Empirical equations for predicting pile/soil setup effect

Lee Min Lee¹, Jasmine Wong Sze Ming², Kok Sien Ti¹, Lau Teck Leong¹, Yeong Tuck Wai¹

¹ Faculty of Science and Engineering, University of Nottingham Malaysia, Selangor, Malaysia 43500.
² Lee Kong Chian Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, Selangor, Malaysia 43000.

*Corresponding author email: minlee.lee@nottingham.edu.my

Abstract. Pile/soil setup effect is a natural phenomenon where pile load capacity increases over time as the results of dissipation of pore-water pressure and soil aging. The magnitude of pile/soil setup is governed by three main factors, i.e. pile slenderness ratio, elapsed time and type of surrounding soil. In this study, empirical correlations were established based on data compiled from previous case studies. Two forms of empirical equations were proposed to predict the pile/soil setup effect subjected to different slenderness ratios and elapsed times. The proposed equations were subsequently verified by actual field data collected from two sites in Malaysia. Results showed that 80% of the pile capacities increased by 1.150-1.875 times per log time cycle. Piles in fine-grained soils generally exhibited a greater pile/soil setup effect than coarse-grained soils.

1. Introduction

Pile/soil setup effect is a natural phenomenon where the load capacity of pile increases over time. The effect was first reported by Wendel [1] through a series of laboratory scaled experiments. He found that the pile load capacity increased over time up to 2-3 weeks after which the increment become insignificant.

Figure 1 shows idealized phases involved in the pile/soil setup processes. In general, the pile capacity gain can be attributed to two main mechanisms, i.e. dissipation of pore water pressure and soil aging. As the result of dissipation of pore-water pressure, the frictional resistance of pile shaft increases leading to an increase in the pile load capacity [2]. The dissipation of pore-water pressure can be divided into 2 phases, namely nonlinear phase and linear phase. During the nonlinear phase, the rate of dissipation of excess pore-water pressure is not constant over time because the soil is highly disturbed upon pile installation. The disturbed soil experiences increases in horizontal and effective stresses, consolidates, and gains strength which constitutes complex behaviours. It is widely agreed that fine-grained soils would experience a longer (up to few days) nonlinear phase than the coarse-grained soils [3]. The dissipation of pore-water pressure subsequently enters into a linear phase whereby the pile/soil setup increases proportionally with the pore-water pressure dissipation. This linear phase may span over weeks, months or even years depending on the type of soil [3]. In the final phase, soil aging takes infinite time for the excess pore water pressure to be fully dissipated. In this phase, the soil has achieved a constant effective stress whereby the pile/soil setup rate is now independent of the effective stress over time. The soil aging effect reduces the soil compressibility, while increasing the shear modulus, stiffness...
and soil dilatancy [4]. Schmertmann [5] suggested that the aging effect is primarily caused by movement of soil particles, changes in soil structures, and chemical effects over geological time. The soil aging effect is generally found to be more significant in granular soil than in cohesive soil [4].

![Figure 1. Idealized phases of pile/soil setup][3]

The study of pile/soil setup effect has been reported by numerous researchers. Konrad and Roy [6] investigated the pile/soil setup effect in a marine clay site in Canada. They found that the pile capacity increased by about 62% over 1 month after the pile installation. Lied [7] compared the capacities of two piles with identical geometry and method of installation at a soft clay site in Iran. One of the piles is an existing pile installed 15 years ago, while another is a newly installed pile. He reported that the load capacity of the existing pile was 2.25 times higher than the newly installed pile. Ng et al. [8] reported six case studies on pile/soil setup in Malaysia consisting of 11 test piles. They observed that the pile/soil setup rates were generally not increasing linearly with logarithmic scale of time. Liu et al. [9] carried out field test on piles jacked into mixed soils. They found that the shaft resistance of pile increased linearly with time by about 44% per log time cycle, while the total pile load capacity increased by about 21% per log time cycle. Liu et al. [10] compiled a database consisting of 1,228 nos. of field load tests on jacked-in concrete pipe piles to establish empirical correlations between the final jacking force and the ultimate capacity. The correlations were mainly developed based on the parameter of pile slenderness ratio.

From the previous studies [4, 8-10], it can be concluded that the pile/soil setup effect is mainly governed by three factors including elapsed time, pile slenderness ratio and type of soil. Soil has a time dependant behaviour in which it gains strength and stiffness over time. As shown in Figure 1, the pile/soil setup increases at different rates depending on the phases of the pore-water pressure dissipation. The pile slenderness ratio affects the pile/soil setup through the interaction of pile surface with surrounding soils. The type of soil governs the dissipation rate of excess pore-water pressure which in turn affects the pile/soil setup rate.

As jacked-in piles are gaining great popularity in recent decades, the consideration of pile/soil setup effect may effectively optimize the pile design and installation. Piles may not necessary to be jacked to the required working load as certain portion of the pile capacity is expected to be gained over time. However, the beneficial effect of the pile/soil setup has rarely been considered in practice owing to the uncertainties and lack of insightful understanding of the mechanisms contributing to the pile/soil setup effect [9]. In addition, the tight construction schedule and budget often restricts the pile load test to be carried out at the initial driving and limits the long term pile capacity verification [11]. This paper aims...
to compile most of the available data pertaining to the topic of pile/soil setup. These data are subsequently filtered and classified in accordance with their governing factors. Empirical equations are developed through correlations between the pile/soil setup effect and the governing factors. It is hoped that this study would provide a more insightful understanding of the pile/soil setup effect and increase the confidence level of considering the pile/soil setup effect in piling design.

2. Methodology

2.1. Data Collection
A total of 2,219 data points were extracted and compiled from previous reported studies, as summarised in Table 1. These data consisted of field pile load tests carried out at different parts of the world including United States, China, Malaysia, Iran etc.

| No. | Reference                           | Nos. of data points compiled |
|-----|-------------------------------------|-------------------------------|
| 1   | Axelsson [4]                        | 99                            |
| 2   | Ng et al. [8]                       | 17                            |
| 3   | Liu et al. [10]                     | 1,228                         |
| 4   | Bullock et al. [12]                 | 38                            |
| 5   | Augustesen [13]                     | 115                           |
| 6   | Alawneh et al. [14]                 | 15                            |
| 7   | Yu and Yang [15]                    | 590                           |
| 8   | Attar and Fakharian [16]            | 49                            |
| 9   | Doherty and Gavin [17]              | 68                            |

2.2. Studied Parameters
Three dominant influencing parameters on the pile/soil setup effect have been identified from the literature review, i.e. elapsed time, pile slenderness ratio, and type of soil. Out of the total 2,219 compiled data points, 398 of the data points consisted of information on the elapsed time. The elapsed time was presented in the form of $t/t_0$, representing the ratio of elapsed time after a pile installation to the time when the pile was initially tested. 1,821 of the data points consisted of information on the pile slenderness ratio. The slenderness ratio ($\lambda$) is defined as the ratio of pile length to diameter. The $\lambda$ considered in this study ranged from 8 to 140. The type of soil was broadly categorized into fine-grained soil and coarse-grained soil. Table 2 tabulates the classification of the collected data points.

| No. | Type of soil       | Nos. of data points |
|-----|--------------------|---------------------|
|     |                    | Elapsed time | Slenderness ratio |
| 1   | Fine-grained soil  | 215           | 630                 |
| 2   | Coarse-grained soil| 125           | 350                 |
| 3   | Unknown            | 58            | 841                 |
2.3. Field Verification

The developed empirical equations in the present study were verified by actual field pile load tests carried out at two selected sites in Malaysia, namely Site A and Site B. Site A is located in Selangor, Malaysia characterized mainly by sandy materials. Pile Driving Analyzer (PDA) tests were performed on a square reinforced concrete pile and 14 nos. of spun piles of 27-45 m long. Site B is located in Penang, Malaysia characterized by compressible soft marine clay. PDA tests were carried out on 24 nos. of square reinforced concrete piles of 21-35 m long. The significance of correlations between the developed empirical equations and the field data were analysed statistically using root mean square error (RMSE) method.

3. Results and Discussion

3.1. Effect of Elapsed Time

From previous studies, the proposed correlation between pile/soil setup effect and elapsed time is generally presented in the form of:

$$\frac{Q}{Q_o} = a \log\left(\frac{t}{t_o}\right) + 1$$  \hspace{1cm} (1)

where

- $Q/Q_o$ = Ratio of pile capacity at time $t$ to pile capacity at the initial reference time $t_o$
- $t/t_o$ = Ratio of elapsed time to the initial reference time from the end of drive
- $a$ = Empirical constant

Figures 2-4 show the plotting of $Q/Q_o$ versus $t/t_o$ for all the compiled data, fine-grained soil, and coarse-grained soil, respectively. The ratio of pile capacity at a specific time to initial pile capacity was correlated linearly with log time using a best fit line. In addition, two boundary lines, namely lower and upper confidence bounds at 10% of unreliability were established to show the correlations with 0.1 probability of exceeding the upper and lower bounds, respectively. From Figure 2, 80% of the collected data showed increments in pile capacity by 1.150-1.875 times per log time cycle. By comparing the data in Figures 3 and 4, it is apparent that piles in fine-grained soil has a more significant pile/soil setup effect than coarse-grained soil, as indicated by the larger empirical constant, “$a$” value in the established correlations. Piles surrounded by fine-grained soil also exhibited larger variations in pile/soil setup effect as indicated by the wider range of the empirical constant, “$a$” between the upper and lower bounds than those of coarse-grained soil. This could be caused by the complex compressibility and pore-water dissipation behaviour in the fine-grained soil which have direct influence on the pile/soil setup particularly during the early phases. Table 3 summarises the empirical constant “$a$” proposed in the present study. The proposed constants in the present study generally fall in the median range of the constants proposed from previous studies [8, 13, 16-18].
Table 3. Summary of proposed empirical constant “a” for correlations of $Q/Q_o$ vs log $(t/t_o)$

| No. | Type of soil        | Empirical constant, a | Present study | Previous studies |
|-----|---------------------|------------------------|---------------|------------------|
| 1   | All data            | Upper bound            | 0.875         | -0.06 – 6.25     |
|     |                     | Best fit               | 0.438         |                  |
|     |                     | Lower bound            | 0.150         |                  |
| 2   | Fine-grained soil   | Upper bound            | 0.990         |                  |
|     |                     | Best fit               | 0.404         | -0.06 – 6.25     |
|     |                     | Lower bound            | 0.104         |                  |
| 3   | Coarse-grained soil | Upper bound            | 0.691         |                  |
|     |                     | Best fit               | 0.365         | 0.20 – 0.99      |
|     |                     | Lower bound            | 0.207         |                  |

Figure 2. Correlations between $Q/Q_o$ and $t/t_o$ for all compiled data (all data)
**Figure 3.** Correlations between $Q/Q_o$ and $t/t_o$ for fine-grained soil

**Figure 4.** Correlations between $Q/Q_o$ and $t/t_o$ for coarse-grained soil
3.2. Effect of Pile Slenderness Ratio
For the correlation between pile/soil setup effect and slenderness ratio ($\lambda$), the previous established empirical equations can be found in the forms of hyperbola or exponential functions:

\[ \frac{Q}{Q_o} = a - b \cdot \lambda^{-1} \quad (2) \]

\[ \frac{Q}{Q_o} = a \cdot \lambda^b \quad (3) \]

where

\[ a \text{ and } b \quad = \text{Empirical constants} \]

In the present study, the correlations between $Q/Q_o$ and $\lambda$ were established in the form of exponential equation (Eq. 3). Despite of the fact that most of the previous studies proposed the hyperbola function (Eq. 2), Yu and Yang [15] suggested that the exponential equation offers the advantage in simulating mathematically the variation in pile capacity ratio at small slenderness ratios. It should be noted that the pile capacity, $Q$ used for the computation of $Q/Q_o$ is the ultimate pile capacity while the $Q_o$ refers to the initial pile capacity or jacked pressure for the case of jacked-in pile. Figures 5-7 show the plotting of $Q/Q_o$ versus $\lambda$ for all the compiled data, fine-grained soil, and coarse-grained soil, respectively. From the results, it can be observed that the ratio of $Q/Q_o$ may fall below 1 particularly for short piles. For instance, it may require a slenderness ratio of $>120$ to yield a lower bound $Q/Q_o > 1$ (Figure 5). This is because the load resistances in deep soil have a higher potential to increase than the soil at shallow depth. The increase could be associated with the mechanism of pile-soil equalization after installation [15]. By comparing the scattered data in Figures 6 and 7, piles in fine-grained soil generally exhibited a slightly more significant pile/soil setup effect than those of coarse-grained soil. Table 4 summarises the empirical constants “$a$” and “$b$” proposed in the present study.

**Table 4. Summary of proposed empirical constants “$a$” and “$b$” for correlations of $Q/Q_o$ vs $\lambda$.**

| No. | Type of soil         | Empirical constant, $a$ | Empirical constant, $b$ |
|-----|----------------------|-------------------------|-------------------------|
|     |                      | Present study | Previous study [15] | Present study | Previous study [15] |
| 1   | All data             | Upper bound | 0.44 | 0.36       |
|     |                      | Best fit     | 0.33 | 0.32       |
|     |                      | Lower bound  | 0.20 | 0.34       |
| 2   | Fine-grained soil    | Upper bound  | 0.52 | 0.32       |
|     |                      | Best Fit     | 0.35 | 0.45       |
|     |                      | Lower bound  | 0.30 | 0.24       |
| 3   | Coarse-grained soil  | Upper bound  | 0.48 | 0.30       |
|     |                      | Best Fit     | 0.32 | 0.32       |
|     |                      | Lower bound  | 0.22 | 0.34       |
Figure 5. Correlations between $Q/Q_o$ and $\lambda$ for all compiled data

Figure 6. Correlations between $Q/Q_o$ and $\lambda$ for fine-grained soil
3.3. Field Verification
The actual field pile load tests results obtained from the Sites A and B were plotted with the established correlations of $Q/Q_o$ vs $\log (t/t_o)$ and $Q/Q_o$ vs $\lambda$ in Figures 8a and 8b, respectively. The data generally fall within the established bounds for the two correlations. Root mean square error (RMSE) values were computed to evaluate quantitatively the fitting of these field data to the established correlations, as tabulated in Table 5. A lower RMSE value indicates a better fit to the established correlation. For the $Q/Q_o$ vs $\log (t/t_o)$ correlation, Sites A and B were fitted better to the correlations established for coarse-grained and fine-grained soil, respectively (as indicated by the lower RMSE values in Table 5). The correlation of $Q/Q_o$ vs $\lambda$ showed a better fit using the correlation established for the all data. The results implied that the type of soil could be less significant in influencing the pile/soil setup effect under different pile slenderness ratios.
Figure 8. Verification of actual field data with the proposed correlations of (a) $Q/Q_o$ vs log ($t/t_o$), and (b) $Q/Q_o$ vs $\lambda$.

Table 5. Summary of RMSE values computed for field verification

| No. | Established correlations | $Q/Q_o$ vs log ($t/t_o$) | $Q/Q_o$ vs $\lambda$ |
|-----|--------------------------|---------------------------|-----------------------|
|     | Site A (Coarse-grained)  | Site B (Fine-grained)     | Site A (Coarse-grained) | Site B (Fine-grained) |
| 1   | All data                 | 0.261                     | 0.132                 | 0.066                 | 0.020                 |
| 2   | Fine-grained soil        | 0.225                     | 0.133                 | 0.038                 | 0.024                 |
| 3   | Coarse-grained Soil      | **0.192**                 | 0.142                 | 0.051                 | 0.028                 |

4. Conclusions

Pile/soil setup effect is a natural phenomenon where the load capacity of pile increases over time. The beneficial effect of the pile/soil setup, however, has rarely been considered in practice owing to the uncertainties and lack of insightful understanding of the mechanisms contributing to the pile/soil setup effect. In the present study, a total of 2,219 field pile load test data were compiled from previous reported studies to provide insights on the factors affecting the pile/soil setup effect. Pile/soil setup effect is affected by three main factors, i.e. elapsed time, slenderness ratio and type of soil. Two forms of empirical equations were proposed to predict the pile/soil setup effect under different slenderness ratios and elapsed times. 80% of the compiled data showed that the pile capacity increased by 1.150-1.875 times per log time cycle. The ratio of $Q/Q_o$ may fall below 1 for short piles. A pile slenderness ratio of $> 120$ is required to yield a lower bound $Q/Q_o$ of $> 1$. This is because the load resistances in deep soil have a higher potential to increase than the soil at shallow depth. Piles in fine-grained soil generally
exhibit a more profound pile/soil setup effect than coarse-grained soil. The influence of soil type is more significant on the \( Q/Q_s \) vs log \((t/t_o)\) correlation than the \( Q/Q_s \) vs \( \lambda \) correlation.

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