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Performance Evaluation of an Instrumented Test Pile Cluster

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PERFORMANCE EVALUATION OF AN INSTRUMENTED TEST PILE CLUSTER

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Abstract: As part of a research project investigating time dependent pile capacity gain, a heavily instrumented test pile cluster was installed at a bridge reconstruction site in Newbury, Massachusetts. The test pile cluster consisted of (i) three-instrumented test piles, (ii) a surrounding ground piezometer field, and (iii) a complex data acquisition array to monitor the instrumentation. An extensive testing program, which included various static, dynamic, and Statnamic tests, was carried out over a lengthy time period to determine the pile capacity with time.

Electrical resistance, piezo-electric, piezo-resistive, and vibrating wire instruments were used throughout the cluster to record acceleration, displacement, pressure, and strain within the test pile cluster. Primary test pile instrumentation consisted of an alternating pattern of piezometers and strain gages. Auxiliary instrumentation within the piles included accelerometers and total pressure gages. The ground piezometer field consisted of a total of 10 vibrating wire pressure transducers installed within normally consolidated and silty sand soil layers. Four separate data acquisition systems were assembled into an on-site data acquisition array to monitor the instrumentation throughout the testing period.

This paper details the maximum loading conditions that each individual test pile was subjected to over the course of the testing program and evaluates the performance of the individual gage models and designs, instrument types, and data acquisition systems. Conclusions are drawn regarding (i) the reliability of the various gages and gage types, (ii) the performance of similar gage types, (iii) the selected measurement frequencies for each gage type, and (iv) the performance of the data acquisition array during the harsh conditions of driving and testing over time.

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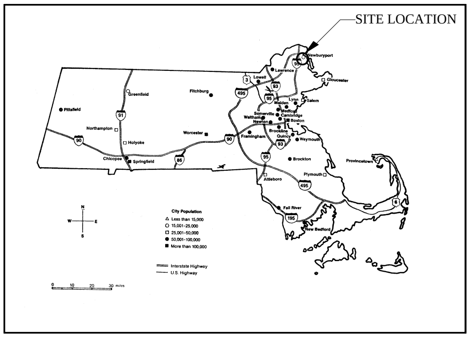
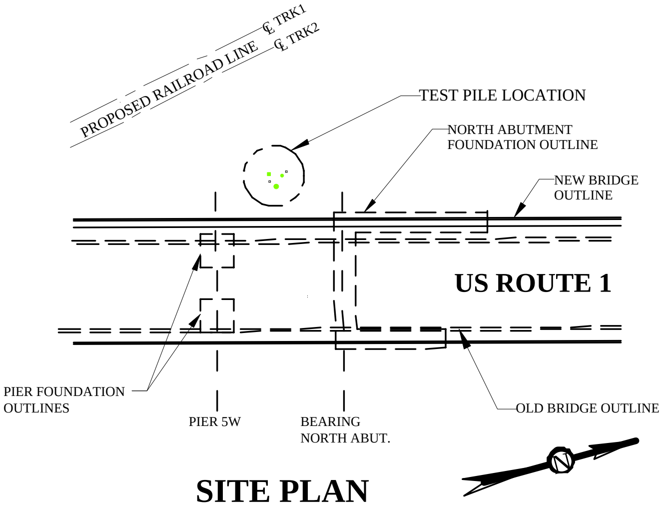
INTRODUCTION

A full-scale instrumented test pile cluster was installed and tested at the University of Massachusetts – Lowell (UML) Geotechnical Engineering Research (Newbury) Site in Newbury, Massachusetts as part of a long-term research investigation of pile capacity gain of driven piles with time. The Newbury Site was located adjacent to a bridge reconstruction site on Route 1 on the Newbury – Newburyport, Massachusetts border. This site was used previously by the University of Massachusetts - Lowell for helical anchor and Multiple Deployment Model Pile (MDMP) testing (Paikowsky and Peach, 1995 and Paikowsky and Hart, 1998). In order to aid in the analysis of these tests and the instrumented test pile data, Paikowsky and Chen (1998) completed a comprehensive study of the engineering parameters of the subsurface at the site based on extensive field and laboratory testing. A locus plan of the site is presented in Figure 1.

The test pile cluster was comprised of three instrumented test piles, a surrounding ground piezometer field, an on-site data acquisition array with remote data retrieval capabilities, and an extensive testing schedule. The instrumented test piles consisted of one 32.4cm (12.75in) diameter x 1.3cm (0.5in) wall thickness x 31.4m (103ft) long closed ended steel pipe end-bearing pile (Test Pile #1 or TP#1), a 32.4cm (12.75in) diameter x 24.4m (80ft) long closed ended steel pipe friction pile (TP#2), and one 35.6cm (14in) square x 24.4m (80ft) pre-stressed concrete friction pile (TP#3). The ground piezometer field, which consisted of 7 piezometers within a normally consolidated clay layer and 3 piezometers within a silty sand layer, was installed around the planned test pile locations to monitor excess pore pressure buildup and dissipation due to test pile installation. The on-site data acquisition array of four separate data measurement and control systems was located within a storage trailer that was placed adjacent to the test pile and ground piezometer locations. Paikowsky and Hajduk (1999) described the design and construction of the test pile cluster in detail. A plan view of the test pile cluster at the Newbury Site is presented in Figure 2. A cross-section of the site, showing the layouts of the test piles and the ground piezometer field relative to the location of TP#1 and the soil profile, is presented in Figure 3. Additional instrumentation, consisting of soil accelerometers and total pressure cells, was also installed at the Newbury Site in a joint research project with GeoDelft of Delft, Holland. The description of this instrumentation is beyond the scope of this paper and will be addressed in future publications (Hajduk et al., 2000).



STATE PLAN



SITE PLAN

SCALE: 1"=100'

Figure 1. University of Massachusetts Lowell's Geotechnical Engineering Testing (Newbury) Site (after Paikowsky and Hajduk, 1999).

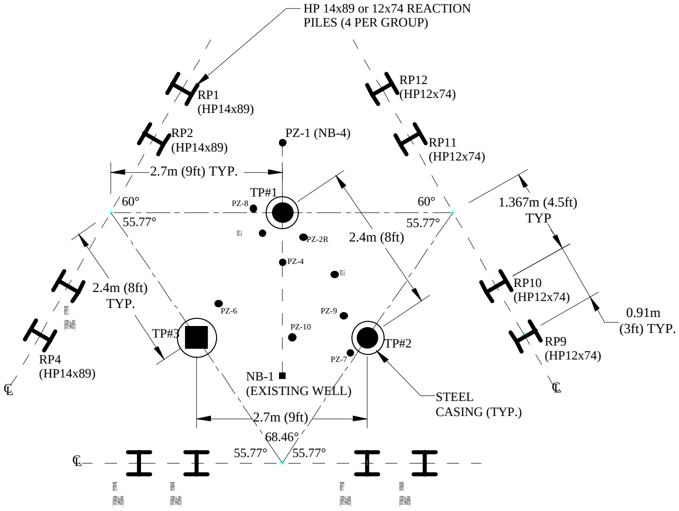


Figure 2. Newbury Site Plan View (Paikowsky and Hajduk, 1999).

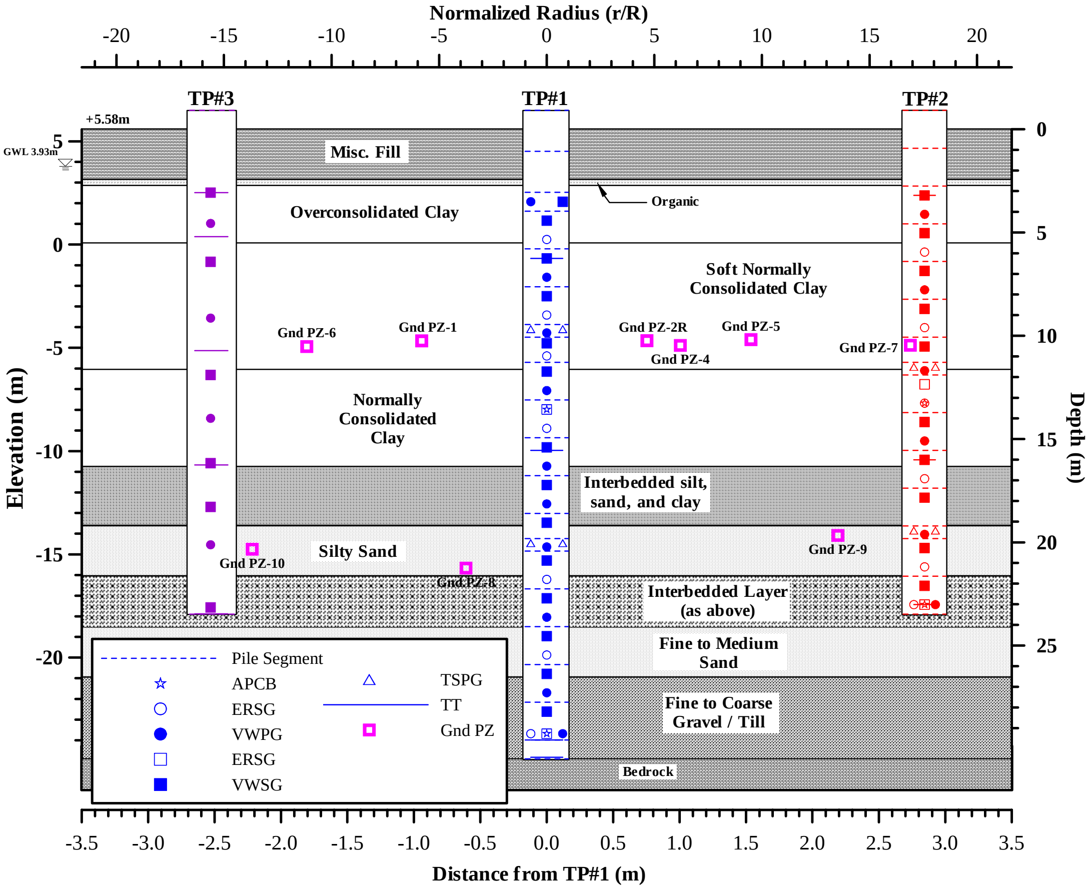


Figure 3. Newbury Site Soil Profile with Test Pile Layouts.

The soil stratigraphy of the Newbury Site is typical of the conditions found in the Boston area. The general soil profile at the pile testing location (from ground surface downward) consists of the following soil strata: 8 feet (2.4 meters) of granular fill composed of very dense, brown sand and gravel intermixed with frequent concrete fragments, overlies a thin layer (approximately 1 foot (0.3 meters)) of highly compressible organic silt and peat. In order to protect the test piles, these layers were excavated and cased with steel pipe sections. Below the fill and organics is an approximately 45 feet (13.7 meters) thick deposit of a marine clay, known as Boston Blue Clay. The clay consists of approximately 9 feet (2.7 meters) of very stiff to medium stiff, overconsolidated layer (crust), over 20 feet (6.1 meters) of soft normally consolidated clay and 16 feet (4.9 meters) normally consolidated clay. An interbedded deposit of silt, sand, and clay approximately 9.5 feet (2.9 meters) thick underlies the clay. Below this interbedded deposit is a layer of silty sand approximately 8 feet (2.4 meters) thick. Another interbedded deposit of silt, sand, and clay approximately 7.5 feet (2.3 meters) thick underlies the silty sand. Below this interbedded deposit is a layer approximately 8 feet (2.4 meters) thick of medium dense to dense, fine to medium sand. Underlying the fine to medium sand is a dense glacial till consisting of medium dense to dense, fine to coarse sand and gravel, with traces of silt and rock fragments. Good quality, unweathered bedrock was encountered at approximately 100 feet below the ground level (elevation 81.7 feet) (Paikowsky and Chen, 1998). A typical soil profile of the site at the test pile cluster is presented in Figure 2.

Over the course of a testing period that lasted approximately 2 years, the test pile cluster was subjected to repeated dynamic and static tension, compression, and Osterberg Cell load tests of various procedures and load rates. In addition, Test Piles #2 and #3 were subjected to incremental Statnamic load tests at the end of the test period.

INSTRUMENTATION

A total of nine different instrument types were installed within the test pile cluster to measure various parameters associated with pile capacity gain with time. A summary of the various instruments and the associated measured parameters is presented in Table 1. Primary instrumentation for the test piles consisted of vibrating wire piezometers and strain gages. Electrical resistance piezometers and strain gages were also installed within the two steel pipe piles to supplement the vibrating wire gages. The layout of each pile consisted of an alternating pattern of piezometers and strain gages, with each piezometer located halfway between two-strain gage sets. This pattern would allow for correlation of pore pressure dissipation and average capacity gain along discrete pile segments.

Table 1. Summary of Measurement Parameters, Instruments, and Instrument Types for the Instrumented Test Piles (after Paikowsky and Hajduk, 1999).

Parameter	Measuring Instrument	Gage Type	Instrument Abbreviation
Excess Pore Pressure Buildup and Dissipation	Piezometers	Electrical Resistance	ERPG
		Vibrating Wire	VWPG
Total Radial Pressure	Liquid Total Soil Pressure Gages	Pressure measurement w/vibrating wire piezometer	TSPG
Dynamic Pile Testing – Interior Stress Wave Measurements	Strain Gages	Electrical Resistance	ERSG
	Accelerometers	Piezo-resistive	APCB
Load Distribution Along Pile During Static Testing	Strain Gages	Vibrating Wire	VWSG
		Electrical Resistance	ERSG
	Tell-Tales	Slender Rod	TT
Telltale Displacement	Displacement Transducers.	Electrical Resistance	LVDT
Pile Temperature	Thermistor	Electrical Resistance	TH

Paikowsky and Hajduk (1999) explain in detail (i) the rationale behind the instrument type selection, (ii) the selection of the individual gage models, and (iii) the various gages, gage assemblies, and installation of these assemblies into the test pile cluster. A summary of the selected gage models for the various instrumentation types installed within the test pile cluster and the corresponding number of gages per pile is listed in Table 2.

Table 2. Test Pile Cluster Instrumentation Summary.

Gage Type	**APCB**	**ERPG**	**ERSG**	**TSPG**	**VWPG**	**VWSG**	
Model	PDA Piezo-resistive	Kistler Type 4100	MG LWK-06-250W-34	Geokon Model 4500H	Geokon Model 4500	Geokon Model VSM-4000	Geokon Model VCE-4200
Test Pile #1	2	7	4	4	12	28	0
Test Pile #2	2	6	4	4	8	20	0
Test Pile #3	0	0	0	0	4	0	6
Gnd PZ	0	0	0	0	10	0	0
Total	**4**	**13**	**8**	**8**	**34**	**48**	**6**

In addition to the above-mentioned instrumentation, an Osterberg Load Cell was installed at the base of Test Pile #1 and the SmartPile System was installed in Test Pile #3. The performance of these systems is not evaluated in this paper.

Instrumentation Identification

An instrumentation identification system was developed to provide classification of the test pile, relative location, orientation, and instrument type for each gage in the test pile cluster. The identification system also assisted in the development and installation of data acquisition systems. The instrumentation identification system used the following nomenclature:

X-Y-Z-Q

Where:

X = Test Pile Number
Y = Segment Number (for TP#1 & 2) or Gage Number (for TP#3)
Z = Gage.
Q = Orientation within the pile (TP#1 & 2 only)

X may be 1, 2, or 3, depending on the test pile. **Y** may be segments 1 through 16 (Test Pile #1), segments 1 through 12 (for Test Pile #2), or gage 1 through 6 (Test Pile #3). The variables for **Z** are listed in Table 1. Variable **Q** may be A or B, according to the orientation of the instrument within the test pile and is discussed in detail by Paikowsky and Hajduk (1999). Two examples of the instrumentation identification system are the following:

1-6-VWSG-A and **2-10-TSPG-B**

The first identification is of vibrating wire strain gage (VWSG) A of segment 6 in Test Pile #1. The second identification is that of the total soil pressure gage (TSPG) B of Test Pile #2 in segment 10. A TH located in front of the gage identification would specify the thermistor of that gage. The ground piezometers were labeled as **Gnd PZ**, with the specific number of the gage following PZ. For example, ground piezometer 3 was labeled as **Gnd PZ-3**.

DATA ACQUISTION ARRAY

Four separate data acquisition systems, assembled into an onsite data acquisition array, were used to monitor the various gages used within the test pile cluster. The core of this array consisted of three separate data acquisition systems, with each system assigned to monitor one of the three primary gage types (vibrating wire, electrical resistance, and dynamic instrumentation). This arrangement was chosen to simplify the setup and design of the data acquisition array and to provide backup measurements should one system fail. The fourth data acquisition system provided flexibility to the array by (i) recording non-essential instruments during pile testing, thereby freeing resources from the core systems and (ii) recording various instruments prior to core data acquisition installation.

The primary data acquisition system used throughout the testing was the Micro-10 (Model 8020) Datalogger, assembled and marketed by Geokon, Inc. of Lebanon, NH. Although the Micro-10 is capable of recording the measurements of a variety of instrumentation, it was only used to monitor the vibrating wire gages and their thermistors. A total of 2 Micro-10 Dataloggers, labeled ADAS-1 and ADAS-2, each with two attached Model 8032 multiplexers, were used during the project. Each Micro-10 was equipped with a modem to allow for remote data retrieval.

A CR9000 Measurement and Control System, manufactured by Campbell Scientific of Logan, UT, was used to record the majority of electrical resistance instrumentation used in the test pile cluster. This instrumentation consisted of the electrical resistance pressure gages (ERPG) and strain gages (ERSG), the linear variable displacement transducers (LVDT), and the thermistors of various gages. The CR9000 is a 16 bit, modular, portable, multiprocessor data acquisition system that can sample at rates up to 100 K readings per second.

Proprietary software developed by Campbell Scientific, named PC9000, was used to control and communicate with the CR9000. PC9000 is a Windows based program that provides program generation, data graphics and analysis, and data retrieval. A modified BASIC programming language, entitled CR BASIC, was used to program the CR9000 for a variety of data processing and analysis routines.

A Hewlett Packard Data Acquisition System (HP DAS) was used at various times during the testing program to record the static load test instrumentation and thermistors. The HP DAS was primarily used to monitor the LVDT's and electrical resistance load cell of a static load test conducted on Test Pile #3 and to record a limited number of thermistors before and after the driving of Test Pile #1. The visual programming language HP VEE was used to trigger the scanning multi-meter, set the number of channels to be monitored and sampling frequency, display the real time data to the computer screen, and store the data to the hard drive with a time stamp (Paikowsky and Hart, 1998).

The final data acquisition system of the instrumented test pile cluster was a Pile Driving Analyzer (PDA). The Pile Driving Analyzer is a dynamic pile testing data acquisition and analysis system developed by Pile Dynamics Incorporated of Cleveland, Ohio. For the test pile cluster, the PDA was used to measure the exterior and interior dynamic response of the tested pile during driving, restrike, and Statnamic tests. This included the interior piezo-resistive accelerometers (APCB). The PDA used during the Test Pile Program consisted of a 486SLC 25MHz processor with 8MB RAM and a 240MB hard drive. A summary of the various data acquisition systems and their assigned instruments is presented in Table 3.

Table 3. Data Acquisition Array Summary.

Gage Type	**APCB**	**ERPG**	**ERSG**	**TH**	**TT (LVDT)**	**TSPG**	**VWPG**	**VWSG**
DAS	PDA	CR9000	CR9000	Micro-10 CR9000 HP DAS	CR9000 HP DAS	Micro-10	Micro-10	Micro-10

Data Acquisition Array Configurations

The four data acquisition systems listed above were incorporated into an array that allowed for flexible configuration and measurement frequency settings. In addition, the system had limited capability to record additional instrumentation installed at the site (pile top load cells, ground accelerometers, dilatometers, miniature piezocones). The array was arranged into three major configurations during the test pile-testing program. Each configuration corresponded to the installation of a specific test pile. Figure 8 shows the schematics for the various configurations of the data acquisition array. Paikowsky and Hajduk (1999) detail the various data acquisition array configurations.

Measurement Frequencies

In order to adequately follow the phenomena of pore pressure buildup and dissipation and pile capacity gain, minimum measurement frequencies were established for each gage and testing event. The recording capabilities of the data acquisition systems and experience of the University of Massachusetts – Lowell in investigating time dependent pile capacity gain with the Multiple Deployment Model Pile (MDMP) (Paikowsky and Hart, 1998) influenced the selection of these recording frequencies. A summary of these frequencies related to testing activity is provided in Table 4.

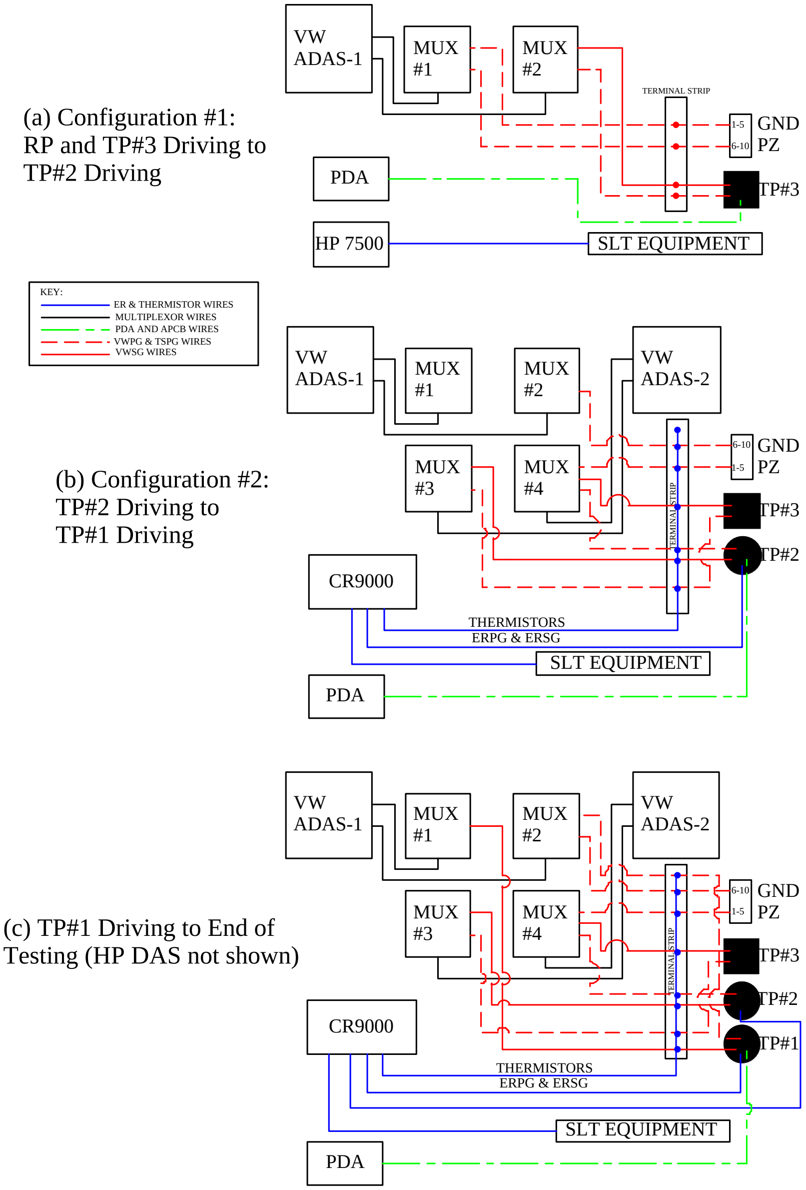


Figure 8. Data Acquisition Array Configurations (Paikowsky and Hajduk, 1999).

Table 4. Frequency of Measurements for Various Test Pile Cluster Instruments (after Paikowsky and Hajduk, 1999).

Test Pile	**Gage Type**	**Testing Activity**				
		During Driving and Restrikes (+ 12 hrs)	**During SLT (+ 12 hrs)**	**EOD to 1st Restrike or SLT**	**Between Restrikes and SLT (before EOD + 7 days)**	**Between Restrikes and SLT (after EOD + 7 days**
Tested Pile	APCB	10000 Hz	N/A	N/A	N/A	N/A
	ERPG	1 Hz	1 Hz	1 Hz	1rdg/15min	1rdg/hour
	ERSG	10000 Hz[1]	1 Hz	1rdg/15min	1rdg/15min	1rdg/hour
	VWPG	1rdg/30sec	1rdg/30sec	1rdg/30sec	1rdg/15min	1rdg/hour
	VWSG	1rdg/30sec	1rdg/30sec	1rdg/15min	1rdg/15min	1rdg/hour
	TSPG	1rdg/30sec	1rdg/30sec	1rdg/30sec	1rdg/15min	1rdg/hour
Adjacent Pile(s) & Gnd PZ Field	APCB	N/A	N/A	N/A	N/A	N/A
	ERPG	1 Hz	1 Hz	1 Hz	1rdg/15min	1rdg/hour
	ERSG	1rdg/15min	1rdg/15min	1rdg/15min	1rdg/15min	1rdg/hour
	Gnd PZ	1rdg/30sec	1rdg/30sec	1rdg/30sec	1rdg/15min	1rdg/hour
	VWPG	1rdg/30sec	1rdg/30sec	1rdg/30sec	1rdg/15min	1rdg/hour
	VWSG	1rdg/15min	1rdg/15min	1rdg/15min	1rdg/15min	1rdg/hour
	TSPG	1rdg/30sec	1rdg/30sec	1rdg/30sec	1rdg/15min	1rdg/hour

[1] During Blows. Measurement frequency between blows is only1 Hz.

EOD = End of driving, SLT = Static Load Test

TESTING CONDITIONS

The instrumentation within the test pile cluster was subjected to a variety of harsh conditions during the testing program. Three different types of tests caused these conditions: dynamic, static, and kinetic (i.e. Statnamic). Each test directly produced an assortment of accelerations, strains, and stresses on the test piles. The shearing and remolding of the surrounding soil caused by these events produced changes in (i) the lateral soil pressure on the pile and (ii) the pore pressures adjacent to the test piles and surrounding ground piezometer field. In addition to these conditions, each pile top was subjected to extreme seasonal temperature variations during the testing period.

An identification system was developed to identify the test number and type for each loading event. This identification system would provide a quick reference that indicated the test pile number, test type, and test number. The following nomenclature was used to identify the testing:

TP#A – B - C

Where:

A = Test Pile Number

B = Test Type
C = Test Type Number

A may be 1, 2, or 3, depending on the test pile. The variables for **B** are listed in Table 5. Examples of typical test identification are the following:

TP#2SLT1 or TP#3R5

The first identification is of Static Load Test #1 of Test Pile #2. The second identification is of Restrike #5 for Test Pile #3.

Table 5. Test Pile Load Testing Abbreviations.

Test Type	**Abbreviation**
End of Driving	EOD
Static Load Test (Axial Compression)	SLT
Static Load Test (Axial Tension)	SLT(T)
Dynamic Restrike	R
Osterberg Load Test	OST
STATNAMIC	STN

The dynamic testing consisted of pile installation (driving) and dynamic restrikes. Dynamic restrikes were performed in accordance with standards of the Massachusetts Highway Department (1995). Up to different static load test methods were conducted on the test piles: short duration, slow maintained, static cyclic, and Osterberg (Test Pile #1 only). All static load tests were conducted as axial compression with the exception of one tension test on Test Pile #2 (TP#2SLT3T) and the Osterberg Load tests. The slow maintained and short duration tests were conducted according to the standards of the Massachusetts Highway Department (1995). The static-cyclic tests were conducted according to criteria developed in a concurrent research project presented by Paikowsky et al. (1999). University of South Florida personnel conducted the Statnamic tests according to standard industry procedures.

The maximum forces, accelerations, and total set for each test pile were determined from the individual data of each separate test. Tables 6 through 8 shows these values for the individual tests for Test Piles #1 through #3, respectively.

Table 6. Maximum Load Testing Conditions of Test Pile #1.

Test	**EOD**	**OST1**	**OST2**	**OST3**	**OST5**	**OST6**	**OST7**	**OST8**	**OST9**	**SLT10**	**SLT11**	**SLT12**
Date	5/29/97	5/30/97	5/30/97	6/5/97	6/13/97	7/11/97	10/6/97	12/11/97	1/11/98	1/13/98	1/14/98-1/15/98	1/20/98
Maximum Load: (kN)	2473	246	285	381	444	589	672	719	456	615	4024	3567
Maximum Acceleration (g):	920	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Number of Blows:	575	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total Set (mm):	N/A	26.2	10.0	11.5	5.6	12.5	10.3	16.7	30.9	40.1	36.6	1.1

Table 7. Maximum Load Testing Conditions of Test Pile #2.

Test	**EOD**	**R1**	**SLT1**	**R2**	**SLT2**	**SLT3 (T)**	**R3**	**SLT4**	**SLT5**	**R4**	**SLT6**	**SLT7**	**SLT8**	**SLT9**	**STN**
Date	2/24/97	2/25/97	2/28/97	3/4/97	3/12/97	3/14/97	3/20/97	3/24/97	5/26/97	5/29/97	10/3/97	10/22/97 10/24/97	10/27/97	10/28/97	4/23/98
Maximum Load: (kN)	2438	5222	623	5138	717	433	2789	720	729	3430	Unk.[1]	853	815	826	1044
Maximum Acc. (g):	1031	928	N/A	1056	N/A	N/A	1231	N/A	N/A	699	N/A	N/A	N/A	N/A	4
Number of Blows:	307	14	N/A	6	N/A	N/A	17	N/A	N/A	5	N/A	N/A	N/A	N/A	4
Total Set (mm):	N/A	216	14.5	64	29	19	91	28.4	30.9	67	5.5	32.3	20.7	21.4	6

[1] Load was not recorded (incomplete test)

Table 8. Maximum Load Testing Conditions of Test Pile #3.

Test	**EOD**	**R1**	**R2**	**R3**	**SLT1**	**R4**	**R5**	**R6**	**SLT2**	**R7**	**SLT3**	**SLT4**	**SLT5**	**STN**
Date	12/13/96	12/14/96	12/17/96	12/27/96	1/14/97	1/15/97	3/4/97	3/20/97	3/26/97	5/29/97	12/2/97-12/4/97	12/4/97-12/5/97	12/5/97	4/23/98
Maximum Load: (kN)	3358	2624	2660	2553	924	2931	3265	3140	1219	4764	1347	1217	1258	2303
Maximum Acc. (g):	218	118	101	140	N/A		217	222	N/A	426	N/A	N/A	N/A	7
Number of Blows:	484	11	6	9	N/A	5	4	9	N/A	6	N/A	N/A	N/A	6
Total Set (mm):	N/A	52	52	52	56	24	18	15	29	24	27	21	50	110

INSTRUMENTATION PERFORMANCE

Performance evaluation of any project is a subjective process that can be influenced by (i) the chosen assessment areas and (ii) the definition of success and failure. Due to the magnitude of instrumentation within this project, it was decided to limit the presented performance evaluation to three areas: (i) instrument durability, (ii) comparisons between similar instrument types, and (iii) measurement frequencies. By limiting the evaluation to these three areas, qualitative and quantitative assessments could be made of individual gages, the various gage types, and the project as a whole.

Instrument Durability

Instrument durability is crucial for a project with the extended testing period. It was therefore important to include an assessment of instrument dependability in the evaluation of test pile performance. Resilience of the instrumentation within the test pile cluster was assessed in terms of overall durability, i.e. the ability to withstand the entire testing period, and performance durability, the ability to take data during actual test events.

The assessment of overall durability was made with a comparison between the number of instruments that worked at the start and end of the testing period for each major test project component and the project as a whole. Instrumentation was broken down into the selected gage types previously described and listed in Table 1. The percentage of working instruments at the end of the testing, labeled as % Durable, was computed to allow comparisons between the major instrument types. The results of this analysis are presented in Table 9. The results of Table 9 show that the majority of vibrating wire instrumentation could withstand the harsh conditions throughout the testing period. Failure of the various vibrating wire instruments did not align with specific testing events.

The majority of electrical resistance gages did not withstand the testing program. Since failure of all the electrical resistance strain gages and piezo-resistive accelerometers did not occur during specific tests, their failures were attributed to the intrusion of water into the two steel pipe piles. The cause of the electrical resistance strain gages malfunctioning during static load testing before complete failure was not discerned. Only the electrical resistance piezometers continued to function throughout the project duration.

Reviewing measurements over the course of the testing period assessed performance durability for each gage. The review of the individual gages showed that, when functioning, the piezo-resistive accelerometers and electrical resistance piezometers and strain gages performed to expectations. This review also showed that several vibrating wire gages experienced sudden measurement changes and erratic readings during and between specific testing events.

Table 9. Test Pile #1 Instrumentation Durability Summary.

Test Pile	Stage	Gage Type					
		APCB	**ERPG**	**ERSG**	**TSPG**	**VWPG**	**VWSG**
TP#1	Start of Testing	2	7	4	4	12	28
	End of Testing	0	7	0	4	11	28
	% Durable	**0**	**100**	**4**	**100**	**92**	**100**
TP#2	Start of Testing	2	6	4	4	8	20
	End of Testing	0	5	0	3	7	20
	% Durable	**0**	**83**	**0**	**75**	**88**	**100**
TP#3	Start of Testing	0	0	0	0	4	6
	End of Testing	0	0	0	0	4	6
	% Durable	**N/A**	**N/A**	**N/A**	**N/A**	**100**	**100**
Gnd PZ	Start of Testing	0	0	0	0	10	0
	End of Testing	0	0	0	0	10[1]	0
	% Durable	**N/A**	**N/A**	**N/A**	**N/A**	**90**	**N/A**
TOTAL	Start of Testing	4	13	8	8	34	54
	End of Testing	0	12	0	7	31[1]	54
	% Durable	**0**	**92**	**0**	**88**	**91**	**100**

[1] Gnd PZ-2 was replaced during the testing period.

Sudden measurement changes were experienced by all three vibrating wire gages: piezometers, total soil pressure gages, and strain gages. Each specific jump occurred during dynamic testing events, either during driving and/or during restrikes. An example of a sudden measurement jump is shown in Figure 9. During the first restrike of Test Pile #2 (TP#2R1), gage 2-6-VWPG-B experienced a sudden jump in pore pressure of approximately 84kPa (12psi), then continued with pore pressure dissipation. Comparison with the measurement of the adjacent gage 2-6-VWPG-A showed that this jump was unrealistic. The sudden measurement increase was subtracted from the subsequent measurements (see area marked with arrow in Figure 9). Comparison with the adjacent gage showed similar pore pressure dissipation measurements after the correction, thereby confirming the assumption that the sudden increase in pore pressure was unrealistic. A total of 4 out of 96 vibrating wire gages experienced significant measurement jumps during dynamic testing.

The sudden changes in the vibrating wire measurements were attributed to relaxation of the gage wire tension caused by dynamic loading. This relaxation, also referred to as slippage, causes a shift in the zero reading (i.e. zero drift) of the gage. Since vibrating wire gages convert the change in wire tension to an applied measurement, such as pressure, a change in the original or zero reading will cause a subsequent change in the measurement.

A number of vibrating wire gages also experienced erratic readings during testing events and over the testing period. An example of erratic gage reading experienced during testing is shown in Figure 10. In this example, the measurements of gage 3-4-VWSG-A are shown compared to the pile top load with time over the length of testing for TP#3 SLT1. The readings show both small and large fluctuations during both loading and constant load periods. Upon removal of these inconsistent readings, a clear measurement can be obtained (see Figure 10). Although minor erratic measurements over the testing period were recorded by the majority of vibrating wire instrumentation, 4 gages experienced continuous and significant measurement variations over the course of testing.

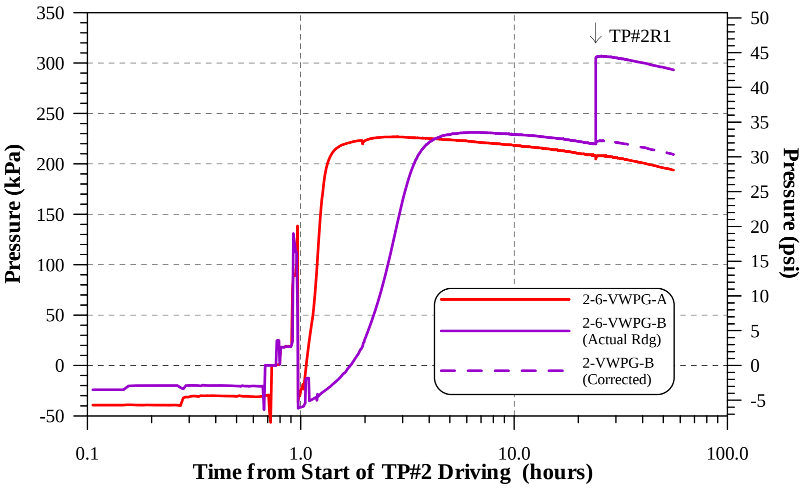


Figure 9. Example of Vibrating Wire Measurement Jump during Dynamic Testing.

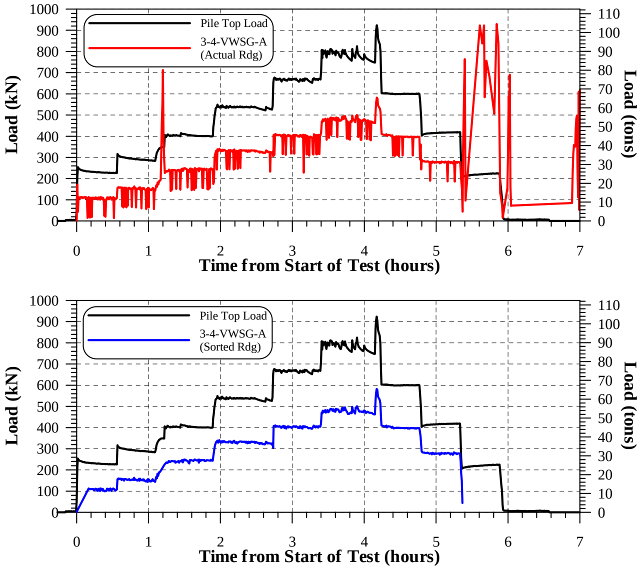


Figure 10. Example of Erratic Vibrating Wire Measurements.

Instrument Comparisons

Comparison of records from two similar instrumentation types would allow for performance assessment between the two major gage types used throughout the project, electrical resistance and vibrating wire. These two gage types were both used to measure pore pressure and pile capacity along the lengths of the two steel pipe piles, TP#1 and #2.

Comparisons between the two gages type measurements with time showed that each gage was capable of measuring pore pressure buildup and dissipation. A typical example of this comparison is shown in Figure 11. Figure 11 shows nearly identical pore pressure measurements with time for gages 1-6-ERSG-A and 1-6-VWPG-A after the driving of Test Pile #1. The shift in pore pressure buildup between 1 and 100 hours from the start of driving is associated with the locations of the gages on the pile, pile installation, and porous stone saturation and is not attributed to a difference between the gages.

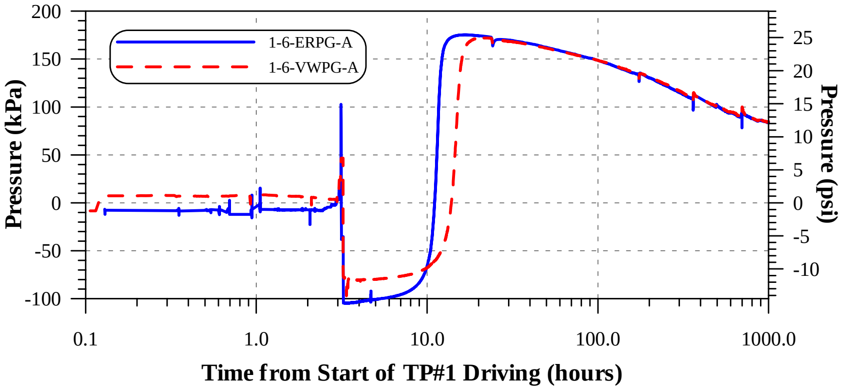


Figure 11. Typical ERPG and VWPG comparison measurements.

Examination of Figure 11 notes a difference in measurements between the two gages at approximately 3 hours from the start of driving. At this time, it appears that the ERPG records a higher pressure before each gage experiences a sudden drop in pressure. By plotting the same gage readings with depth, a better understanding of the measurement difference is observed. Figure 12 shows that during penetration into the overconsolidated clay layer, each gage experiences a loss in pressure. Before this loss of pressure occurs, a slight pressure buildup was registered by each gage. The ERPG, which is being recorded at a higher frequency than the VWPG, records more data points of the buildup. The lower recording frequency of the VWPG misses the majority of this buildup. Examination of similar comparisons between the two gage types for the installation of each of the steel pipe piles reveals comparable patterns of measurement.

A comparison of the performance of the electrical resistance and vibrating wire strain gages could not be conducted since there were no concurrent measurements involving the two gage types. The lack of simultaneous readings was a result of the failure of the ERSG's during static load testing and the inability of the VWSG's to record measurements during dynamic events.

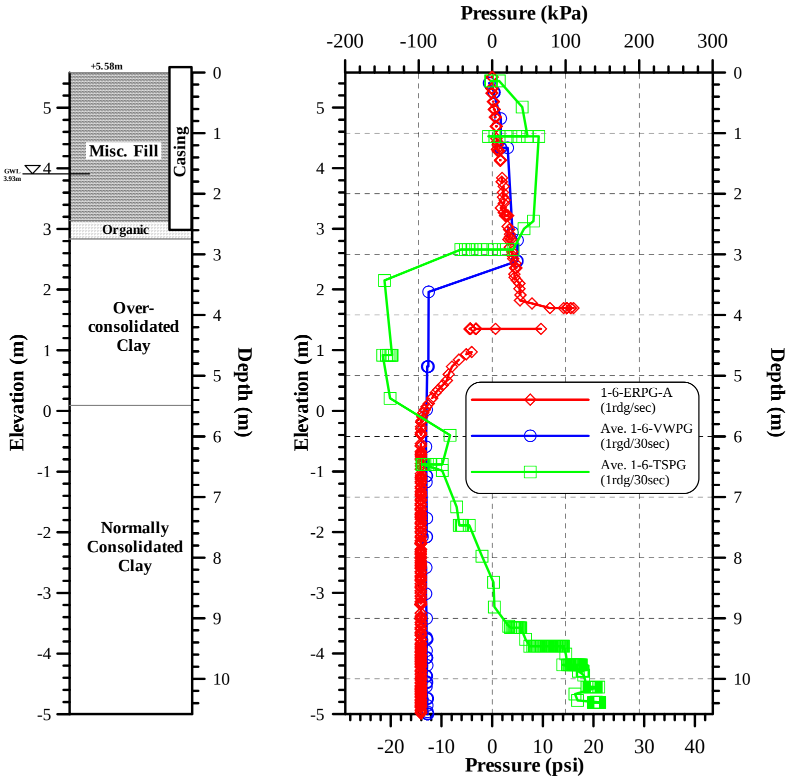


Figure 12. Typical ERPG, TSPG, and VWPG measurements with depth through the overconsolidated clay layer.

Measurement Frequencies

The measurements from each gage were examined to determine if the selected sampling frequencies for the various testing events (see Table 4) adequately monitored the desired phenomena. For the majority of test pile cluster instrumentation, the selected recording rates were adequate to measure the desired phenomena. However, rapid total and pore pressure buildup along the pile and in the ground piezometer field, caused by pile installation and other dynamic events, were not adequately recorded by the corresponding vibrating wire instrumentation. For example, comparison between the readings of electrical and vibrating wire piezometer types revealed that the reading rate of the vibrating wire instrumentation was not adequate to record the buildup of pore pressure during pile penetration into the overconsolidated layer (see Figure 12). Comparison of ERPG to adjacent TSPG recordings, also shown in Figure 12, revealed that the same problem existed for the total soil pressure measurements.

Piezometer Assembly Evaluation

Examination of the pile piezometers based on durability and comparative analysis also produced an evaluation of the piezometer assemblies used with the test piles. A consistent loss of pore pressure was observed for all test pile piezometers during instrument penetration into the overconsolidated soil layer. A substantial delay was also observed in the pile piezometers before an increase in pore pressure was recorded.

To determine the cause of this delay in pore pressure measurements, additional comparisons were made between adjacent pore and total pressure measurements. Typical comparisons between the ERPG, TSPG, and VWPG measurements are shown in Figures 12 and 13 with depth and time, respectively. In Figure 13, an initial decrease in pressure is observed in both gage types, a substantial time lag occurs before the pile piezometers register an increase while the total pressure cell records an almost immediate pressure increase. The pressure vs. depth plots in Figure 12 show that the total pressure cells begin to register pressure increases within the normally consolidated layers while the piezometers remain constant.

Based on these observations, it was concluded that a loss of saturation occurred within the piezometer assemblies during penetration into the overconsolidated clay, most likely due to dilation of the clay during shear caused by the installation. The only common element of both piezometer assembly designs was the size and material type of the porous stones (see Paikowsky and Hajduk, 1999). It was therefore assumed that the permeability of these porous stones was too high to prevent a loss of saturation due to dilation of the overconsolidated clay.

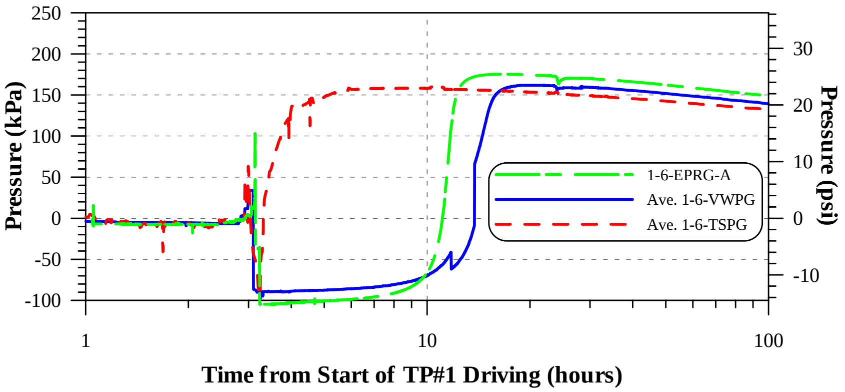


Figure 13. Typical ERPG, TSPG, and VWPG measurements with time.

Data Acquisition Array

The data acquisition array was able to provide near continuous measurements of the different gages employed throughout the 17 months of testing during the project. Although supplied with constant power and equipped with battery backups, several significant data gaps that ranged from several hours to 5 days were experienced during the testing period due to power loss at the site. Individual DAS battery backups were not adequate to operate the various components of the array during extended blackout periods. To prevent extended periods of time with no instrument recordings, the download of data from the array was adjusted during the testing program.

Although housed in a trailer adjacent to the test site, the data acquisition array was subjected to extreme temperature variations over the course of the 17 month testing program. These temperature variations did not affect the array performance.

Piezometer measurement comparisons revealed that the VWPG and TSPG did not effectively record the complete pore and total pressure buildup along the pile during pile installation. This limitation was not due to the performance of the array but rather due to the recording limitation of vibrating wire gages, which have a maximum rate of approximately 1reading per gage per second. In order for the vibrating wire piezometers to have a recording frequency comparable to the electrical resistance piezometers, a Micro-10 would have to be assigned to each VWPG. However, the addition of more Micro-10 dataloggers to the array would not be economically or practically feasible for the project.

The propriety software of each component data acquisition system used within the array provided sufficient flexibility to change instrument-recording frequencies according to the testing event. The finite memory capabilities of the individual data acquisition systems limited the capabilities of the array to store large quantities gathered at high measurement frequencies. Required downloads on data where then conducted at various intervals to prevent data loss. These intervals were dependent on recording frequency and array component. The finite amount of memory also affected the ability of certain components to perform multiple recording tasks. For example, the CR9000, which recorded the electrical resistance instrumentation, could not simultaneously record the ERSG's during driving and provide continuous monitoring of the ERPG's in the configuration used during the project. The ERPG's were therefore not recorded during actual pile driving, but during the periods between blows. This produced time gaps in the EPRG measurements. Examples of these time gaps as they relate to pile penetration are shown in Figure 12.

Aside from the loss of data from power outages and system limitations, several large blocks of data were lost due to operator inexperience and error. A data acquisition array of the size and complexity used for the instrumented test pile cluster requires a trained engineer to set recording frequencies, synchronize time measurements, and download the acquired data.

Measurement coordination between components of the data acquisition array was achieved through use of absolute date/time measurements and synchronization of the component time clocks.

CONCLUSIONS

The performance evaluation of the instrumented test pile cluster presented in this paper yielded several conclusions:

1. The vibrating wire instrumentation proved to be more durable to the testing and site conditions than the piezo-resistive and electrical resistance gages used throughout the project. All the piezo-resistive accelerometers stopped functioning during the testing period, which resulted in a failure rate of 100% (4 out of 4 gages). Of the electrical resistance components, all electrical resistance strain gages failed during the duration of testing, resulting in an overall failure rate of 43% (9 out of 21) for these gages. In comparison, only 4 out of 96 (4%) vibrating wire gages ceased recording over the testing duration.
2. An additional 8 out of the 96 vibrating wire gages suffered from significant erratic readings and/or zero drifts at various times over the course of testing. Two of these gages that experienced zero drift also experienced complete failure. When combined with the gages that failed, a total of 10 out of 96 vibrating wire (10%) did not function to expectations. This percentage was considered an excellent rate of success for this gage type.
3. The overall instrument failure rate for the instrumentation within the test pile cluster was 17% (21 out of 121 gages). This failure rate considered the gages that ceased operating (17 gages) and the erratic vibrating wire gages that did not completely fail (4 gages). The failure rate was considered excessive even for a project of this size and complexity.
4. Comparison of the vibrating wire and electrical resistance piezometers showed that the vibrating wire gages did not sample at a rate high enough to accurately capture the buildup of pore pressure in the overconsolidated layer along the piles during driving. This limitation was attributed to limitations of the gage type and not the data acquisition array.
5. Comparison of the adjacent pore and total pressure measurements showed that the porous stones used in the piezometer assemblies did not have a permeability that could prevent loss of saturation during driving through the overconsolidated clay layer. Therefore, there was a lack in gage response until the system could become saturated and take relevant measurements.

6. The data acquisition array performed adequately during the test pile project and was not affected by the site conditions. Data gaps were attributed to extended power outages and operator error.

Overall, the performance of the instrumented test pile cluster was considered to be outstanding when taking into account the length of test period and the amount and variety of testing involved. Lessons learned in this evaluation should be applied in the reuse of the two steel pipe piles.

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