Execution of a Large Scale Design-Phase Pile Test Program for the I-480 Valley View Bridge

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ABSTRACT

An extensive design-phase test pile program for the new I-480 Valley View Bridge Project near Cleveland, OH was performed with the explicit purpose of measuring long-term set-up and estimating pile lengths for use in structural design and subsequent construction. The program consisted of installing 24 test piles, each 18-inch-diameter closed-ended steel pipes, to depths ranging between 90 and 225 feet into glacial silts and clays in the Cuyahoga River Valley. Short-term (1-7 day and long-term (30+ day) restrikes were conducted, with the long-term restrikes utilizing a drop hammer to ensure pile mobilization. Three static loading tests were performed, each internally instrumented with strain-gages to evaluate the shaft resistance distribution. Piling exhibited considerable set-up, with 30-day restrike events showing set-up between 160 and 700 percent of end-of-initial-drive capacity, with magnitudes between 400 and 1400 kips. This paper focuses on the technical aspects of collecting and interpreting the wealth of dynamic data and static loading test data from the program. Characteristics of pile behavior and development of pile set-up in the glacial fine-grained soils are described, as are observations of pile set-up as a function of driven pile length and elapsed time.

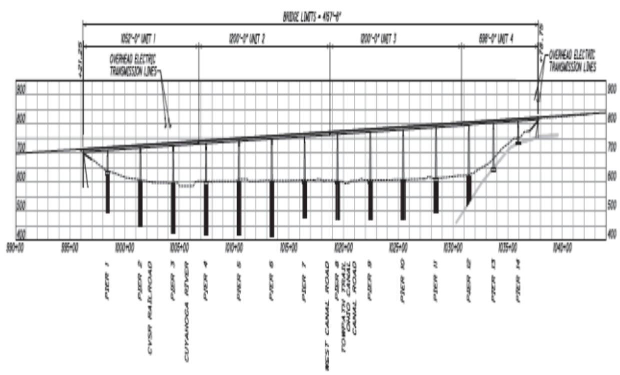
PROJECT DETAILS

The project involves the construction of a new bridge on I-480 between two existing bridges that convey interstate highway traffic over the Cuyahoga River valley in Valley View and Garfield Heights, Ohio. The project was delivered as design-build for the Ohio Department of Transportation (ODOT) with Walsh Construction as team lead and general contractor and Jacobs as lead designer. The existing, 4,155-foot-long twin bridges carrying I-480 Eastbound and Westbound over the Cuyahoga River Valley were constructed in the early 1970's and opened to traffic in 1977 and are currently in need of being redecked. High traffic volumes mandated that a third bridge be constructed to provide traffic flow while the existing bridges are being rehabilitated; after both bridges have been redecked the third bridge will provide additional capacity for future corridor improvements. The new bridge was designed as a 15-span structure, with spans varying between 180 to 300 feet, with each typical pier foundation subjected to a factored load of 22,000 kips plus significant overturning forces from wind and thermal effects.

The existing bridge foundations consisted of step taper piles for the majority of the bridge piers. While records were available for dynamic and static load tests on the piles (Goble et al, 1973), this pile type and the relatively low pile loads were not economical to the current bridge foundation design. However, the results of the testing, along with local knowledge of pile performance in the Cuyahoga Valley soils, indicated that a significant amount of pile capacity increase after installation, referred to as soil/pile set-up, was expected. The design-build team chose to develop a design-phase pile test program to quantify the soil set-up and include those findings into the final pile design to realize significant cost savings (Winter, et al., 2019).

Figure 1. Aerial view of existing I-480 bridges

Figure 2. Profile View of New I-480 Bridge Geology



Soil conditions are relatively uniform across the site, and with depth. The soils are glacial silts and clays. Some thin layers of sand or gravel are present, but not prevalent. Sloping shale bedrock was encountered at relatively shallow depths at the eastern end of the bridge, but sloped precipitously to the west, making driving piles to bedrock not practical by the fourth pier from the east end (Pier 11).

Groundwater was quite shallow along the Cuyahoga River valley, approximately coincident with the elevation of the river, increasing along the sides of the valley. Saturated silts and clays were prone to high pore-water pressures during pile driving. This was evident in CPT logs as well as noted from other projects in the same Cuyahoga River Valley silt and clay soils.

SOIL SET-UP **-** Based on the soil conditions, water table elevation, and past experience with pile driving in the area, a significant amount of set-up was expected. Many papers exist which discuss the mechanisms for soil set-up, a detailed review of literature and state of practice is provided in Komurka, et al. [2003]. When a pile is driven, soil is displaced both radially and vertically to varying degrees based on the pile type (e.g., displacement, non-displacement) and soil type. In addition, pore-water pressures increase near the pile toe during driving, reducing the effective stress of the soil in the area. Soil set-up is the dissipation of the elevated pore-water pressure and reconsolidation of the soil surrounding the pile providing additional soil resistance, primarily along the sides of the pile, as an increase in shaft resistance.

PILE TEST PROGRAM

The design-build team evaluated several pile types and determined that 18-inch-diameter, closed-ended, pipe piles would be the most cost-effective pile size and type for the project, given site access, available equipment, and anticipated minimum number of piles for lateral stability. Preliminary design pile lengths were developed using traditional FHWA static methods and modified given existing pile information.

As part of a pre-bid Alternate Technical Concept (ATC) the design-build team developed a pile test program. The goal of the pile test program was three-fold: (1) to justify a high geotechnical resistance factor (under AASHTO guidelines), (2) to quantify "long term" set-up to be incorporated into the design of production piling, and (3) provide reliable estimate of pile quantity. The pile test program was only for the West Abutment and Piers 1 through 11, as (eastern) Piers 12 through 14 and the East Abutment were founded on shallow bedrock. The pile test program was conducted coincident with the design of the bridge to provide the greatest cost benefit to the project. The program included dynamic load testing of the piles during initial driving, during short-term restrikes (1 to 7 days after installation), and during long-term restrikes (26 to 57 days after installation). Signal matching analysis, using CAPWAP® software, was performed on all end-of-drive and restrike events. In addition, three static load tests were performed, one each at Piers 1, 4, and 9. A total of 24 piles were installed, including one pile at each pier / abutment location and 5 piles at each pier with a static load test (4 reaction piles and 1 load test pile). Given the structural capacity of the proposed pile section, preliminary structural calculations, and estimated depth versus capacity relationships, the initial "target" long-term pile resistance goal was set at 1,100 kips. Wave Equation analyses were performed to evaluate the proper pile hammer size. The piles were installed and short-term restrikes performed with an ICE I-46 single-acting diesel hammer. All piles were filled with concrete after the short-term restrikes, but considerably prior to the long-term restrikes. To ensure all piles would be mobilized during long-term restrike events, a 56-kip drop hammer was used to supply the impact.

INITIAL DRIVING **-** Initial-drive testing was performed on each test pile. Piles were generally installed in 3 sections (2 splices) and dynamic testing was performed during installation of the second and third sections. At the beginning of the pile test program, the target capacity was approximately 650 kips at the end of driving, anticipating that the capacity would double through soil set-up. However, after testing at a few locations, it became apparent that some areas exhibited higher magnitudes of short-term set-up, therefore, the target capacities were adjusted, and in some cases driving was stopped, at depths which made sense for production pile driving even though the end-of-drive capacity was lower than anticipated. The final pile tip depths ranged from 90 feet to 225 feet below existing grade.

SHORT-TERM RESTRIKES **-** Short-term restrikes were performed to give an idea of the magnitude of soil set-up so that reasonable decisions regarding future restrikes could be made, as well as to be used for comparison to production pile testing to evaluate the consistency of the soil set-up at a substructure. In some cases, a restrike after just one day indicated that the I-46 hammer could not mobilize all of the soil resistance, in other cases, the hammer was able to mobilize the full soil resistance even up to 9 days after initial driving. This is an indication of the variability of the driving conditions as well as the magnitude of soil set-up. The number of impacts during the restrike was limited to 6 to limit degradation of set-up of long-term restrike events.

Static Load Tests

Static loading tests were designed to sustain a load as great as 2000 kips. In addition to the standard pile top-load and displacement measurements, 12 to 15 vibrating wire strainmeters were placed in the piles prior to placing concrete. Also, four weldable vibrating wire strain gages were placed above grade on the exterior of the piles. Strain measurements were used to develop an internal force profile along the pile which can be equated to a shaft resistance distribution and end-bearing component of the soil resistance. The resistance distribution found from the static load test was used to refine the resistance distributions in CAPWAP analyses. The static load tests were performed 39 to 43 days after pile installation.

Long-Term Restrikes

Long-term restrikes were critical in the development of the soil set-up profiles. The longer the wait time, the more soil set-up, and the more cost savings potentially realized. However, the project schedule limited long-term restrikes to between 26 and 57 days after installation. The 56-kip drop weight was able to fully mobilize the soil resistance at drop heights up to 5 feet. Fully mobilizing the soil resistance was considered movement of the pile toe, both elastic and plastic, of greater than D/60, or 0.3 inches.

Figure 3: 2000-kip Static Load Test Frame (Top) – 56-kip Drop Weight Hammer (Bottom)

SIGNAL MATCHING ANALYSIS CHALLENGES AND DIFFICULTIES **-** The CAse Pile Wave Analysis Program (CAPWAP) is a signal matching software which uses several parameters and inputs to match the measured force and velocity curves collected during dynamic testing. The results yield, amongst other information, a total static soil resistance and a distribution of the resistance along the shaft. The authors acknowledge that a CAPWAP solution is not a unique solution, and often the approach by the user to performing a CAPWAP analysis can yield different resistance distributions, even if the total static resistance is similar. It is for these reasons that the static load tests included instrumentation along the length of the pile. In addition, a single experienced user was responsible for performing all CAPWAP analyses to maintain consistency. Also, obtaining an acceptable match using the CAPWAP software on data collected in a high pile rebound or high pore-water pressure situation can be challenging, as discussed in Morgano et al. [2008]. In this case, it was best to perform the analysis in conjunction with the restrike data once pore water pressures have dissipated.

PILE TEST PROGRAM RESULTS

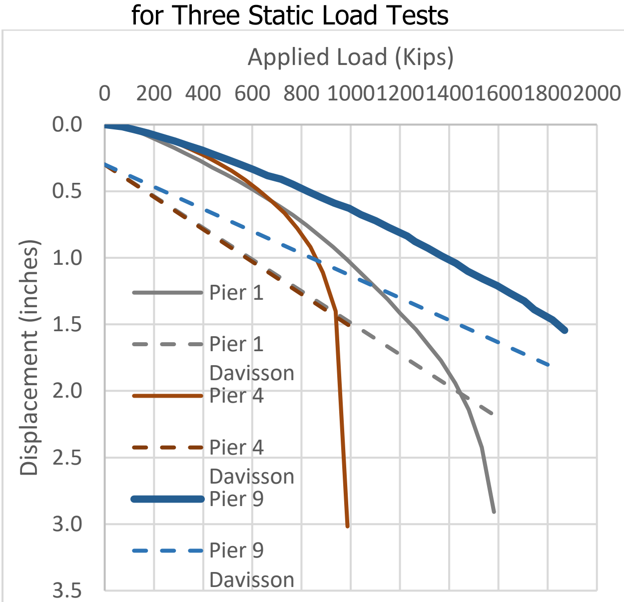
INITIAL DRIVE RESULTS - Initial drive dynamic testing indicated a wide variation in driving behavior and soil resistance at the end of driving. Relatively hard soil layers were encountered at Piers 7 through 11 (the eastern half of the test program area) which provided significant end bearing, with end-of-drive soil resistances ranging from 610 to 830 kips. However, the relatively harder layers were absent to the east, (toward the Cuyahoga River); the end-of-drive soil resistances ranged from 234 kips to 502 kips for the test piles in the west abutment through Pier 6.

In addition to variable soil resistance, the driving behavior was somewhat variable from pier to pier as well as over the depth of driving. High pile rebound was observed during driving at some locations and at some depths, likely due to high plasticity soils at the pile toe and increased pore water pressures due to pile driving. The high rebound behavior resulted in high blow counts, moderate strokes, with minor amount of dynamic resistance.

SHORT-TERM RESTRIKE RESULTS - As anticipated, short-term restrikes using the installation hammer indicated significant increases in soil resistance over a relatively short time period. The amount, and rate, of short-term soil set-up was quite variable, however the magnitude of the set-up is as high as 4 times the initial drive shaft resistance in a single day and 6 times higher after 7 days. In many cases the full shaft resistance was not mobilized by the installation hammer as very small displacements were observed during some restrikes. As stated earlier, these results were primarily used for comparison with production pile short-term restrikes to evaluate consistency of soil set-up at a substructure location, and not used directly in design.

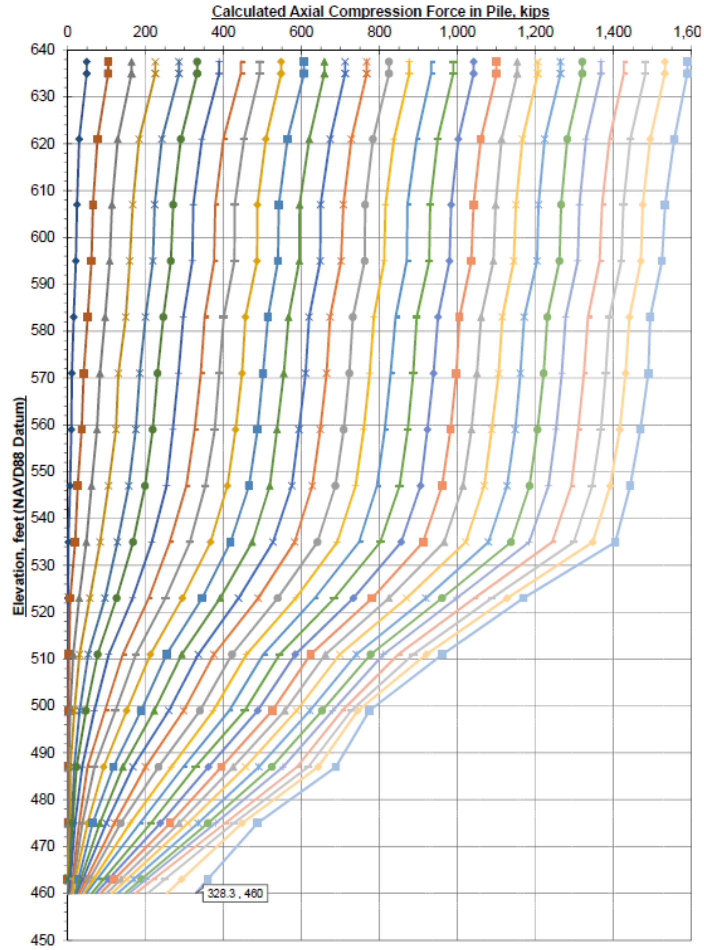
STATIC LOAD TESTING RESULTS - Static load tests were performed at Piers 1, 4, and 9. Static load tests were loaded as high as 2000 kips, if necessary, to cause geotechnical failure (pile plunging). Plunging failure occurred at Piers 1 and 4, but not at Pier 9, where a relatively hard bearing soil provided substantially higher end bearing. Figure 4 presents the load vs. pile head displacement curves for all three tests, which indicated significant variation from each other, along with their respective Davisson failure criteria lines.

Figure 4: Applied Load vs. Pile Head Movement for Three Static Load Tests



Internal force profiles were developed using strainmeter measurements collected throughout loading. The Incremental Rigidity (IR) method was used to develop the internal force profiles. The IR method is derived from the Tangential Modulus method (Fellenius, 1989). However, the IR method more directly estimates internal forces by determining the foundation axial rigidity, EA, at each strain measurement level, from applied loads and measured strains, rather than by a stress-strain relationship. For example, the internal force profile from the load test at Pier 1 is shown in Fig. 5.

Figure 5: Internal Force Profile from Pier 1 Static Load Test



The steeper slope in the curves below elevation 535 feet (100 feet below grade) indicates in increase in shaft resistance. This was typical in both the results from CAPWAP analysis and the internal force curves from the static load tests. Finally, the average segmental unit shaft resistance vs. segmental displacement, referred to at t-z curves, are plotted. The t-z curves from the Pier 1 load test are presented in Fig. 6.

Figure 6: Average Segmental Unit Shaft Resistance vs. Segmental Displacement (t-z) – Pier 1

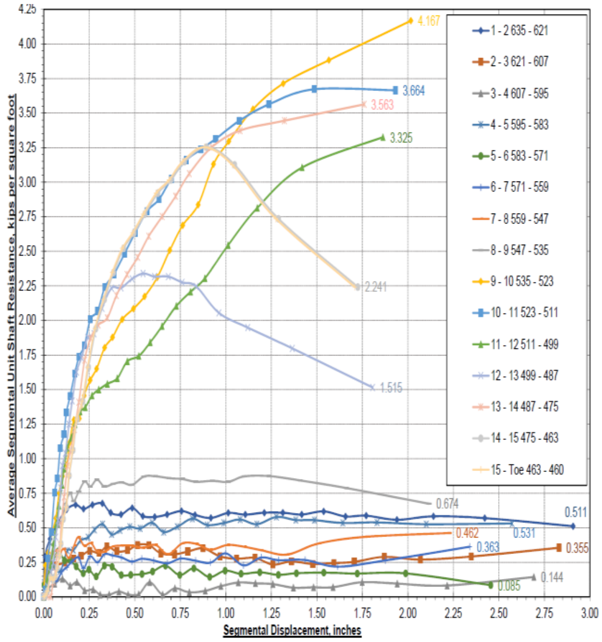
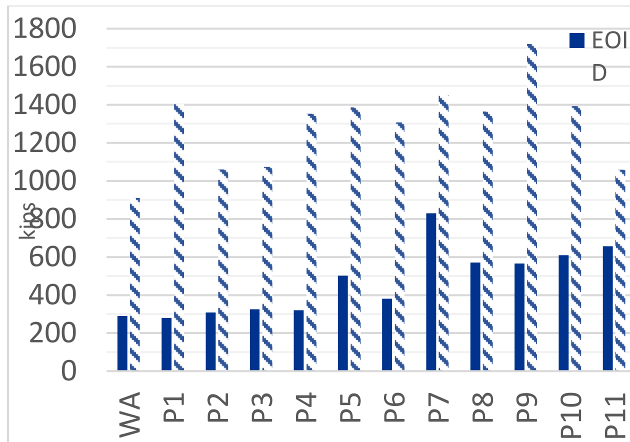


Figure 7: Comparison of End-of-Initial-Drive (EOID) and Long-Term Restrike Resistances Note: WA = West (rear) abutment and Piers P1 through P11 are oriented west to east. Piers P1, P4, and P9 show average values obtained in the multiple piles installed.



LONG-TERM RESTRIKE RESULTS - Prior to the long-term restrikes, the piles were filled with concrete. The drop hammer was placed over the pile and multiple impacts were applied to the pile until sufficient pile set was observed, typically approximately 0.25 inches under a single impact. All piles tested indicated significant increases in shaft resistance over the 26 to 57 day wait period, with some dramatic increases up to 10 or more times the shaft resistance at initial installation.

CAPWAP analysis for the long term restrikes incorporated the results from the static load tests. The values from the t-z curves and internal force profiles were used to refine the resistance distribution in the analyses. For test piles at piers where a static load test was not performed, the resistance distribution was adjusted based on the force and velocity curves, but general trends in the resistance distribution were similar. The results from the instrumented static load tests gave confidence in using higher than anticipated unit resistance values in CAPWAP analysis, which ultimately provided more set-up.

Table 1. Results from Design-Phase Pile Test Program

Pier	Pile no.	Installation		Static load test		Long-Term Restrike	
		Depth (ft)	Initial capacity (kips)	Capacity (kips)	Age (days)	Capacity (kips)	Age (days)
Rear Abt	RA-TP	160	290	--	--	910	54
1	P1-A*	140	250	--	--	1171	49
	P1-B*	140	280	--	--	--	--
	P1-C*	175	285	--	--	1543	50
	P1-D*	140	304	--	--	--	--
	P1-1**	175	279	1450	43	1495	45
2	P2-1	159	309	--	--	1060	39
3	P3-1	173	325	--	--	1074	39
4	P4-A*	179	293	--	--	1449	51
	P4-B*	225	401	--	--	1292	55
	P4-C*	179	312	--	--	1405	52
	P4-D*	190	234	--	--	1672	57
	P4-1**	180	365	950	42	945	48
5	P5-1	140	502	--	--	1386	50
6	P6-1	150	381	--	--	1307	49
7	P7-1	124	830	--	--	1451	26
8	P8-1	122	570	--	--	1364	36
9	P9-A*	120	722	--	--	--	--
	P9-B*	117	520	--	--	1707	44
	P9-C*	112	460	--	--	1376	43
	P9-D*	116	420	--	--	1716	44
	P9-1**	120	710	1800	39	2081	43
10	P10-1	110	610	--	--	1393	40
11	P11-1	90	657	--	--	1059	37

* Reaction Pile

** Static Loaded Pile

DEVELOPING SOIL SET-UP PROFILES - Once the CAPWAP analyses were completed for initial driving and restrikes, soil set-up profiles were generated to quantify the amount of soil set-up vs. depth.

Figure 8: Soil Set-up Profile and Required EOID Resistance vs. Elevation (Pier 1)

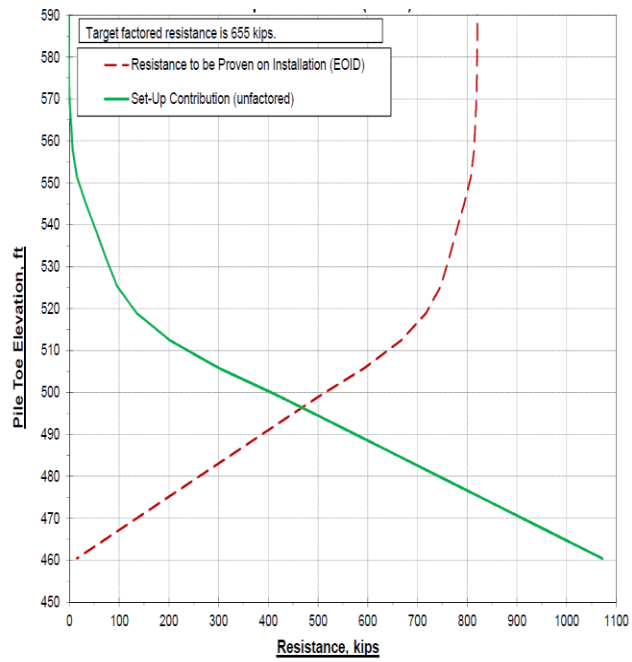


Figure 8 shows a somewhat typical soil set-up curve with higher set-up values at deeper depths. Consequently, the "target" end of drive resistance decreases with depth because additional soil set-up will be realized. Theoretically, the target end of drive resistance could become zero if the set-up measured at a depth exceeds the required nominal load.

CONSIDERATIONS FOR A SUCCESSFUL PILE TEST PROGRAM

Proper planning, implementation and evaluation of a pile test program is critical in realizing cost savings. A considerable amount of time was spent discussing and considering several options and approaches for the pile test program. While there are certainly many approaches to developing a pile test program to evaluate soil set-up at a particular site, there are a few important considerations.

DYNAMIC TESTING LIMITATIONS - Dynamic measurements and analysis are critical to a pile test program evaluating soil set-up. Therefore, it is critical that the pile test program developer understands the limitations to the testing technology. It is important that the full soil resistance is mobilized at the end of initial driving and on restrike. The proper hammer is key to providing an impact with high enough energy to mobilize the soil resistance but keep the stresses in the pile reasonable. If very little (or no) movement occurs, it may be possible to apply superposition principles (Hussein, 2002) to estimate the total shaft and end bearing resistance. However, this introduces much more difficulty and uncertainty and is not recommended for this application.

Another limitation is the non-unique solution provided by signal matching analyses (CAPWAP). While this can't be completely avoided, having a single experienced user (or perhaps two users working closely to maintain similar approach) perform all analyses maintains consistency in the results.

UTILIZING AN INSTRUMENTED STATIC LOAD TEST - Performing a static load test not only provides the opportunity to use a higher resistance factor, it also provides the opportunity for refinement of the CAPWAP analysis. This is particularly important for piles that may develop soil plugs (H-piles, open-end pipe piles, etc.), or for non-uniform piles (ACIP, CFA, Displacement piles, etc.). In these cases, the user must use all available information to correctly model the pile/soil interaction to complete the analysis. Properly evaluated data from embedded instrumentation can provide critical information for the analysis. In the subject test program, the CAPWAP user was able to model higher than expected unit soil resistances based on the results of the instrumented static load tests. This provided larger set-up values in the set-up profile and additional cost savings on the production piles.

PILE INSTALLATION SEQUENCE - Another topic that was extensively discussed was the driving sequence of the test piles compared to the production piles. In the subject test program, most of the test piles were driven in 3 sections continuously, with pauses in driving for splicing. However, the contractor desired to install the production piles by driving all of the bottom sections, welding all of the second sections, driving all the second sections, welding all of the third sections, and driving all the third sections. This is the most efficient method of group pile installation. However, these different installation techniques can affect the soil set-up profile.

The maximum amount of disturbance to the soil occurs when the pile tip passes. At this point the soil is displaced radial and vertically and likely the pore-water pressures are increased. If a pile section is left for some time, say overnight, the pore-water pressures dissipate and the soil begins to reconsolidate; soil set-up occurs. When driving begins again, the gain in shaft resistance is likely broken down, but the soil is disturbed only a relatively small amount (possibly vertically) and pore water pressures are not increased along the side of the pile. The soil now provides a residual resistance during driving and may be subject to friction fatigue effects (Moghaddam, 2017), or a reduction in shaft friction attributed to the cyclic shearing process of pile driving. This area of soil will likely not have the same amount of soil set-up comparing to the set-up after initial driving. Therefore, it is important to install the test piles in a similar manner to the installation method anticipated for production piles, this will increase the applicability of the findings of the pile test program for the production piles.

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