# Evolution of Pile Shaft Capacity over Time in Soft Clays Case Study: Leda Clay

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M.A. Hosseini, M.T. Rayhani
*Carleton University, Ottawa, ON, Canada*

*Department of Civil and Environmental Engineering – Carleton University, Ottawa, ON, Canada*

ABSTRACT
This paper presents a comprehensive experimental investigation to examine the evolution of pile shaft capacity over time. This phenomenon is observed in pile foundations that are driven into soft clays, and is referred to as pile set-up. In this research, a series of pile load testing was performed on steel and concrete piles driven into Leda clay in Gloucester, Ontario. The piles were tested immediately after driving to measure their initial bearing capacities, and were tested repeatedly over different elapsed time to study the change in pile shaft capacity over time. The excess pore water pressure around the pile was also monitored by a piezometer. The average pile capacity measurements for steel and concrete piles indicate that there is approximately an 80% increase in the pile capacity after 30 days from the initial day.

RÉSUMÉ
Cet article présente une étude expérimentale global pour examiner l'évolution de la capacité de l'arbre de pile au fil du temps. Ce phénomène est observé dans les fondations sur pieux qui sont enfoncées dans les argiles molles, et est appelée pile set-up. Dans cette recherche, une série de tests de charge de la pile a été réalisée sur l'acier et des pieux en béton enfoncés dans l'argile Leda à Gloucester, en Ontario. Les pieux ont été testés immédiatement après la conduite de mesurer leurs capacités portantes initiales, et ont été testés de façon répétée sur différents temps écoulé pour étudier la modification de la capacité de l'arbre de pile au fil du temps. La surpression de l'eau interstitielle autour de la pile a également été suivie par un piézomètre. Les mesures moyennes de capacité de pile pour l'acier et des pieux en béton indiquent qu'il ya environ une augmentation de 80% de la capacité de la pile après 30 jours de la date initiale.

## 1 INTRODUCTION

Piles driven into various types of soil specifically in clay experience an increase in capacity as a function of time due to dissipation of excess pore water pressure generated around the pile during pile driving. This phenomenon of time-dependant capacity increase is referred to as set-up or freeze. Pile set-up occurs in almost all types of soils including organic or inorganic clay, loose to medium dense silt, sandy silt, and fine sand (Astedt and Holm, 1992; Hannigan et al., 1997).

Pile set-up is of critical importance in the design of piles. In clay soils, the set-up is related to the reconsolidation of the disturbed soil around the pile, and aging (Randolph et al., 1979). The time to dissipate excess pore water pressure is relevant to the permeability of the soil along with the coefficient of consolidation.

The pile driving may cause disturbance and remolding of the soil around the pile. De Mello (1969) classified the effect of pile driving in clay in four categories; remolding to the structure of the soil around the pile; variations in the state of stress of the soil and the pile which is referred to formation of excess pore water pressure; dissipation of excess pore water pressure; and long term increase of the strength in the soil.

During pile driving, high excess pore water pressure is normally developed in the surrounding soil near the pile. This excess pore water pressure will cause reduction in the effective stresses and, hence, the shear strength of the soil for a specific period of time after driving. The amount of excess pore water pressure can approach up to twice the in-situ vertical effective stress, although there is much higher pore water pressure at the toe of the pile and this can reach up to 3 to 4 times the effective stress (Randolph et al., 1979). In case of sensitive soils such as Leda clay, the result of pore water pressure could be greater, i.e., up to 8 times of the effective stress (Poulos and Davis 1980). The concept of pore pressure dissipation was used to explain the gain in pile capacity after driving over time by Seed and Reese (1955).

Excess pore water pressures equal to or even greater than overburden pressure were shown to be developed in a soil due to pile driving (Lambe and Horn 1965, Orrje and Brom 1967, D'Appolonia and Lambe 1971, Poulos and Davis 1980). When piles are driven into saturated soils, the surrounding soils are compressed and remolded (disturbed). As stated by Broms (1966), this remolded region spreads from one to three pile diameters laterally, while the remolded zone will be only one pile diameter at the toe of the pile.

In order to illustrate the rate of change in pore water pressure, the pile set-up mechanism can be classified into three stages (Komurka et al., 2003). At phase 1, the rate of the set-up coincides to the rate of dissipation. The condition of the soil in this phase is disturbed and the rate of the excess pore water pressure dissipation is not constant as called non-linear phase. The extent of the non-linear rate of pore water dissipation is shorter for more permeable soil and inversely it is longer for less permeable soil. Eventually, the rate of excess pore pressure dissipation shifts to a consistent and linear rate (phase 2). In cohesive soils, this phase may remain for several weeks, months and sometime years (Skov and Denver 1988). Azzouz et al. (1990) suggested that for a 380-mm-diameter full-displacement pile, it might require 200-400 days to reach complete consolidation. At phase 3, aging of the soil will occur which could be related to thixotropy, secondary compression, particle interference, and clay dispersion (Schmertmann, 1991; Camp and Parmar, 1999; Long et al., 1999). Aging may increase the pile–soil interface friction (McVay et al., 1999) at an approximately linear rate with the log of time (Schmertmann, 1991). A small portion of the set-up is related to the non-linear dissipation, and the majority of the set-up is related to the linear dissipation. Consequently, the aging mechanism may account for relatively little set-up in clayey soils (Komurka et al., 2003).

A number of researchers examined the rate of set-up in different types of soil using pile load tests. In most of the cases, the pile set-up is developed within several days to a few weeks after pile driving, and the rate of the increase was eventually stabilized. Evaluated series of empirical formulas were also proposed to predict the magnitude of the set-up. One of the popular empirical formulas was suggested by Skov and Denver (1988) that presents a linear relationship between the logarithm of time and pile set-up. This empirical relationship was developed based on the result of three case studies of dynamic and static load testing on driven piles in different soil types, including soft clay. Most of these suggested relationships, however, are limited in their widespread application due to the complexity of the set-up mechanism and various set-up controlling factors.

This research evaluates the pile set-up phenomenon in a sensitive clay known as Leda clay by developing a series of medium-scale pile load tests in a field site located at south-east of Ottawa region, called Gloucester (Figure 1).

Figure 1. Gloucester Site in South of Ottawa

## 2 MATERIAL CHARACTERIZATION

### 2.1 Gloucester Site Characteristics

The soil used in this study is a type of marine sensitive clay called Leda clay which covers Ottawa valley and south of Province of Quebec. This clay was formed near the end of the most recent glaciation period in the pre-historic Champlain Sea. The soil unit weight was measured to at 15.3 kN/m$^3$. From the Atterberg test, the plasticity index of this Leda clay was determined at about 23% and liquid limit of 51% (referred to ASTM D4318). The particle size distribution of this soil using a hydrometer test showed a clay fraction of about 40% (ASTM D422). The soil was classified to be highly plastic clay (CH) according to United Soil Classification System (referred to ASTM D2487). The water content of soil was measured at about 52% (referred to ASTM D2216). The vane shear test was performed according to ASTM D2573to specify the undrained shear strength which was estimated to be about 35 kPa. The internal friction angle of the soil was measured as 24˚from a direct shear box test according to ASTM D3080. The coefficient of 1-D consolidation was measured according to ASTM D2435/2435M (2011) and presented a value of 1.4×10$^{-4}$ cm$^2$/s (Table 1).

Table 1. Index properties of soil samples

| ***LL* (%)** | ***PI* (%)** | ***$C_v$* (cm$^2$/s)** | ***$S_u$* (kPa)** | ***Φ'* (˚, deg)** |
|---|---|---|---|---|
| ***51*** | ***23*** | **1.40E-04** | ***35*** | ***24*** |

Notes: LL, liquid limit; PI, plasticity index; $S_u$, undrained shear strength; Φ', friction angle; $C_v$, coefficient of consolidation.

### 2.2 Pile Properties

Two types of steel pile, including open-ended and closed-end steel pipe, were used to perform the pile load tests in order to study the evolution of pile capacity over time in sensitive clay. The surface of these piles was fairly smooth and the average of roughness of the steel piles was about 11.3 µm. The surface roughness of the pipes were estimated as the mean displacement measured by LVDT during the pile load tests, and the root mean square of it was calculated to determine the average roughness of the steel pipes. The geometry of these piles is summarized in Table 2.

Table 2. Model pile geometric properties

| Pile Type | Outside Diameter (mm) | Toe Area (mm$^2$) | Length (mm) | Wall Thickness (mm) |
|---|---|---|---|---|
| **Closed-end** | 101.6 | 8107.3 | 2000 | - |
| **Open-ended** | 101.6 | 8107.3 | 2000 | 5.47 |

### 2.3 Experimental Procedure

In this study, static load tests were used to measure the pile capacity according to ASTM D3689. A reaction frame was designed to apply the load in both tension (upward) and compression (downward) directions (Figure 2). A calibrated load cell and hydraulic hack with maximum ram height of 50 mm were used as shown in Figure 3. The pile load test was conducted at a displacement rate of 5 mm/min. The applied load was released to prevent excessive soil disturbance at the point of the failure.

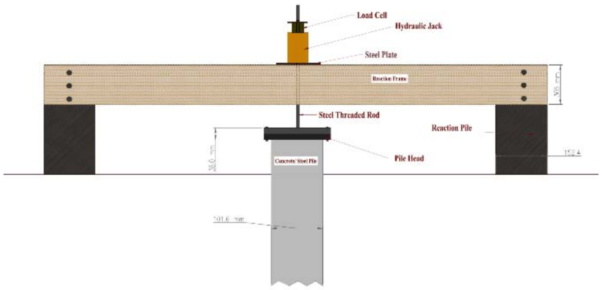


Figure 2. Pile resistance versus elapsed time

Figure 3. Pile load test in the Gloucester site

## 3 RESULTS AND DISCUSSION

Table 3 presents the pile load test results for both open-ended and closed-end steel piles. The shaft bearing capacity of both piles under tension test was similar at about 945-969 N. When the pile load test was repeated three day after initial driving, the load carrying capacity for both piles was significantly increased to more than 5 times their initial capacity. The average increase in pile shaft capacity was approximately 4-5 times their initial capacity 14 days after the initial pile driving. The lowest and highest set-up values were in the range of 4-6, respectively. By measuring the shaft capacity of each pile at different elapsed day, a normalized chart was used to explore and compare the rate of set-up for each pile. The normalization was based on the maximum pile capacity at different elapsed time divided by their initial load capacity measured immediately after pile driving as shown in following Figure 4. It can be seen that the rate of increase in pile capacity was significant in the first couple days from initial pile driving. This rate was eventually decreased as the elapsed time increased up to 30 days; these changes could be due to quick dissipation of excess pore water pressure and possibly greater rate of consolidation of the soil in earlier periods. While the pile is driven, an excess pore water pressure is created in the soil around the pile due to increase in total stress as the soil is being disturbed and forced outward; and also partially due to the variations in mean effective stress during shearing (Randolph 2003).

Immediately after driving the pile, the excess pore water pressure begins to dissipate in the surrounding soil. As this stage is taking place, the effective stress increases therefore the surrounding soil consolidates and eventually this leads to strength gain. This reveals that the dissipation of pore water pressure is a main contributor to the increase in capacity of the pile over time.

Table 3. Pile Shaft Capacity and elapsed time

| **Elapsed Time (day)** | **Pile Shaft Capacity (N)** | |
|---|---|---|
| | **Open-ended steel pile** | **Closed-end steel pile** |
| **0** | 969.6 | 945.1 |
| **1** | 2450.5 | 1135.2 |
| **3** | 5500.0 | 5053.6 |
| **7** | 5961.84 | 5537.5 |
| **14** | 4720.6 | 5100.2 |
| **30** | 4649.8 | 5294.41 |

### 3.1 Empirical Relationship to Estimate Pile Capacity

The Canadian Foundation Engineering Manual suggests estimating pile capacity as a function of the pile geometry and the interface resistance of pile-soil. The shaft resistance ($Q_s$) is calculated from the following expression:

$$Q_s = C L q_s \quad (1)$$

Where $C$ is pile circumference, $L$ is pile embedment length, and $q_s$ is unit shaft resistance, which is related pile-soil interface. The unit shaft resistance is expressed in terms of the undrained shear strength ($S_u$) and an empirical adhesion coefficient ($\alpha$) which is shown in following expression:

$$q_s = S_u \, \alpha \quad (2)$$

The bearing capacity of piles is provided by the shaft and toe resistance. However, these model piles were tested under tensile loading, so the pile capacity only comes from the shaft resistance. The estimated shaft resistance is a simple theoretical value which is calculated and then compared with the measured shaft resistance from the field experiment.

As shown in Table 4, the estimated shaft capacity for closed-end and open-ended steel piles is almost 1.5 times the initial measured capacity which was obtained immediately after driving the piles. However, it can be seen that the capacity increased up to 5 times from their initial capacity after 30 days. The result underscores the importance of considering the pile set-up in pile design. Consequently, the implementation of the set-up in design can reduce the number of piles and/or the embedment of the piles, which would reduce the cost of the construction.

Table 4: Summary of Measured and Estimated Shaft Capacity

| Pile Type | Measured Shaft Capacity (N) | | Estimated Shaft Capacity (N) | Rate of Increase |
|---|---|---|---|---|
| | Initial-Day 0 | Day 30 | | |
| **Closed-end Steel** | 960 | 4650 | 1435 | 3.2 |
| **Open-ended Steel** | 945 | 5295 | 1412 | 3.7 |

3.2 Estimation of Pile Capacity Considering Set-up

Several expressions were suggested and developed to predict the magnitude of pile capacity over time. Skov and Denver (1988) proposed an expression to estimate pile capacity ($Q_t$) at different elapsed time (*t*) from the pile capacity at the end of initial driving (EOID), $Q_0$.

$$Q_t=Q_0[A \log (t/t_0) +1] \qquad [3]$$

where $A$ and $t_0$ are constant parameters based on the type of the soil. It is suggested to use a value of $A= 0.6$ and $t_0=1$ day for clay. These parameters are measured from a case study of 13 driven piles and almost 21 pile load test data.

This empirical relationship could be used to evaluate $A$ value from collected data in this study. From the limited data presented here, the set-up parameter $A$=1.5 to 3.0, is suggested for this Leda clay in Ottawa for an elapsed time of 1 day to one month. The pile capacity at different elapsed time may be estimated using this parameter and formula. This approach may be used as a consideration in design of pile foundation and this may lead to significant saving in pile foundation costs.

3.3 Effect of Pile Type

The piles in this research can be divided into two major types, displacement and non-displacement piles. These piles have different characteristics, i.e., the closed-end pile requires higher energy to drive and it can cause more soil disturbance than open-ended pile. The penetration resistance of the closed-end pile was slightly higher than the open-ended pile, while there was approximately higher resistance at some points in open-ended pile due to the soli plug.

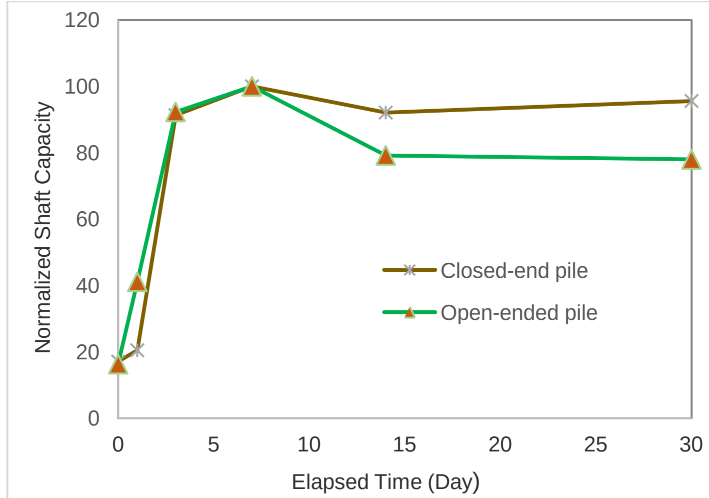


Figure 4. Normalized shaft capacity over time

As shown in Figure 4, the rate of set-up for non-displacement pile was marginally greater than the displacement pile during the first week of pile load recording. This was due to excess pore water pressure which built up during pile driving. On the other hand, the actual shaft capacity for the closed-end pile is slightly lower than the open-ended pile as shown in Figure 5. This underscores that the open-ended pile would probably be a preferred option providing higher initial capacity and lower soil disturbance.

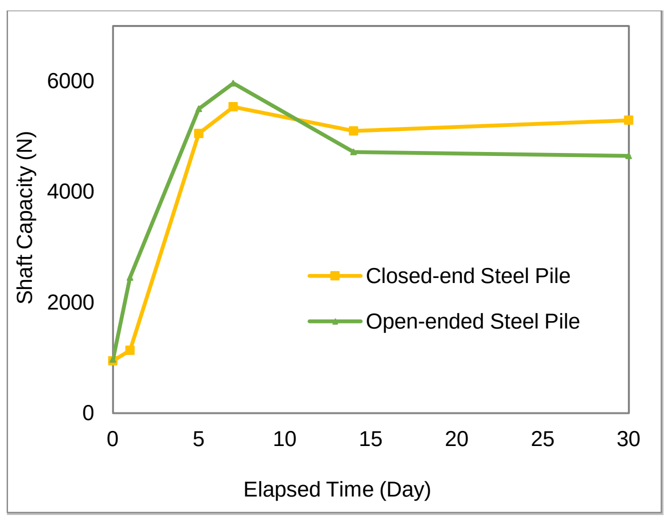


Figure 5. Pile resistance versus elapsed time

3.4 Excess Pore Water Pressure

The pore water pressure (PWP) was monitored using a piezometer at the toe of the closed-end pile during the pile driving and pile load testing. The change in pore water pressure over time was recorded and the result is presented in Figure 6. During pile driving, the pore water pressure was fluctuating and demonstrating non-linear change in PWP. Ultimately, at the end of initial driving, the PWP reached a maximum pressure of about 90 kPa a result of increase in total stress and soil disturbance.

The initial static load test was performed immediately after driving while monitoring the change in PWP. The PWP recording was continuously repeated during every test over elapsed time of 0, 1, 3, 7, 14, and 30 days after the EOID. The results have shown that the PWP began to decrease due to dissipation until reached a stable value over time. This result demonstrates that there is relationship between the PWP dissipation and pile shaft capacity over time. The result determined that excess pore water pressure that was built by driving the pile has begun to dissipate in the surrounding soil, therefore, the effective stress increased, and the surrounding soil consolidates and ultimately gains strength.

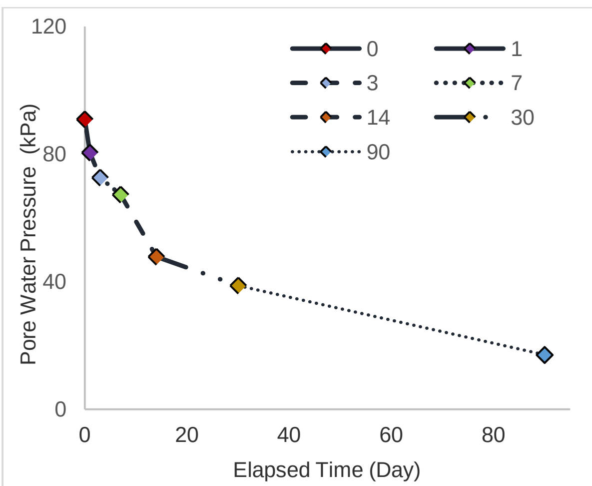


Figure 6. Excess pore water pressure versus elapsed time (adjacent to closed-end pile)

## 4 CONCLUSION

Two steel piles with closed-end and open-ended pipes were driven into Leda clay, with an embedment depth of 2.0 m to study the increase in capacity of pile over time. The piles were tested under static load test (in tension). Pile load tests were performed immediately after driving and repeated 1, 3, 7, 14, and 30 days after initial driving. The shaft capacity and displacement of these piles were measured by load cell and LVDT respectively. The pore water pressure was monitored while driving and through each test.

Both of the piles illustrated an increase in capacity approximately 5 times after 7 days from the initial capacities. Pile set-up was generated in first days due to higher rate of pore water pressure dissipation. After the seventh day, the rate of increase slowed, as well as the rate of pore water pressure dissipation.

The displacement pile showed a slightly higher rate of pile set-up compared to the non-displacement pile since the displacement pile caused larger soil disturbance, thus higher excess pore water pressure. However, non-displacement piles consist higher resistance than displacement piles and this is due to soil plug.

It is significant to consider set-up in soil by performing pile load test and using the observation and results to make consideration into pile designs. This phenomena may be effective in new or rehabilitated structures specifically in Leda clay.

## ACKNOWLEDGEMENTS


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