Dependent Behavior of Driven Piles in Bangkok Subsoil: A Statistical Evaluation of Set-Up Using Dynamic Load Tests

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Abstract

This paper presents the findings of a study on driven pile set-up behavior in Bangkok and its surrounding regions. A total of 81 dynamic load tests were conducted at various time intervals, including at the end of initial driving (EOD) and at 1 minute, 10 minutes, 120 minutes, 1 day, and 14 days post-driving. The study utilized I-shaped pre-stressed concrete piles measuring 0.22 m in width and ranging from 11 to 25 m in length. All piles were driven through a soft clay layer and embedded in a stiff clay layer, with certain piles extending beneath the stiff clay and bearing on a medium-dense sand layer. The results of the study indicate the following key findings: 1) The pile capacity at 14 days was between 1.5 to 5.4 times greater than that measured at 1 minute after driving. 2) The ratio of pile capacity at any elapsed time to that at 1 minute follows a power function of time (in minutes), with an exponent ranging from 0.035 and 0.17. 3) The exponent of the power function decreases as the pile capacity per linear meter at 1-minute increases, suggesting that piles with higher initial capacity exhibit a slower rate of capacity gain over time.

Keywords: *pile set-up, driven piles, time-dependent behavior, dynamic load testing, statistical regression, Bangkok subsoil*

1. Introduction

The driven pile capacity has been observed to grow over time for many years (Vesić, 1977). While driving the piles, this phenomenon is usually observed, wherein slowing down the drive may result in significantly higher blow counts when driving is resumed. The process has been investigated by many researchers, commonly termed "set-up," and these researchers are Skov and Denver (1988), Svinkin (1996), Long et al. (1999), Augustesen et al. (2005), and Bullock (2008). Over the past few decades, the phenomenon of pile set-up, where the capacity of driven piles increases over time, has been extensively studied. Researchers such as Vesić (1977), Skov and Denver (1988), and Svinkin (1996) have proposed models to explain this behavior, often based on small datasets or site-specific conditions. In Bangkok and its surrounding areas, pile set-up is more complex due to the layered nature of the subsoil, which typically includes thick deposits of soft clay, stiff clay, and sometimes a sand layer. While recent studies by Wangmo (2020) and Tonglee (2023) have investigated pile behavior through dynamic load tests, their findings were limited by smaller datasets and less in-depth statistical analysis. This leaves a gap in the literature when it comes to fully understanding of how pile capacity evolves over time in Bangkok’s unique soil conditions. This study aims to fill that gap by combining a large dataset of 81 dynamic load tests with regression-based modeling to provide new insights into the time-dependent behavior of piles. There have been extensive efforts made to determine the root causes of set-up and empirical correlations have been proposed to measure its impact.

Pile set-up mechanisms are typically classified into two groups: those related to effective stress and those that are independent of it (Komurka et al., 2003). The first mechanism is attributed to excess pore water pressure generated during pile driving, which gradually dissipates over time. The second mechanism, also referred to as aging, encompasses time-dependent alteration of soil properties under constant effective stress, e.g., thixotropy, secondary compression, and particle interference.

Studies on driven pile set-up in the subsoil of Bangkok, conducted byy Wangmo (2020) and Tonglee (2023), involved dynamic pile load testing at various, extending intervals up to 14 days after driving. Their findings revealed significant variations in the increase of pile capacity over time, with the axial capacity at 14 days ranging from 1.5 to 5.5 times that measured at 1 minute. This variation is likely due to piles in the Bangkok area are driven through a soft clay layer with a sensitivity of 3–4 before embedding in a stiff clay layer. Additionally, some piles extend beyond the stiff clay and rest on a medium-dense sand layer. Consequently, the pile set-up mechanism in Bangkok is complicated due to several influencing factors that contribute to the increase in pile capacity over time.

To allow for a more statistically robust analysis of the factors contributing to pile set-up and to gain a deeper understanding of the factors influencing pile set-up in the Bangkok area, this study builds upon the research conducted by Wangmo (2020) and Tonglee (2023). Thus, this research extends the scope by performing another dynamic pile load test to the number of tests to 81. By incorporating quantitative analyses and statistical models, the study aims to enhance predictive models, advance the precision in pile capacity prediction, and upgrade the development of engineering practices in pile foundation construction and design under Bangkok's unique subsoil conditions.

The findings on pile set-up reported in the literature can be categorized into two main groups. The first group observed that pile capacity increases linearly with the logarithmic of time. Skov and Denver (1988) proposed a semi-logarithmic time function to describe the relationship between time (t) and pile capacity (Q):

$$\frac{Q}{Q_0}=1+A\log_{10}\left(\frac{t}{t_0}\right) \tag{1}$$

where Q_0 represents the reference, capacity measured at time t_0, and A denotes the capacity increase per log cycle of time. They determined that the values of A for piles in sand, clay, and chalk are 0.2, 0.6, and 5.0, respectively. The reference time (t_0) is typically assumed to be 0.5, 1.0, or 5.0 days to ensure a steady increase in capacity. Prior to this period, pore pressure had not yet stabilized, and soil remolding was still occurring. Similarly, Bullock (2008) found that pile shaft capacity increased linearly with logarithmic time immediately after driving, with A values derived from dynamic pile load tests (conducted immediately after end-of-driving (EOD) and at elapsed times of 15 minutes and 1 hour) aligning closely with those obtained from static pile load tests performed between 1 day and 4.7 years.

The second group of findings suggested that pile capacity follows a power function of time. Based on load test data from five concrete piles in dense silty sand, Svinkin (1996) developed the following equations:

$$\frac{\mathbf{Q_t}}{\mathbf{Q_{EOD}}}=\mathbf{1.4t^{0.1}} \quad \textbf{(Upperbound)} \tag{2.1}$$

$$\frac{\mathbf{Q_t}}{\mathbf{Q_{EOD}}}=\mathbf{1.025t^{0.1}} \quad \textbf{(Lowerbound)} \tag{2.2}$$

where Q_t is the pile capacity at time t (in days), and Q_{EOD} is the pile capacity at the end of initial driving. Khan and Decapite (2011) proposed a similar equation for piles in clay-silt mixed soils, with slightly different coefficients. Notably, in a semi-logarithmic plot, a power function appears as a concave upward curve. Similar concave-up trends in pile capacity versus logarithmic time plots have also been reported by Axelsson (2000) and Lee et al. (2010).

2. Objectives

The objectives of the study are as follows:

1) To examine the relationship between pile capacity and time.
2) To assess the factors influencing the increase in pile capacity over time.

3. Materials and Methods

Eighty-one dynamic load tests were used in this study to measure pile capacities at the end of initial driving (EOD) and at intervals of 1 minute, 10 minutes, 120 minutes, 1 day, and 14 days after driving. In this study, I-shaped pre-stressed concrete piles with equal width and height of 0.22 m and lengths ranging from 11 to 26 m were used. The study areas were in Bangkok and its surroundings areas. A typical Bangkok soil profile includes a soft clay layer 10 to 18 meters thick, underlain by a stiff clay layer 5 to 10 meters thick, and a medium-dense sand layer at the bottom of the stiff clay layer (see Fig. 1). All piles were driven through the soft clay layer and embedded in the stiff clay layer, with 16 piles passing through the stiff clay layer and sitting on the medium dense sand layer. Table 1 summarizes the number of tested piles in each zone.

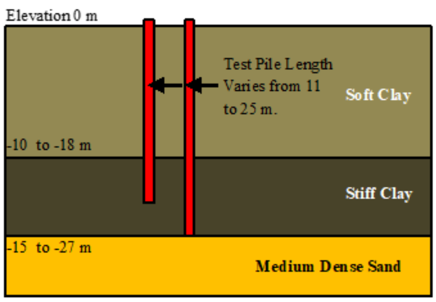

Figure 1 Typical soil profile in Bangkok Area

To verify whether the relationship of the pile capacity and logarithmic of time is linear or not, this study performed regression analysis of all test results using both linear and non-linear functions and the regression results were then compared. For the linear function, this study adopted the equation proposed by Skov and Denver (1988) as its foundation. Equation 3 was rearranged from Equation 1, with t_0 was set to 1 minute.

$$\frac{Q}{Q_1}-1=A\log_{10}(t) \qquad (3)$$

Where,
Q = is the capacity of the pile at time t.
Q_1 = is the capacity of the pile at 1 minute after driving
A = is the increase in power per logarithmic cycle of time.
t = time in minutes

In this study, a simple linear regression analysis was conducted with (Q/Q_1) as the dependent variable and $\log_{10(t)}$ as the independent variable. The regression line was constrained to pass through the origin (0,0). The parameter A was determined from the slope of the regression line. For the non-linear function, Equation 4 was derived from Equation 2 suggested by Svinkin (1996).

$$\frac{Q}{Q_1} = t^m \qquad (4\text{-}1)$$

Or

$$\log_{10}\left(\frac{Q}{Q_1}\right) = m\log_{10}(t) \qquad (4\text{-}2)$$

Where,
m is the parameter value
t is time in minutes

The m parameter was determined using simple linear regression, with $\log_{10}(Q/Q_1)$ as the dependent variable and $\log_{10(t)}$ as the independent variable. The relationship line is set to pass through the point (0,0), and the value of m was determined from the slope of the regression line.

4. Results and Discussion

4.1 Results

Figure 2 presents the results of ratios of pile capacities at various time to those at 1 minute (Q/Q_{1min}) plotted against logarithmic of time (t). The results are highly scattered. The ratios of pile capacity at 14 days compared to those at one minute vary from 1.5 to 5.5.

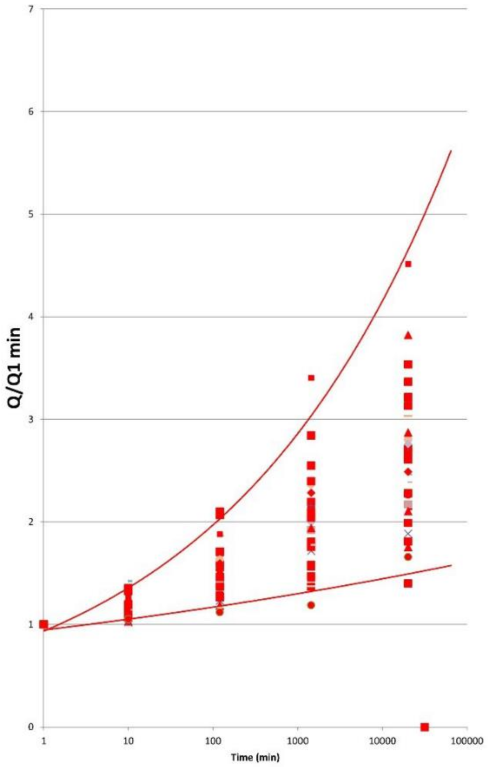

Figure 2 Ratio of Q/Q_{1min} vs. logarithmic of time

Table 1 Summary of A and m parameters

Parameter	Max. Value	Min. Value	Avg. Value	Standard Deviation SD	R^2 max	R^2 min
A	0.912	0.097	0.329	0.146	0.988	0.730
m	0.173	0.035	0.087	0.027	0.997	0.835

Table 1 presents a statistical summary of the regression analysis for parameters A and m, carried out as established above. In order to ascertain the precision with which these parameters in predicting pile capacity over time, an analysis of the R-squared (R^2) values obtained from the regression was performed. Figures 3 and 4 illustrate the distribution of R^2 values for different cases of A and m, giving an impression of their comparative accuracy.

As illustrated in Figure 4, parameter m consistently yields high R^2 values (mostly in the range of 0.95 to 1) with minimal variation, suggesting a strong correlation with pile capacity increase over time. In contrast, Figure 3 however, demonstrates that parameter A displays greater variability in R^2 values, suggesting a less consistent predictive capability. The results indicate that parameter m provides a better fit for modeling pile capacity over time than compared to parameter A, further adding to the likelihood of pile capacity in Bangkok subsoil increases non-linearly with the logarithm of time.

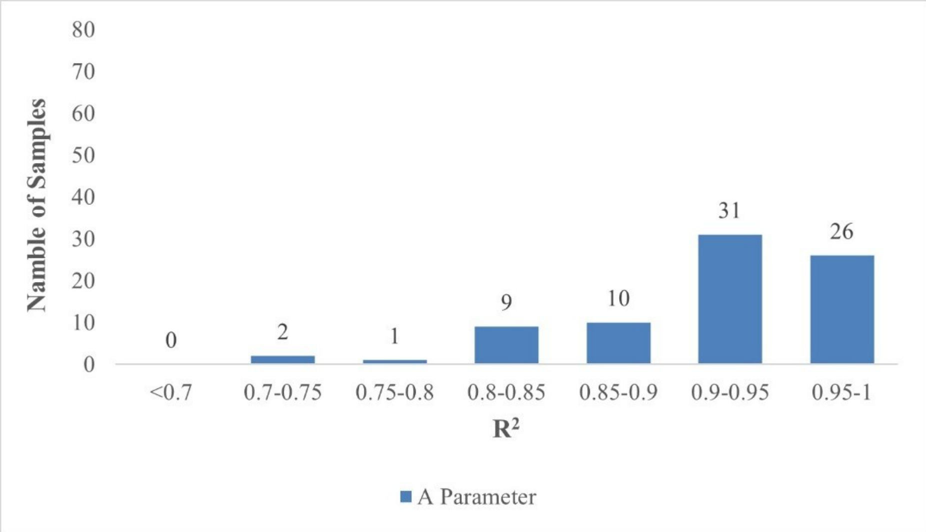

Figure 3 Frequency distribution graph of the R-squared value of A parameter

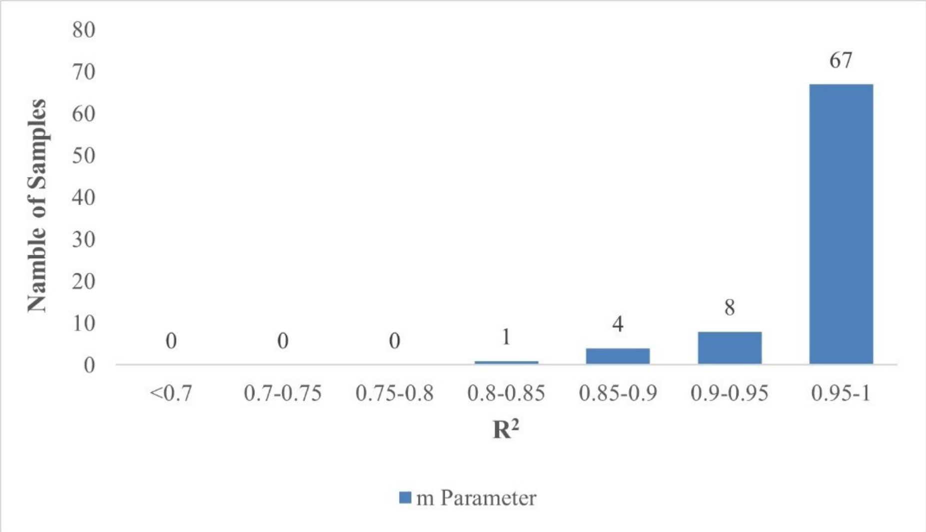

Figure 4 Frequency distribution graph of the R-squared value of m parameter

Table 1 indicates that the m parameter varies widely, ranging from 0.035 to 0.173. However, Figure 5 reveals a clear trend: the m parameter decreases as the pile capacity at 1 minute per linear meter (Q_{1min}/L) increases. In this figure, results for piles with tips embedded in stiff clay and sand are distinguished using different markers. The data suggest that the type of soil at the pile tip does not significantly affect pile set-up, as both groups of results align along the same trend line. Additionally, the lower bound line for the 95% confidence level is also displayed in the figure, providing a statistical reference for the observed trend.

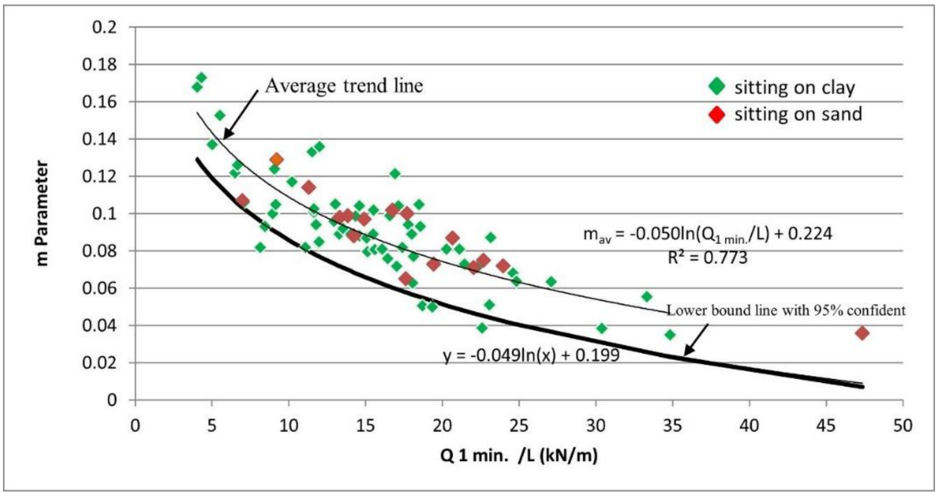

Figure 5 Estimating 14-day pile capacity from 10-minute pile capacity test

4.2 Discussion

The findings of this research exhibit that pile capacity in Bangkok subsoil increases in a nonlinear manner with the logarithm of time, underscoring the time-dependent nature of pile set-up. Among the regression parameters analyzed, the m parameter was found to be a more reliable predictor of pile capacity increase with time compared to the A parameter, as evidenced by its consistently higher R^2 values.

Moreover, the research indicates a negative correlation between the m parameter and the initial pile capacity per linear meter at 1 minute (Q_{1min}/L)—that is, as the initial pile capacity increases, the m parameter decreases. This trend suggests that piles driven in softer soils exhibit a higher rate of increasing capacity with time, as reflected by larger m values, whereas stiffer soils undergo a gradual increase in capacity. These findings reinforce the necessity of taking soil type into account in estimating pile set-up behavior and can be utilized to improve the engineering design of foundations in Bangkok's peculiar subsoil conditions.

5. Conclusion

This paper examines the pile set-up behavior of driven piles in Bangkok and its surrounding areas. A total of 81 dynamic pile load tests were conducted on I-shaped prestressed concrete piles with a width of 0.22 m and lengths ranging from 11 to 26 m. Load tests were performed at multiple time intervals, including at the end of initial driving (EOD), and at 1 minute, 10 minutes, 120 minutes, 1 day, and 14 days after driving. Based on the findings of this study, the following conclusions can be drawn:

1. Pile set-up behavior in the Bangkok subsoil varies significantly, with ratios of pile capacity at 14 days to that at 1 minute (Q_{1min}) ranging from 1.5 to 5.5. This variation highlights the complexity of pile capacity gain over time in different soil conditions.
2. The pile capacity (Q), normalized by the capacity at 1 minute (Q_{1min}), follows a power function of time. When plotted on a semi-logarithmic scale, this function displays a concave upward trend, reinforcing the time-dependent nature of pile set-up.
3. The m parameter decreases as the initial pile capacity per linear meter at 1-minute (Q_{1min}/L) increases. This trend suggests that piles driven into softer soils exhibit a greater rate of capacity gain over time, as indicated by higher m values. These findings emphasize the importance of soil characteristics in predicting the long-term pile capacity behavior in Bangkok's subsoil.

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