A CASE STUDY ON INSTRUMENTING AND TESTING FULL-SCALE TEST PILES FOR EVALUATING SET-UP PHENOMENON

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Keywords: Test pile; Static Load Test; Dynamic Load Test; Pile Set-up; Excess Pore Water Pressure.

ABSTRACT:

Piles driven in cohesive soils usually experience a large increase in resistance over time, known as set-up or freeze. Dynamic load tests (DLT) and Static load tests (SLT) are usually performed to verify the axial resistances of piles at specific times after end of driving (EOD) and to quantify these resistances. An extensive field testing program was performed on full-scale instrumented precast prestressed concrete (PSC) piles driven in cohesive soils at the Bayou Lacassine Bridge, Louisiana, to evaluate the pile set-up phenomenon. Five SLTs and three DLTs were conducted on each test pile at different times after EOD in order to quantify the magnitude of set-up. Measurements from the load tests on both piles confirmed that the pile set-up after EOD follows a logarithmic rate with time. An increase in piles' total resistances (or set-up) of 1.60 to 1.77 times the EOD resistances were observed after the final restrikes. Piezometer data demonstrated close relationship between the dissipation of excess pore water pressures that were generated during pile driving, following EOD, and pile set-up. The load transfer curves derived from the strain gage measurements were used to separate the side and tip resistance profiles from the total resistance.

1. INTRODUCTION:

It is well-known that the axial resistance of piles driven in soils increases with time after driving (1-3). This phenomenon is called pile set-up or "freeze" and has been reported and discussed by many researchers (e.g., 1, 4-6). The set-up phenomenon occurs in soils can be attributed to dissipation of excess pore water pressure (or consolidation), thixotropy, and aging. Several empirical (e.g., 7), numerical (e.g., 8) and analytical techniques have been proposed and developed over the past few decades to predict the amount of set-up with time. In addition, several researchers (e.g., 3-5) have conducted full-scale experimental field tests to measure the increase in pile resistance with time using static and/or dynamic tests.

Soil around the pile usually experiences plastic deformation and pore pressure changes during pile driving (1, 4, 6). Excess pore water pressure develops as the result of pile driving (2, 8). After the completion of pile driving, a certain degree of excess pore water pressure dissipates at the soil-pile interface zone, usually resulting in an increase in pile resistance (3, 6). At early stages after driving, the dissipation of excess pore water pressure can be non-uniform with respect to time depending on soil permeability and the extent of soil disturbance. According to Komurka et al. (9), set-up at early stages is mainly due to the non-linear rate of excess pore water pressure dissipation and thixotropy (stress-dependent gain in strength). After this initial non-linear rate of excess pore water pressure dissipation (Phase-1), the rate of excess pore water pressure dissipation becomes uniform (Phase-2) and the set-up rate becomes linear. These initial two phases resemble the consolidation phenomenon of soil. The duration of these first two phases depends on the soil type (cohesive or noncohesive), soil properties such as permeability and sensitivity, and pile type and size (2, 5). In cohesive soils, the induced excess pore water pressure may dissipate slowly (4). However, for noncohesive soils, the duration of the first two phases are expected to last several hours to several days since the completion of excess pore water induced by pile driving usually takes a shorter time to dissipate for coarse grained soil (10). The last stage (Phase-3) of set-up, which is independent of the effective stress, can be continued from several years to infinite time for both cohesive and noncohesive soils (1, 10). Practically, after a certain time, there is no effect of the consolidation process on the increase of pile resistance. This third stage of set-up is related to the “aging” phenomenon (9, 10). It is due to the combined effect of secondary compression (creep), particle interference and clay dispersion (9, 10). Aging effects increase the soil’s shear modulus, stiffness, and dilatancy, and reduce the soil’s compressibility (10).

The current engineering practice in the design of piles in Louisiana is based on pile loading test performed 14 days after driving. Although the results of several field studies, along with literature, show that pile set-up continues to occur after 14 days (e.g., 4, 5), which is ignored in the current design practice beyond that period, resulting in a conservative pile design. In order to quantify the amount of set-up for piles driven in cohesive soils in Louisiana, a long-term field experimental pile resistance study was conducted. This study consists of driving two instrumented 762 mm (30 inch) PSC piles and conducting SLTs and DLTs over a period of six months after EOD. Load tests were conducted on each pile at predetermined intervals to assess the development of “pile set-up” as a function of time following the EOD.

2. PROJECT DESCRIPTION AND GEOTECHNICAL CONDITION:

The Louisiana Department of Transportation and Development (LADOTD) replaced the old Bayou Lacassine Bridge located on Highway 14 in Jefferson Davis Parish, Louisiana. A total of three test piles were driven and monitored with Pile Driving Analyzer (PDA) and subsequent Case Pile Wave Analysis Program (CAPWAP) analysis was run to aid in the determination of production pile lengths and pile driving criteria. Two test piles; Test Pile-1 (TP-1) and Test Pile-3 (TP-3) were driven on both ends of the bridge and were fully instrumented, while Test Pile-2 (TP-2) was driven in the waterway and was not accessible for instrumentation. However, only the results of TP-1 and TP-3 will be discussed in this paper.

Two boreholes were drilled on the site near the test piles and high quality Shelby tube samples were retrieved from both boreholes at different depths for comprehensive laboratory testing. The subsurface soil stratigraphy as revealed from boring were depicted in Figure 1a and 1b. The natural water table was 2.44 m (8 ft) below the ground surface for both test piles. Figures 1a and 1b present the profiles of different soil properties including soil boring log, undrained shear strengths, and the coefficient of consolidation for TP-1 and TP-3, respectively. Three cone penetration tests (CPT) were conducted on the site near the test piles to profile the subsurface soils. The profile of the CPT test results are presented in Figures 1a and 1b for TP-1 and TP-3, respectively, which agree with the classifications from the soil borings.

3. INSTRUMENTATION AND INSTALLTION:

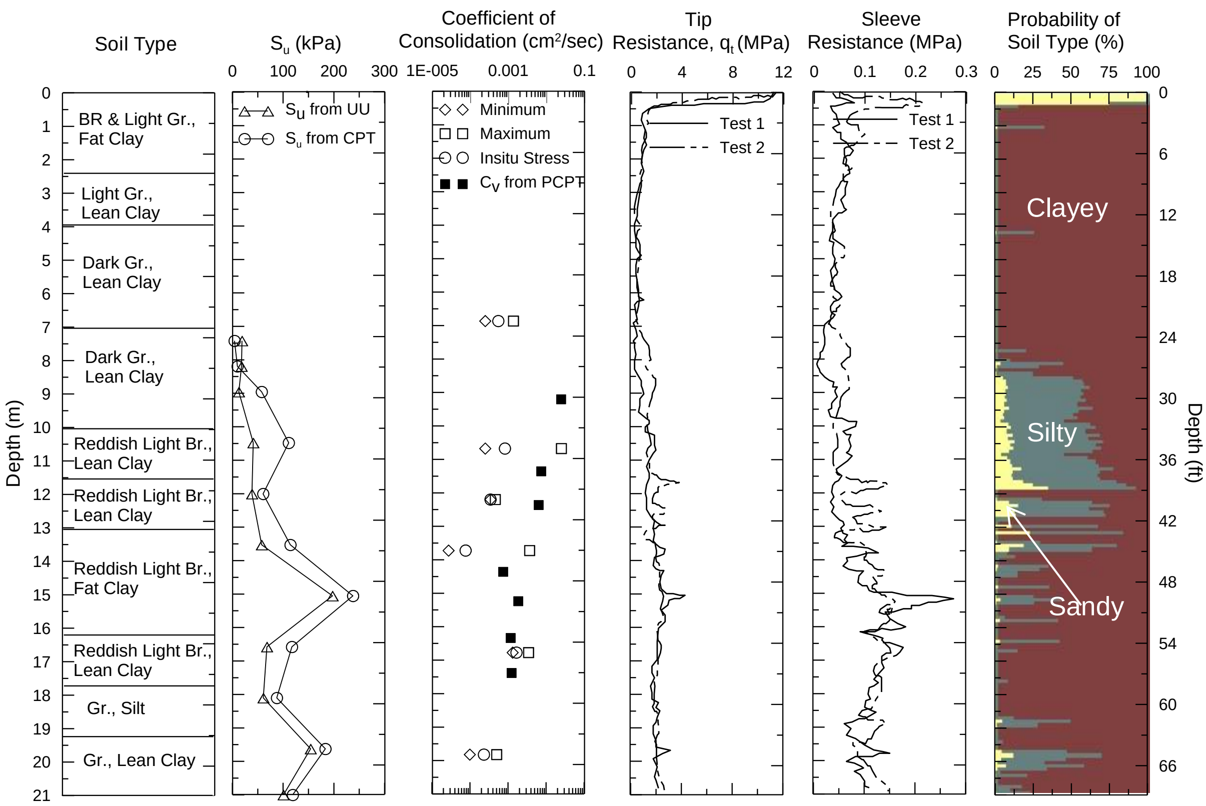
3.1 Instrumentation of the Test Piles and Surrounding Soils

The test piles were 762.2 mm (30 inch) square PSC with a 419.2 mm (16.5 inch) diameter circular void. The test piles were 22.86 m (75 ft) in length, with 20.42 m (67 ft) embedment depth. The top 2.44 m (8 ft) of pile remained above the ground level to conduct the SLT and to provide enough vertical clearance between the bottom of the reaction pile frame and the pile top.

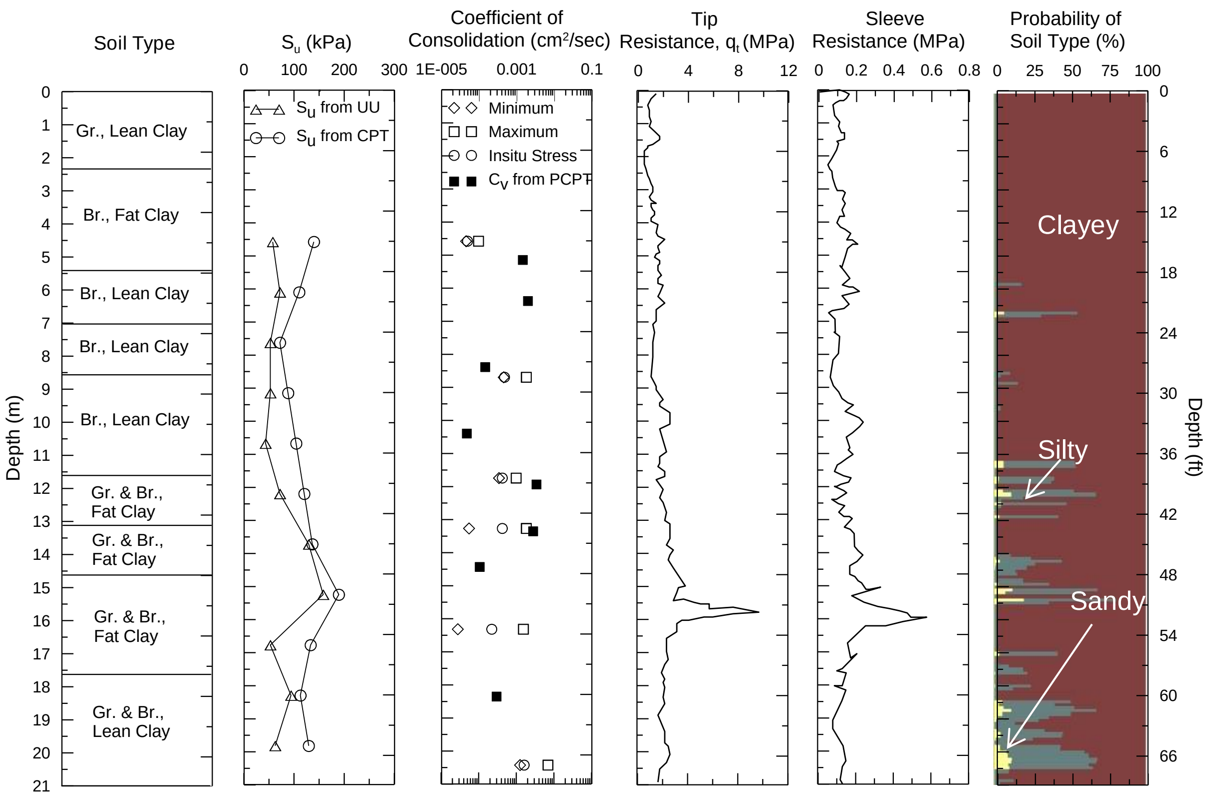
In order to fulfill the goal of calculating set-up of individual layer, several instruments were installed on the piles during casting, prior to pile driving. Each test pile was instrumented with eight pairs of “sister bar” strain gages (Geokon Model 4911) in order to evaluate the load distribution along the length of the piles and to calculate the tip resistance during the SLT. Four sets of pressure cells (Geokon Model 4820) and vibrating wire piezometers (Geokon Model 4500S) were installed on the surface of both piles to measure the responses of surrounding soil during pile driving and the following load tests. Schematic drawings showing instrument locations of TP-1 and TP-3 are presented in Figures 2a and 2b, respectively. Nine multilevel ground piezometers (Geokon Model 4500MLP) were also installed in the ground at three different levels for both test piles as presented in Figures 2a and 2b. The distances were 1B, 2B, and 3B from the face of the driven pile, with B being the pile width. A Geokon 8020 data logger system with a solar panel system was used for data collection during these periods.

3.2 Installation of the Test Pile

The 22.87 m long test piles were driven and dynamically tested using a single acting diesel hammer of model ICE I-62v2 having a ram weight of 6,621 kg (14,600 lbs) and a rated stroke energy of 224 kJ at fuel pump setting and a maximum ram stroke height of 4.34 m (14.25 ft). The piles were driven to a final tip elevation of 20.43 m (67 ft). A 6.4 m (21 ft) scour depth was estimated at both locations and 1.14 m diameter casings were installed and driven prior to drive the piles at a tip elevation of 6.4 m for both test piles.

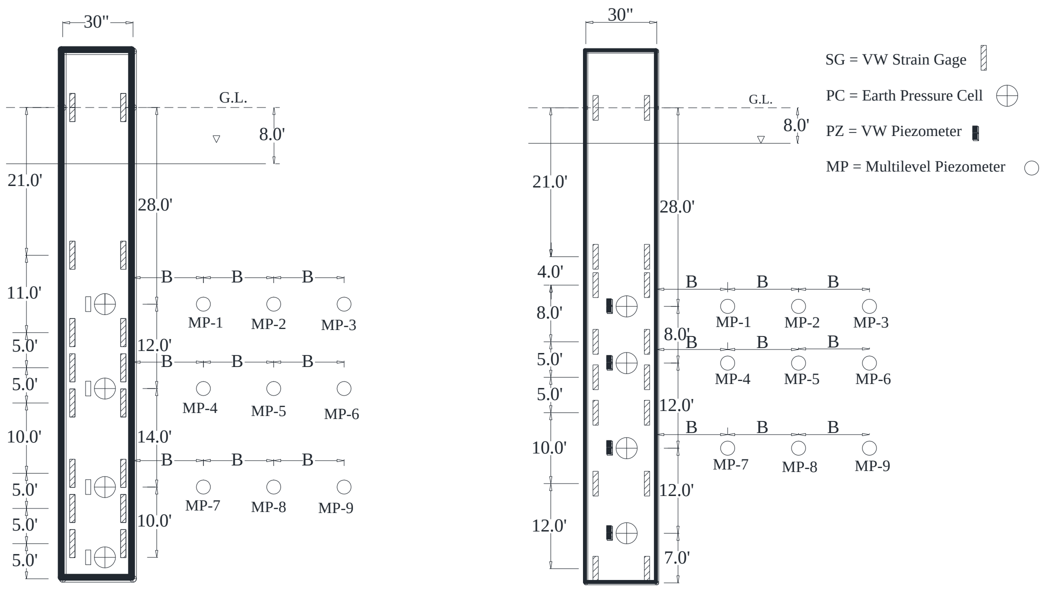


(a) TP-1.



(b) TP-3

Figure 1. Soil Profile of Test Piles.



(a) TP-1 (b) TP-3

Figure 2. Instrumentation Plan and Photos of the Instrument.

4. LOAD TEST PROGRAM AND MEASURED SET-UP:

An extensive load test program was carried out after pile installation using both SLTs and DLTs in order to measure the increase in pile resistance with time (or pile set-up). The test program began with a DLT conducted within 1 hour after EOD. Five SLTs and three additional DLTs were then conducted on both test piles over a six months period after EOD. The measured side, tip and total resistances with time for all tests are tabulated in Table 1. The plots of total pile resistance with time after EOD are presented in Figures 3a and 3b for TP-1 and TP-3, respectively. The figures show that the total resistances at the final restrike were 1.77 and 1.60 times higher compared to EOD resistances for TP-1 and TP-3, respectively. More discussion on the rate of set-up will be discussed later in Section 5.

4.1 Dynamic Load Tests (DLT):

Three high strain DLTs were carried out on each test pile at different time intervals from 30 minutes after EOD, up to a maximum of 217 days after EOD for TP-1 and 181 days after EOD for TP-3. The time intervals of conducting the DLTs and corresponding total, side and tip resistances are tabulated in Table-1 for both test piles.

The test results showed a significant increase in resistance for both test piles started immediately after driving. The 2nd restrike, which was conducted within 24 hours after EOD on both test piles, showed that the total resistance was increased by 19% and 28% for TP-1 and TP-3, respectively. Initial excess pore water dissipation and thixotropy may attribute to this significant amount of set-up over a very short time period, which will be discussed later in Section 5. The final restrike showed that the total resistance was 1.77 and 1.60 times the EOD resistance values for TP-1 and TP-3, respectively.

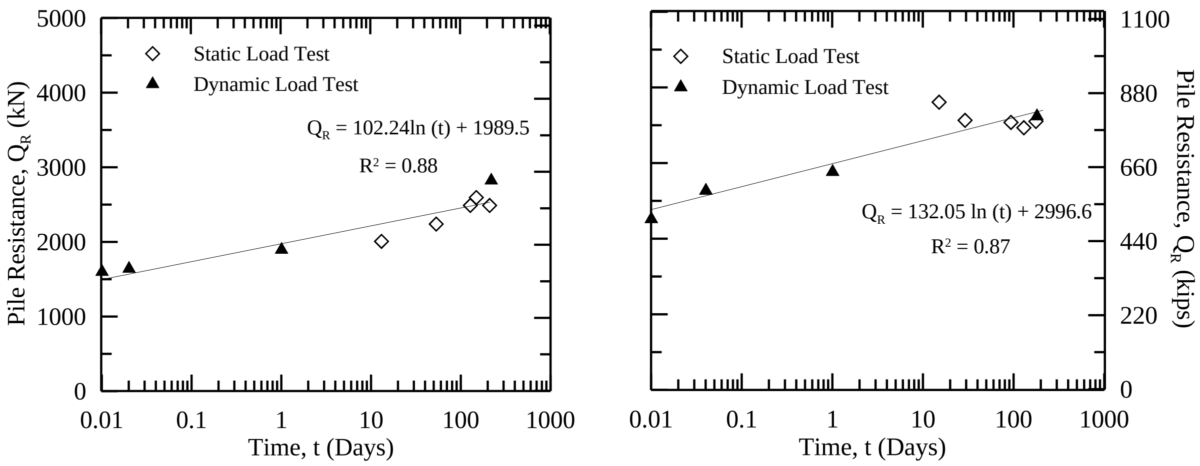
4.2 Static Load Tests (SLT):

Five SLTs were conducted on both test piles over a period of six months after EOD in accordance with ASTM Standard D1143. The time schedule of each SLT is tabulated in Table-1. Figures 4a and 4b present the measured static load-displacement curves for TP-1 and TP-3, respectively. The ultimate resistance of each pile was calculated using the modified Davisson interpretation method, and the values are presented in Table-1. Test results of TP-1 showed that the total pile resistance increased by approximately 26% by the 1st SLT (13 days after EOD) and increased up to 62% by the 4th SLT (148 days after EOD). However, the pile resistance decreased slightly (~5%) during the 5th SLT (208 days after EOD) as compared to the 4th SLT, which was still 1.57 times higher compared to EOD. The last restrike (217 days after EOD) immediately after the 5th SLT supports the set-up trend, and the total resistance was finally 1.77 times higher compared to EOD. The set-up behavior of TP-3 was slightly different from TP-1. The total resistance of TP-3 increased significantly by 67% at the 1st SLT (15 days after EOD) as compared to EOD. However, the total resistance stayed almost constant during the following SLTs. The total resistance for TP-3 at the 5th SLT (175 days after EOD) was 1.57 times higher than the EOD value. The behavior of TP-3 will be discussed later in Section 5.

Figures 5a and 5b present the load distribution curve of the 5th SLT for TP-1 and TP-3, respectively. The loads were calculated from the vibrating wire strain gage measurements, in which the measured strains at the start of the load test were set as reference points (i.e., assuming no load prior to starting the SLT) at the eight levels. The pairs of strain gages that were installed near the top and bottom of the casing showed no load transfer was observed in the top 6.4 m (21 ft) for both test piles.

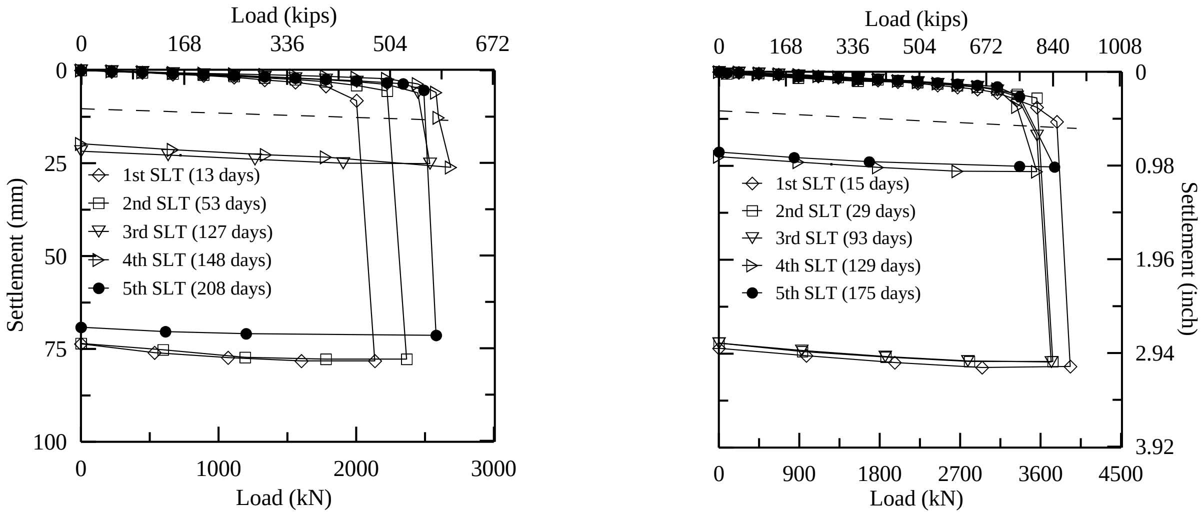
Table 1. Driving, SLTs and Restrikes resistance for all Test Piles

Events	Time from EOD	Total Resistance	Increase from EOD	Side Resistance	Increase from EOD	Tip Resistance	Increase from EOD	Set-up factor for Total Resistance
	Days	(kN/kips)	%	(kN/kips)	%	(kN/kips)	%	(R_t/R_o)
TP-1								
EOD	-	1602 / 360	0	1263 / 284	0	339 / 76	0	1.00
1st RST	0.02	1645 / 370	3	1290 / 290	2	355 / 80	5	1.03
2nd RST	1	1899 / 427	19	1545 / 348	23	354 / 79	4	1.19
SLT1	13	2011 / 452	26	1695 / 381	34	316 / 71	-7	1.26
SLT2	53	2224 / 500	39	1901 / 427	51	323 / 73	-5	1.39
SLT3	127	2491 / 560	55	2130 / 479	71	361 / 81	7	1.56
SLT4	148	2598 / 584	62	2191 / 493	73	407 / 91	20	1.62
SLT5	208	2509 / 564	57	2094 / 471	66	415 / 93	22	1.57
3rd RST	217	2827 / 636	76	2376 / 534	88	451 / 102	33	1.77
TP-3								
EOD	-	2260 / 508	0	1495 / 336	0	765 / 172	0	1.00
1st RST	0.04	2642 / 594	17	1851 / 416	24	791 / 178	3	1.17
2nd RST	1	2891 / 650	28	2171 / 488	45	720 / 162	-6	1.28
SLT1	15	3781 / 850	67	3100 / 697	107	681 / 153	-11	1.67
SLT2	29	3576 / 804	58	2909 / 654	95	667 / 150	-13	1.58
SLT3	93	3514 / 790	55	2821 / 634	89	693 / 156	-9	1.55
SLT4	129	3443 / 774	52	2786 / 626	86	657 / 148	-14	1.52
SLT5	175	3541 / 796	57	2896 / 651	94	645 / 145	-16	1.57
3rd RST	181	3621 / 814	60	2856 / 642	91	765 / 172	0	1.60



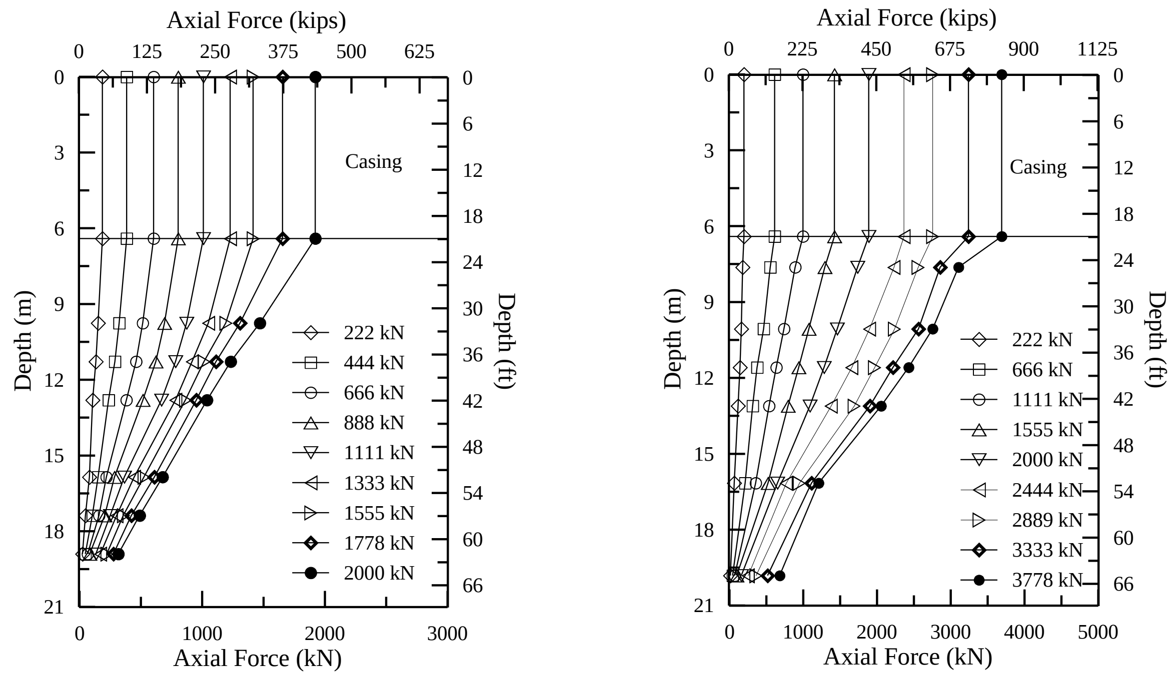
(a) TP-1 (b) TP-3

Figure 3. Total Pile Resistance versus time elapsed for (a) TP-1 and (b) TP-3.



(a)TP-1 (b) TP-3

Figure 4. Static Load Tests results (a) TP-1 and (b) TP-3.



(a)TP-1 (b) TP-3

Figure 5. Static Load Tests results (a) TP-1 and (b) TP-3.

5. DISSIPATION OF EXCESS POREWATER PRESSURE

In order to evaluate the set-up phenomenon of the soil layers, it was necessary to examine the behavior of excess pore water pressure during pile installation and subsequent restrikes and SLTs. The buildup of excess pore water pressure on the pile-soil interface due to pile driving and subsequent dissipation with time was recorded by piezometers installed on the pile face and are presented in Figures 6a and 6b for TP-1 and TP-3, respectively. One can observe from Figure 6a that the excess pore water pressure for the piezometer installed at 8.54 m (28 ft) below ground level (GL) for TP-1 exhibited a faster dissipation rate compared to the other piezometers. A complete dissipation was observed after about 10 days. This is possibly due to the presence of thin interlayer of silty-sandy clay soil close to the piezometer as the CPT shows (Figure 1a). The excess pore water pressure for the other piezometers of TP-1was completely dissipated after about 80 days. The prolonged dissipation may explain why a longer period of set-up was observed for TP-1. On the other hand, Figure 6b showed that the piezometers of TP-3 exhibited faster dissipation rates compared to the piezometers of TP-1. The dissipation processes were almost completed in about 10 to 20 days, except for the piezometer located at 8.54 m below GL. The faster dissipation rate may explain why significant amount of set-up (67%) was observed in the 1st SLT (15 days after EOD), after which the total resistance of TP-3 was almost constant. Several events, such as restrikes, installation of reaction frame, and SLTs, took place after pile driving. Significant excess pore water was generated during these events as shown in Figures 6a and 6b for TP-1 and TP-3, respectively. However, it dissipated and porewater pressure returned to its original position within a short period of time.

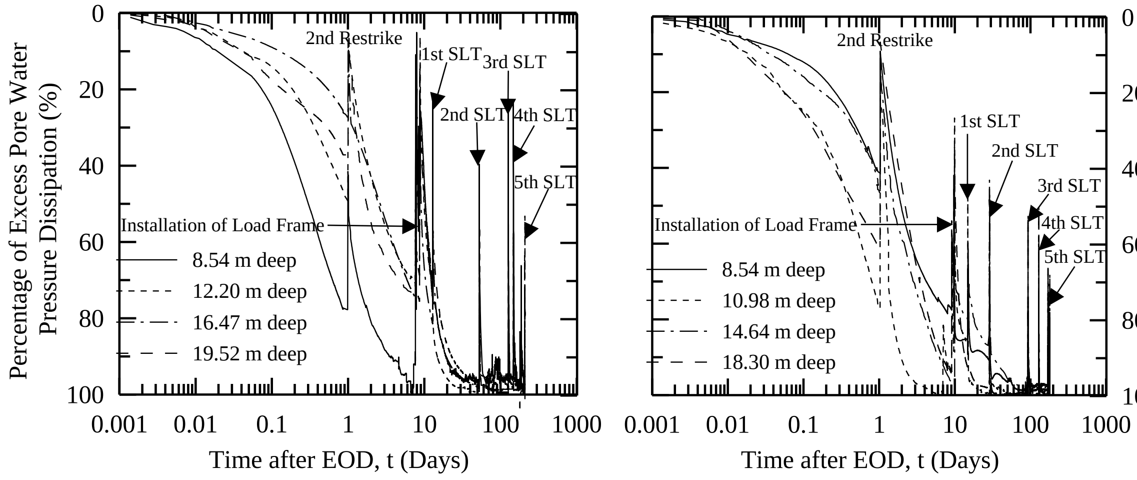


Figure 6. Distribution of Excess Pore Water Pressure Measured by Piezometers.

6. COMPARISON OF INCREASE IN HORIZONTAL EFFECTIVE STRESS WITH SIDE RESISTANCE

In order to evaluate the set-up of the soil layers along the pile length, the horizontal effective stress for each soil layer was calculated from the pressure cells and piezometers measurements, and was compared with the total side resistance obtained from the CAPWAP analysis. Figures 7a and 7b present the comparison between the percentage increase of horizontal effective stress and the side resistance with time of specific soil layers for TP-1 and TP-3, respectively. The figures show that the horizontal effective stress started to increase immediately after pile driving, mainly due to consolidation, and continued to increase for the next six months of the monitoring period after EOD. The continuing increase of the horizontal effective stress after the end of consolidation process can be attributed to aging (i.e., time-dependent change in soil properties).

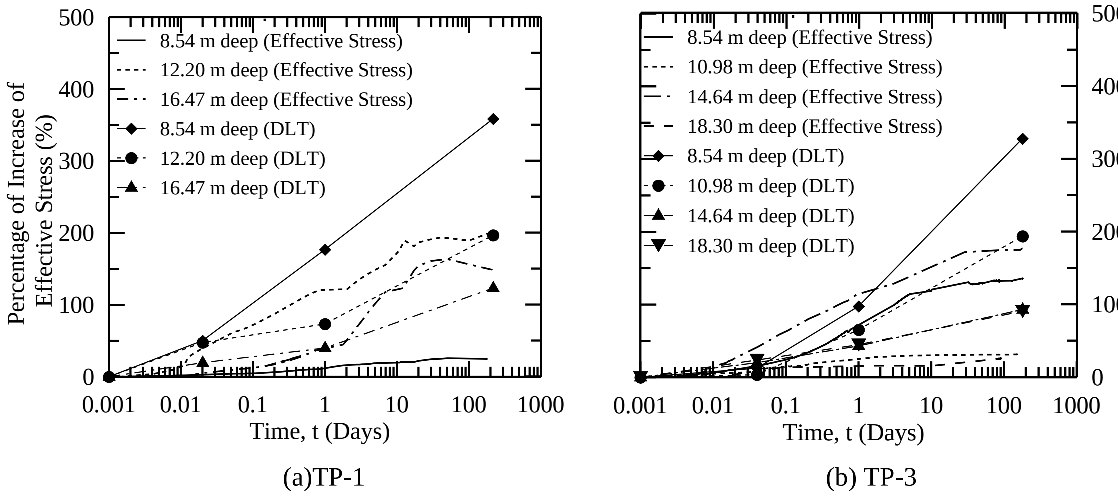


Figure 7. Comparison of Percentage Increase of Horizontal Effective Stress versus Side Resistance.

Figure 7a shows that the pressure cells of TP-1 installed at depths of 12.20 m and 16.47 m below GL, after the 5th SLT (208 days after EOD), experienced an increase in horizontal effective stresses by 201% and 148%, respectively. Similar trend of increase in side resistance was also observed from the CAPWAP analysis. The CAPWAP analysis documented side resistance increase of 196% and 123% for these two specific soil layers. Soil type plays a significant role in the development of excess pore water pressure due to pile driving, and hence the increase in horizontal effective stress with time after driving. Due to the presence of an interlayer of silty-sandy clay close to the pressure cell at depth of 8.54 m below GL, it did not exhibit a major increase in horizontal effective stress (24%). The same results were also observed for the pressure cells of TP-3 from Figure

7b. The pressure cells installed at depths of 10.98 m and 18.30 m below GL exhibited insignificant increase in horizontal effective stress. This small increase in horizontal effective stress may be also attributed to the presence of silty-sandy clay interlayers soil (Figure 1b). On the other hand, the pressure cells of TP-3 installed at the clayey soil layers (i.e., 8.54 m and 14.64 m below GL) exhibited significant increase in horizontal effective stresses. This increase in the horizontal effective stresses with time significantly contributed to the set-up of piles.

8. CONCLUSIONS:

A field testing program was performed on full-scale instrumented PSC piles driven in cohesive soils to evaluate the pile set-up phenomenon. Based on the analyses of load tests and interpretation of instrument results, the following conclusions can be drawn:

a. The increase in total resistance for the test piles exhibited a linear trend with logarithmic of time. TP-1 exhibited slower set-up rate due to slower dissipation of excess pore water pressure after EOD as compared to TP-3. After the dissipation of excess pore water completed, the final restrike for TP-1 (217 days after EOD) showed a total resistance increase of 1.77 times the EOD resistance. On the other hand, TP-3 experienced a faster set-up rate compared to TP-1, probably due to faster dissipation of excess pore water pressure. The final restrike of TP-3 (181 days after EOD) recorded a total resistance increase of 1.60 times the EOD resistance.
b. The load distribution curves from strain gages and the CAPWAP analysis showed that the majority of pile set-up is attributed to the increase in side resistance. The side resistance was increased by 88% and 91%, at the last restrike, for TP-1 and TP-3, respectively.
c. Results of field measurements showed that the horizontal effective stress, side resistance, and total resistance continue to increase after the completion of consolidation process, which can be attributed to aging effect. The results also show direct relationship between the measured horizontal effective stresses and the side resistance of soil layers along the pile length.
d. Measurements from the pressure cells and piezometers showed lower excess pore water pressure and lower increase in horizontal effective stress for depths close to the silty-sandy clay interlayer as compared to other depths.

9. ACKNOLWEDGEMENT:

This research project is funded by the Louisiana Department of Transportation and Development (State Project No. 736-99-1732) and Louisiana Transportation Research Center (LTRC Project No. 11-2GT). The authors would also to thank the DOTD geotechnical section for the help and support they provided in this study.

REFERENCES:

1. Lee, W., Kim, D., Salgado, R., and Zaheer, M. (2010), “Setup of Driven Piles in Layered Soil.” Soils and Foundations, Vol. 50 (5), pp. 585-598.
2. Fellinius, B. H. (2008), “Effective Stress Analysis and Set-up for Shaft Capacity of Piles in clay.” *Proc. to from Research to practice in Geotechnical Engineering, Geo-Institute of the American Society of Civil Engineering*. Alberta, Canada, pp. 384-406.
3. Ng, K. W., Suleiman, M. T., and Sritharan, S. (2013), “Pile Setup in Cohesive Soil: Analytical Quantification and Design Recommendations.” Journal of Geotechnical and Geoenviromental Engineering, Vol. 139(2), pp. 210-222.
4. Chen, Q., Haque, M. N., Abu-Farsakh, Y. M., and Fernandez, B. A. (2013), “A Field Investigation of Pile Set-up in Mixed Soil.” Geotechnical Testing Journal, In Production.
5. Bullock, P, J., Schemertmann, J. H., McVay, M. C., and Townsend, F. C. Side Shear Setup I: (2005a), “Test Piles Driven in Florida.” Journal of Geotechnical and Geoenvironmental Engineering, Vol. 131(3), pp. 292-300.
6. Paikowsky, S. G., and Hajduk, E. L. (2005), “Comparison between Model and Full Scale Pile Capacity Gain in Boston Area.” *Proc. to Advances in deep foundations Geo-frontiers*, TX, USA.
7. Skov, R, and Denver, H. (1988), “Time-Dependence of Bearing Capacity of Piles.” *Proc., of the 3rd International Conference on the Application of Stress-Wave Theory to Piles (B. G. Fellenius, ed.),* Vancouver, British Columbia, Canada, pp. 879-888.
8. Titi, H. H., and Wathugala, G. W. (1999), “Numerical Procedure for Predicting Pile Capacity Set-up/ freeze.” Transportation Research Record: Journal of the Transportation Research Board No. 1663, TRB, National Research Council, Washington, D.C., pp. 25-32.
9. Komurka, Van E., A. B. Wagner, and E. Tuncer B. (2003), “*Estimating Soil/Pile Set-up*.” Wisconsin Highway Research Program #0092-00-14, Wisconsin Department of Transportation.
10. Schmertmann, J. H. (1991), “The Mechanical Aging of Soils.” Journal of Geotechnical Engineering, Vol. 117(9), pp. 1288-1330.