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Evaluation of Long-term Capacity of Piles Subjected to Consolidation and Aging Setup using CPT Design Methods

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ABSTRACT: This paper focused on assessing the increase in axial resistance of piles that are subjected to both consolidation and aging setups. Initially, models for consolidation and aging setups were developed to estimate the setup parameters based on data gathered from literature, which includes 10 instrumented piles for the consolidation setup and 26 test piles for long-term aging. The eight top-performing pile-CPT methods evaluated in a prior study were employed to estimate the side resistance of soil layers at 14 days post pile driving. Subsequently, the developed consolidation and aging setup models were utilized to extrapolate the results to assess the side resistance of each soil layer at the end of consolidation and for long-term aging. The estimated values for side and total resistance were compared with measurements obtained from pile load tests (PLTs), considering both consolidation and aging setups. The resistances estimated before and after the dissipation of excess pore water pressure completion indicate that significant aging occurs following the consolidation setup. The value of the consolidation setup parameter, A_c, was determined to be 0.53, while for aging, the setup parameter, A_g, was found to be 0.23 in clay and 0.16 in sand. The findings reveal that all pile-CPT methods, with/without utilizing the consolidation setup, tend to underestimate the unit side resistance of clay soil layers. The application of pile-CPT methods in conjunction with the aging model enhanced the accuracy of the pile-CPT methods, which was corroborated by load test results for five piles subjected to aging. The Philipponnat and UF methods demonstrated to be the best-performed pile-CPT method in estimating the total resistance of piles subjected to aging.

KEYWORDS: Consolidation setup, Aging, Cone penetration test (CPT), pile resistance, direct pile-CPT methods.

1 INTRODUCTION

Piles that are driven into fine-grained and granular soils generally undergo an increase in resistance over time, a phenomenon referred to as pile "setup" or "freeze," which primarily impacts side resistance. Researchers have propsed models to forecast pile resistance at designated time intervals following driving and to incorporate setup effects into design considerations. Komurka et al. (2003) categorize pile setup into three distinct phases: logarithmic nonlinear, logarithmic linear, and aging (see Figure 1). Initially, because of soil disturbance, the dissipation of excess pore water pressure (PWP) follows a nonlinear log-time pattern, which is influenced by the properties of the soil and the characteristics of the pile. As time progresses, the dissipation of PWP shifts to a linear log-time rate, which corresponds with the rate of pile setup. The moment at which this transition occurs is referred to as the initial time, t_0, in empirical models.

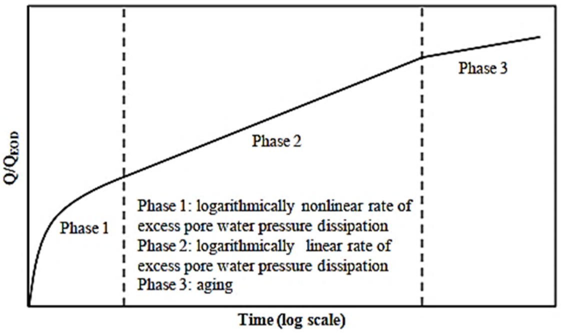


Figure 1. Three phases of pile setup (Haque 2015)

The third phase of pile setup, known as aging, occurs independently of effective stresses and entails time-dependent alterations in soil properties under constant stress. Factors such as thixotropy, secondary compression, particle interference, and clay dispersion play important role in this phenomenon. Schmertmann (1991) observed that aging is more significant in soils with a high organic content due to secondary compression. During this phase, the shear strength, stiffness, and interface friction angle between the surrounding soil and pile increase, while the compressibility of the soil decreases. In Louisiana, pile design generally depends on load testing conducted at 14 days post-installation, overlooking long-term setup effects, which leads to conservative designs. Nevertheless, the resistance gains associated with aging could prolong the service life of superstructures and facilitate the reuse of existing pile foundations. A major challenge lies in accurately estimating the additional resistance that develops over decades. Given that pile evaluation long after installation is essential, the 14-day testing standard may not be the most suitable. This study focuses on the effects of aging, where pile resistance continues to rise beyond the consolidation phase following the dissipation of excess pore water.

Tavenas and Audy (1972) presented the first thoroughly documented case of aging in cohesionless soils. Initially, the effects of setup were ascribed to both tip and shaft resistance; however, recent research indicates that only shaft resistance plays a significant role, with the tip having a minimal effect (Attar and Fakharian 2013). Although consolidation and aging setups may take place simultaneously, they are two separate processes. During the reconsolidation phase, the dissipation of excess pore water pressure primarily dictates strength recovery, rendering the effects of aging negligible. Conversely, aging setup becomes the prevailing factor once reconsolidation has been finalized. To facilitate analysis, researchers such as Gong et al. (2020) propose that aging transpires solely after the consolidation setup, as illustrated in Figure 2.

The majority of earlier research regarding pile setup has suggested a correlation between the pile/soil setup effect and the elapsed time, t, specifically for the linear logarithmic phase 2:

$$\frac{Q}{Q_0}=A\times\log\left(\frac{t}{t_0}\right)+1 \qquad (1)$$

where Q/Q_0 = ratio of pile resistance at time t to pile resistance at the initial reference time, t_0; t/t_0 = ratio of elapsed time to the initial reference time from the end of the drive; and A = setup parameter.

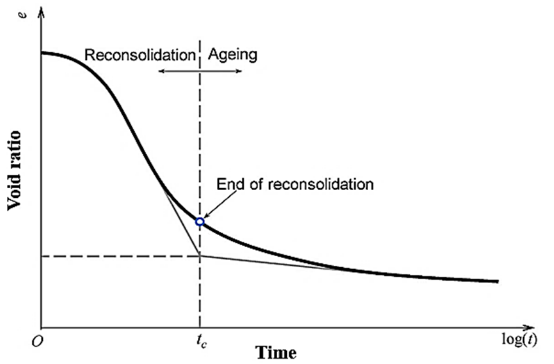


Figure 2. Reconsolidation and aging of surrounding clay (Gong et al. 2020)

The logarithmic setup parameter (A) in Equation 1 is influenced by various factors including soil type, pile type, material, size, and overall pile resistance. Skov and Denver (1988) suggested values of A = 0.2 for sand and A = 0.6 for clay, with reference times t_0 = 0.5 day for sand and t_0 = 1 day for clay.

This research assesses the increase of axial pile resistance, which is attributed to the effects of both consolidation and aging. In order to facilitate this, data was gathered from 10 instrumented test piles related to the consolidation setup and 26 test piles concerning long-term aging, sourced from existing literature. Models were created to evaluate the variations in resistance over time for each effect independently. The study employs the top eight pile-CPT methods identified in a previous study to estimate pile resistance at 14 days post-driving as a benchmark. Subsequently, the developed models were utilized to extrapolate or interpolate resistance values at the conclusion of consolidation and for the long-term aging process. The estimated values were then compared with field-measured resistance to ensure validation.

2 COLLECTED SETUP DATABASE IN LOUISIANA

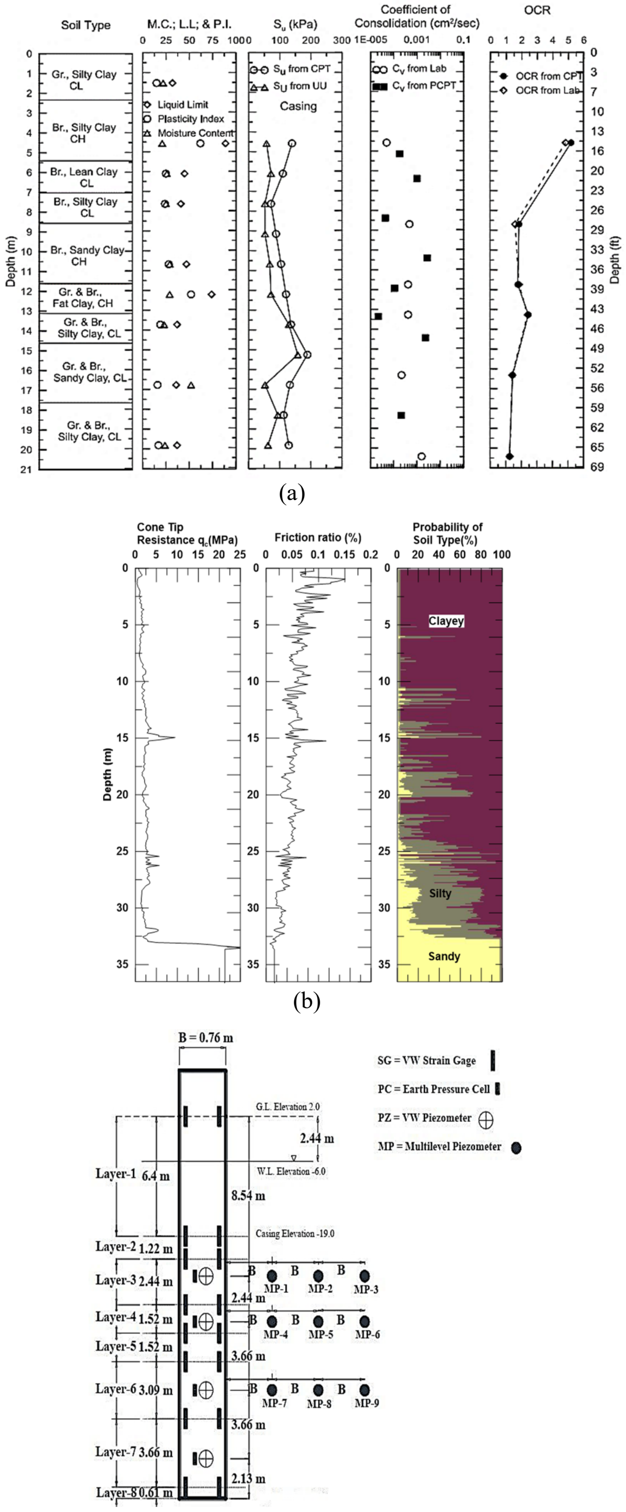
Abu-Farsakh et al. (2016) performed an extensive study aimed at estimating the magnitude of setup and the setup parameter (A) by examining the increase in the pile's side resistance across various soil layers. The research concentrated on four project locations in Louisiana: Bayou Lacassine, Bayou Boeuf, Bayou Zourie, and LA-1, utilizing 10 fully instrumented precast concrete test piles (refer to Table 1). Among these, six piles were tested at the LA-1 site, two at Bayou Lacassine, one at Bayou Zourie, and one at Bayou Boeuf. The piles were instrumented with strain gauges, earth pressure cells, and piezometers on pile face to track changes in resistance, along with additional multilevel piezometers installed in the surrounding soil to measure the buildup and dissipation of excess porewater pressure.

The subsurface soil conditions at the four sites in Louisiana were assessed through comprehensive laboratory and in-situ testing. Laboratory examinations of 3-inch (76 mm) Shelby tube samples encompassed Atterberg limits, soil classification, water content, unit weight, unconsolidated undrained (UU) triaxial, and one-dimensional consolidation tests. In-situ testing included conducting Standard Penetration Tests (SPT) during soil boring and Cone/Piezocone Penetration Tests (CPT/PCPT) near the test piles. For the BL3 test pile, necessary soil properties such as moisture content, liquid limit, plasticity index, shear strength, coefficient of consolidation, and Overconsolidation Ratio (OCR) were evaluated (refer to Figure 3a). The results from the CPT, which include cone tip resistance (q_a) and friction ratio (R_x), are illustrated in Figure 3b. The instrumentation plan (depicted in Figure 3c) incorporated strain gauges, earth pressure cells, and piezometers positioned on the pile face and the adjacent soil. At Bayou Lacassine, a casing was installed to a depth of 21 ft. (6.4 m) to reduce the risk of potential scour. The unit side resistance for BL3 was determined across seven soil layers utilizing strain gauge data.

Table 1. Database of the 10 instrumented test piles.

Project Name	Pile ID	Width, in (mm)	Embedded length, ft. (m)	Scour elevation, ft. (m)
Bayou Lacassine	BL-1	30 (762)	67 (20.4)	21 (6.4)
	BL-3	30 (762)	67 (20.4)	21 (6.4)
Bayou Zourie	BZ	24 (610)	51 (15.5)	20 (6.1)
Bayou Boeuf	BB3	30 (762)	130 (39.6)	6 (1.8)
LA-1	LA1-2	16 (406)	120 (36.6)	-
	LA1-3	30 (762)	180 (54.9)	70 (21.3)
	LA1-4a	24 (610)	150 (45.7)	-
	LA1-4b	24 (610)	201 (61.3)	-
	LA1-5a	24 (610)	139 (42.4)	-
	LA1-5b	24 (610)	160 (49.7)	-

This research study investigated the setup in both clay and sandy soil layers, placing a greater emphasis on clay since it experiences more significant setup magnitude. Sandy layers demonstrated minimal setup. Piezometers that were installed on the faces of piles and in the surrounding soils recorded excess pore pressure over time, which facilitated the distinction between consolidation setup, thixotropy, and aging setup. Nevertheless, data from pile load tests (PLTs) for various soil layers at Bayou Bouef were not available due to the implementation of the O-Cell test, which restricted the study to nine instrumented piles. Measurements of side resistance from clay layers were monitored until the excess pore pressure dissipation was complete, thereby defining the end of consolidation setup. Any additional resistance beyond this phase was ascribed to aging setup. The times for dissipation varied, with piles at the LA-1 site averaging 7 days (13 days for LA1-3), Bayou Zourie reaching 77 days, and piles at Bayou Lacassine taking between 13 to 29 days. By employing a logarithmic time scale, pile resistances were plotted against time, and the consolidation setup factor (A_c) was calculated (refer to Figure 4). Given the brief dissipation time in sandy layers, all setup data pertaining to sand were incorporated into the aging database. This classification was intended to quantify the long-term effects of both consolidation and aging setups on pile side resistance. The normalized resistance values exhibited a distinct trend over time, with an average A_c value of 0.53. This relationship is crucial for predicting increases in the side resistance in clay layers up to the end of consolidation setup.



(a)

(b)

(c)

Figure 3. Reconsolidation and aging of surrounding clay (Gong et al. 2020)

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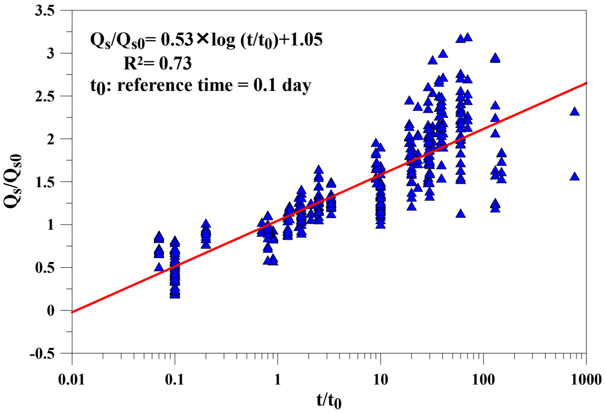


Figure 4. Louisiana database for consolidation setup.

3 COLLECTED DATABASE FOR AGING SETUP

Research studies regarding the increase in pile resistance attributed to aging effects are few. This investigation gathered a total of 26 test piles from 17 case study sites, as illustrated in Table 2, which analyzed pile aging in both clayey and sandy soils. The piles tested were made from various materials, including precast concrete, steel, or wood, with diameters ranging from 4 to 30 inches and lengths varying between 16 and 230 feet. These investigations included several load tests on individual piles. To guarantee reliability, aging setup data, especially for clay soils, were collected based on established excess pore water pressure (PWP) values and the available pile load test outcomes conducted at or after the completion of PWP dissipation.

The normalized aging database (Q_s/Q_{s0} or Q/Q_0) was graphed against the logarithmic time ratio (t/t_0), with the outcomes illustrated in Figures 5a and 5b for clayey and sandy soil layers, respectively. Despite the differences in loading histories across the 17 case studies, most piles demonstrated a consistent trend of increasing resistance over time in clay soils (Figure 5a). However, a notable exception was observed in a large-diameter pile located at West Delta, Gulf of Mexico, where side resistance diminished by 3.5% after one year due to decreased long-term radial stresses surrounding the shaft (Chan and Birrell 1998). In sandy soils, the side resistance of piles exhibited a logarithmic increase over time; nevertheless, some instances revealed reductions in resistance at later stages, resulting in a lower R² value of 0.62. This decrease may be linked to disturbances in the aging process of cohesionless particles caused by repeated load testing, which leads to a reduction in the interface friction angle.

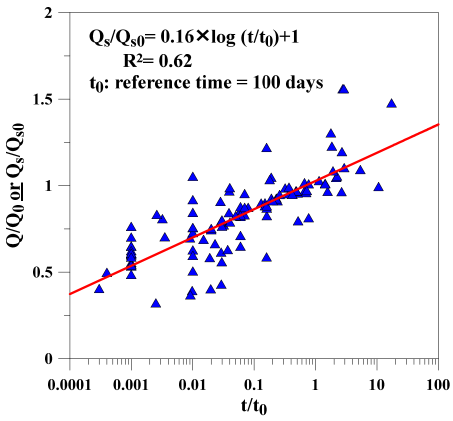
A reference time of 100 days was established for both sand and clay soils, in accordance with previous research regarding the effects of pile aging. This selection corresponds with the standard timeframe for the dissipation of excess pore water pressure, as assessed by various methods, including measurements from piezometers. It is crucial to highlight that the aging setup parameter (A_g) and the initial resistance (Q_0) fluctuate with alterations in the reference time. As illustrated in Figure 5, the aging factor for sand (A_g = 0.16) is less than that for clay (A_g = 0.23). Nevertheless, owing to insufficient data and the variable nature of long-term soil behavior, a conclusive explanation for this discrepancy is not presently found in the literature.

Table 2. Summary of aging setup database from 17 case studies.

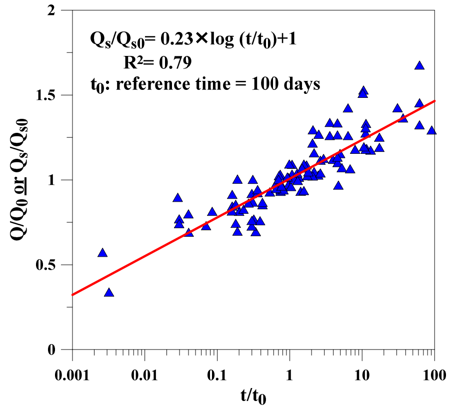
Site	Soil type	Pile material	Pile dia./ width (in)	# of PLTs
Cowden	Clay	Steel	18	4
Canons park	Clay	Steel	7	15
Houston	Clay	Steel	11	3
Nitsund	Clay	Timber	7	10
Drammen	Clay	Timber	10	3
Ska-Edeby	Clay	Timber	4	17
Belfast	Clay	PPC	10	7
Haga	Clay	Steel	6	6
Bothkennar	Clay	PPC	4	2
Buckman Bridge	Sand	PPC	18	4
Aucilla River	Sand & clay	PPC	18	10 clay 6 sand
Vilano Bridge East	Sand & clay	PPC	18	3 clay 4 sand
Vilano Bridge West	Sand & clay	PPC	18	6 clay 4 sand
Seabreeze Bridge	Sand & clay	PPC	18	5 clay 6 sand
West Delta	Clay	Steel	30	2
Bayou Zourie	Sand	PPC	24	2
Bayou Lacassine	Clay	PPC	30	9
Bayou Teche	Sand	PPC	24	3
LA-1	Sand	PPC		25
Alberta	Sand	H-Steel	HP (12.20× 3.1)	2
Hamburg	Sand	PPC	14	4
Alborg	Sand	PPC	10	3
Stockholm	Sand	PPC	10	13
New York	Glacial Sand	Steel	14	30
Victoria	Sand	PPC	18	2
Dunkirk	Sand	Steel	12	4

4 ESTIMATING THE RESISTANCE OF CLAY LAYERS WITHIN CONSOLIDATION SETUP USING PILE-CPT METHODS

The equation developed for the consolidation setup was utilized to extrapolate (or, in certain instances, interpolate) the estimates of pile resistance derived from the eight best-performed direct pile-CPT methods. These methods were selected based on their proximity in predicting the actual pile capacity, as established in a previous study (Abu-Farsakh et al., 2023; Amirmojahedi 2020) that utilized a database comprising of 80 precast pre-stressed concrete (PPC) piles installed in Louisiana soils. The direct pile-CPT methods underwent calibration in Louisiana, employing a database of pile load tests performed 14 days post-driving. As a result, the 14-day pile resistance is regarded as the reference point for this study. Subsequently, the side resistance of each soil layer was extrapolated (or interpolated) using the consolidation setup model illustrated in Figure 4 to estimate resistance at the time of end of excess pore water pressure dissipation, and the outcomes were compared with the measured resistances from pile load tests, as depicted in Figure 6. The comparison indicates that the integration of the direct pile-CPT methods and the consolidation setup model provides reasonable estimations of the measured accumulated side resistance over time.



(a) Sandy soil



(b) Clayey soil

Figure 5. Normalized pile resistance versus normalized time for aging database based on collected pile load tests with time from literature.

5 ESTIMATION OF THE SIDE RESISTANCE CONSIDERING AGING SETUP

This research study utilized the findings from the Missouri Department of Transportation (MDOT) to assess the top-performed eight pile-CPT methods and the aging model illustrated in Figure 5. The MDOT investigation evaluated the axial resistance of in-situ piles from two bridges constructed in the 1960s and replaced in 2017, the UU Bridge and the WW Bridge (Boeckmann et al. 2018). The WW Bridge was supported by driven, closed-end steel pipe piles filled with concrete (CIP piles); whereas the UU Bridge employed octagonal precast concrete piles. Testing commenced in 2016, nearly 50 years post-construction. Five piles (four vertical and one battered) were examined on the UU Bridge, and six piles (four battered and one vertical) were tested on the WW Bridge. This research specifically concentrates on evaluating the eight pile-CPT methods for the precast concrete piles at the UU Bridge. The subsurface conditions at the UU Bridge consist of highly plastic soft clays in the upper 5 to 8 feet, underlain by medium to very dense poorly graded sand extending to a depth of 66 feet. The water table was located approximately 20 feet beneath the surface. Soil boring was performed on one side of the embankment, while the CPT test was conducted on the opposite side. Figure 7 displays the soil boring and CPT data, revealing similar soil profiles despite a 65-foot distance between the test locations, which suggests low site variability.

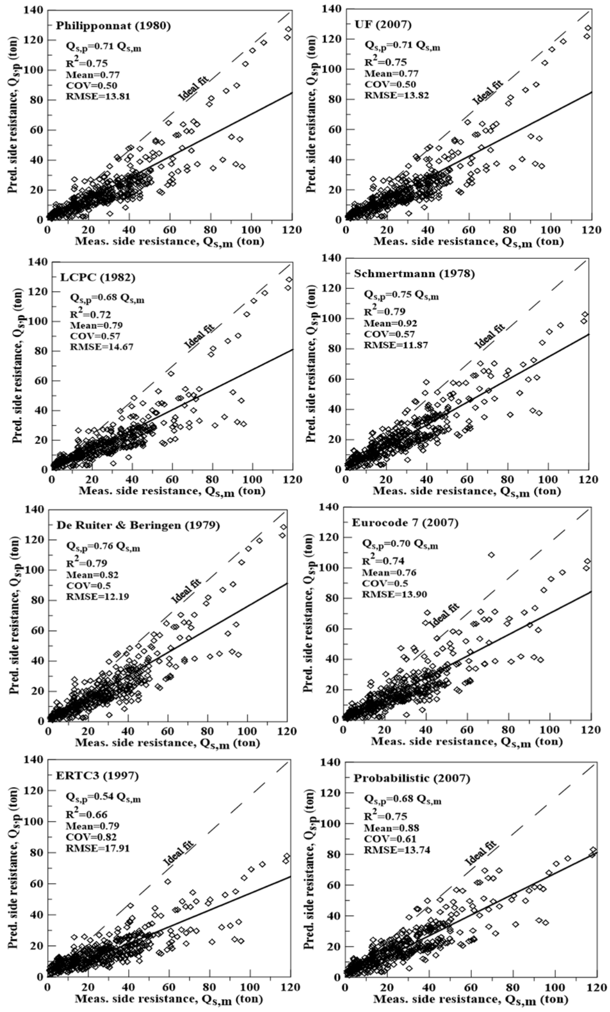


Figure 6. Measured versus predicted capacities for clay layers considering consolidation setup.

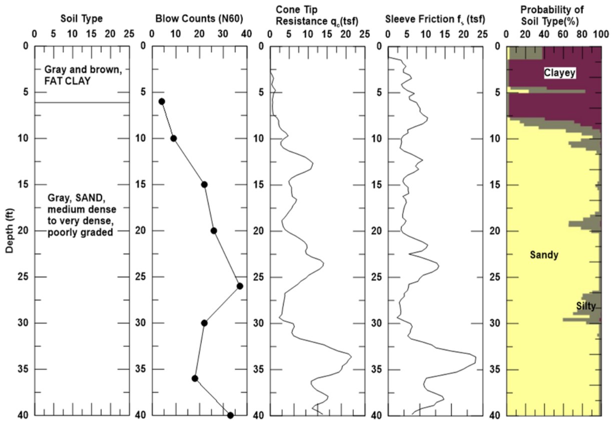


Figure 7. Soil profile and CPT data at UU Bridge.

The eight direct pile-CPT methods were employed to estimate the axial resistance of tested piles at 14 days, followed by an extrapolation to 50 years utilizing the aging model illustrated in Figure 5. The CPT profile indicated an 8-ft clay layer situated above sand, necessitating the estimation of consolidation setup for pore pressure dissipation prior to the application of aging effects. Due to the absence of pore pressure data above the 20-ft water table, only the aging model was implemented to this depth. The side resistance for both clay and sand layers were initially calculated at 14 days, subsequently adjusted using the aging models, with end-bearing resistance incorporated to determine total capacity. Figure 8 displays the results for pile #1 (embedment depth = 21.3 ft.).

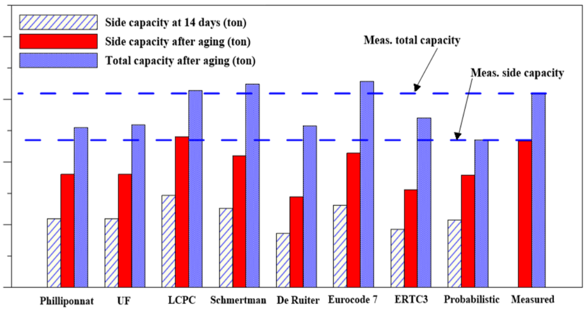


Figure 8. Predicted resistance of pile #1 based on the 8 direct-CPT methods.

The side and total resistances for all tested piles at the UU Bridge were determined using the eight direct pile-CPT methods and aging models (refer to Figure 5, which is applicable solely to side resistance). A statistical analysis of the ratios of predicted to measured resistance (Q_s,p/Q_s,m and Q_p/Q_m) was conducted, with the findings displayed in Table 6. The mean (μ) of Q_s,p/Q_s,m varied from 0.76 (De Ruiter) to 1.29 (LCPC), accompanied by a coefficient of variation (COV) ranging from 0.16 (De Ruiter) to 0.29 (Eurocode 7). For Q_p/Q_m, the mean (μ) fluctuated between 0.85 (De Ruiter) and 1.20 (LCPC), with a COV spanning from 0.09 (De Ruiter) to 0.21 (LCPC). Most of the pile-CPT methods (except for De Ruiter, ERTC3, and Probabilistic) tended to overestimate the end-bearing resistance (μ >1.0). Nevertheless, the inclusion of end-bearing resistance alongside side resistance (factoring in aging) enhanced accuracy by lowering the COV. In summary, the Philipponnat and UF methods yielded the most precise estimations among the eight direct pile-CPT methods investigated in this study.

Table 3. Statistical analysis of predicted versus measured capacities.

CPT method+ Aging model	$Q_{s,p}/Q_{s,m}$			Q_p/Q_m		
	μ	COV	RMSE	μ	COV	RMSE
Philipponnat	1.01	0.24	17.72	0.97	0.13	15.09
UF	1.01	0.24	17.61	0.98	0.12	13.59
LCPC	1.29	0.28	31.87	1.20	0.21	30.29
Schmertman	1.12	0.26	19.71	1.12	0.15	19.44
De Ruiter	0.76	0.16	30.72	0.85	0.09	25.84
Eurocode 7	1.22	0.29	27.01	1.19	0.16	27.89
ERTC3	0.84	0.20	25.08	0.91	0.11	19.65
Probabilistic	0.95	0.21	17.66	0.89	0.13	21.76

6 SUMMARY AND CONCLUSIONS

This research assessed the increase in axial resistance of piles considering the effects of both consolidation and aging with time. Models for consolidation and aging were developed utilizing data from 10 instrumented test piles for consolidation and 26 test piles for long-term aging. The top-performed eight pile-CPT methods identified in a previous study were employed to estimate the side resistance at 14 days after driving, with the models utilized to project the resistance at the end of consolidation and during long-term aging. The estimated values were corroborated with the field measurements obtained from pile load tests (PLTs). Based on the results of this study, the following conclusions can be made:

- In clay, the consolidation setup parameter (A_c) was 0.53, and the aging setup parameter (A_g) was 0.23; in sand, A_g was 0.16.
- All eight pile-CPT methods underestimated unit side resistance in clay, with predicted/measured (μ) values ranging from 0.71 to 0.85, with Schmertmann showing the highest ($\mu = 0.85$).
- Combining pile-CPT methods with the consolidation model also underestimated side resistance in clay. De Ruiter and Beringen performed best ($Q_{s,p} = 0.76Q_{s,m}$), while ERTC3 had the lowest accuracy ($Q_{s,p} = 0.54Q_{s,m}$).
- Significant aging effects were observed beyond consolidation setup.
- The predicted/measured side resistance ($Q_{s,p}/Q_{s,m}$) ranged from 0.76 (De Ruiter) to 1.29 (LCPC), while total resistance (Q_p/Q_m) ranged from 0.85 (De Ruiter) to 1.20 (LCPC). Most methods overestimated end-bearing resistance ($\mu > 1.0$), except De Ruiter, ERTC3, and Probabilistic methods.
- The Philipponnat and UF methods provided the most accurate total resistance estimations.
- Integrating aging models into pile-CPT methods significantly improved prediction accuracy.

7 ACKNOWLEDGEMENTS

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