16 State House Station
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Transportation Research Division

Technical Report 15-09

Experimental Evaluation and Design of Unfilled and Concrete-Filled FRP Composite Piles

Task 6 - FRP Composite Pile Axial Compression Testing

Final Report – Task 6, April 2015

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16. Abstract (Limit 200 words)

The overall goal of this project is the experimental evaluation and design of unfilled and concrete-filled FRP composite piles for load-bearing in bridges. This report covers Task 6, FRP Composite Pile Axial Compression Testing.

Hollow and concrete-filled fiber reinforced polymer (FRP) piles with a nominal diameter of 24 inches were tested in axial compression to examine degradation in apparent longitudinal modulus due to pile driving. All specimens achieved the proof load of 1000 kips with no visible damage. Hollow piles showed no reduction in apparent longitudinal modulus due to driving. No definitive trend in apparent longitudinal modulus could be seen in the concrete-filled piles, because the driven piles were filled with concrete from a different supplier 205 days prior to the baseline piles.

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Experimental Evaluation and Design of Unfilled and Concrete-Filled FRP Composite Piles

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An ISO 17025 accredited testing laboratory, accredited by the International Accreditation Service.

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1. EXECUTIVE SUMMARY

Hollow and concrete-filled fiber reinforced polymer (FRP) piles with a nominal diameter of 24 inches were tested in axial compression to examine degradation in apparent longitudinal modulus due to pile driving. All specimens achieved the proof load of 1000 kips with no visible damage. Hollow piles showed no reduction in apparent longitudinal modulus due to driving. No definitive trend in apparent longitudinal modulus could be seen in the concrete-filled piles, because the driven piles were filled with concrete from a different supplier 205 days prior to the baseline piles.

2. REFERENCES

1. Lawrence, Dale et al. "Guide Specifications for Unfilled and Concrete-Filled FRP Composite Piles"
2. Lawrence, Dale et al. "FRP Composite Pile Driving at the Richmond-Dresden Bridge Over the Kennebec River", ASCC technical report 14-14-1199. 2014.
3. Enerpac. (n.d.) "RR-Series, Double Acting Cylinders" Retrieved from: http://www.enerpac.com/en/industrial-tools/hydraulic-cylinders-jacks-lifting-products-and-systems/long-stroke-high-cycle-cylinders/rr-series-double-acting-cylinders. Accessed 21 July 2014.
4. Wight, J.K & MacGregor, J.G. (2012). Reinforced Concrete Mechanics and Design: Sixth Edition. Pearson Education Inc., Upper Saddle River, NJ.
5. Lawrence, Dale et al. "FRP Composite Pile Flexural Testing", ASCC technical report 14-XX (report number not assigned at the time of this report). 2014.

3. MATERIALS AND SAMPLE DESCRIPTION

Fiber Reinforced Polymer (FRP) piles were manufactured in July of 2013 by Harbor Technologies LLC with a nominal diameter of 24 inches. Driven piles were manufactured with a nominal length of 40 feet, and baseline piles were manufactured with a nominal length of 20 feet. The FRP shell consists of a stitched E-glass fabric with 0, 90, and +/-45 degree fibers and a polyester resin. Concrete-filled piles have 4 layers of reinforcement which gives a nominal shell thickness of 1/2 inch, and hollow piles have 8 layers of reinforcement which gives a nominal shell thickness of 1 inch.

Specifications for dimensional tolerances and physical properties were established prior to the manufacturing of FRP piles. All piles fell within the range of acceptable dimensions. Additional details on the specifications can be seen in Reference 1 .

Driven piles were delivered to the Richmond-Dresden bridge site (MDOT PIN 12674) in early August 2013. This set of piles contained (1) 4 ply pile and (3) 8 ply piles. On August 14, 2013, (1) 4 ply pile (Pile A) was completely filled with concrete and (1) 8 ply pile (Pile B) had a 4 foot concrete plug cast at its toe. All driven piles were stored on site until pile driving took place on August 28, 2013. Piles remained in the ground until they could be removed and shipped to the University of Maine on October 15, 2013 and November 8, 2013. Pile A was tested in flexure before being cut into 2 axial compression samples.

All driven piles showed various levels of damage from driving and/or extraction. A summary of this damage and a summary of driving can be seen in Reference 2.

Baseline piles were delivered to the Richmond-Dresden bridge site in early September. Piles remained on site until they could be shipped to the University of Maine on November 8, 2013. Baseline piles were then cut into specimen with a nominal length of 5 feet. Tops and bottoms of the pile sections were sanded so that they were plumb and level within 1/16 inch. Concrete was cast in 3 baseline pile sections on March 7, 2014. MDOT Class A concrete was provided by O.J. Folsom's in Old Town, ME.

4. TEST SETUP

4.1. General Test Setup

Axial compression samples were loaded under a test frame with 4 concentric hydraulic cylinders. Load was distributed over the top of the pile section using a 3 inch thick steel plate and at the bottom using a 2 inch thick steel plate supporting a larger 1 inch thick steel plate that was used to move samples in and out of the frame. The test configuration can be seen in Figure 1.

Figure 1: Test Configuration for Axial Compression Samples

Pile sections were loaded using 4 double acting 150 ton Enerpac RR1502 hydraulic cylinders powered by a 10,000 psi Enerpac ZU4 Series hydraulic pump. The cylinders and pump can be seen in Figure 2 and Figure 3 respectively.

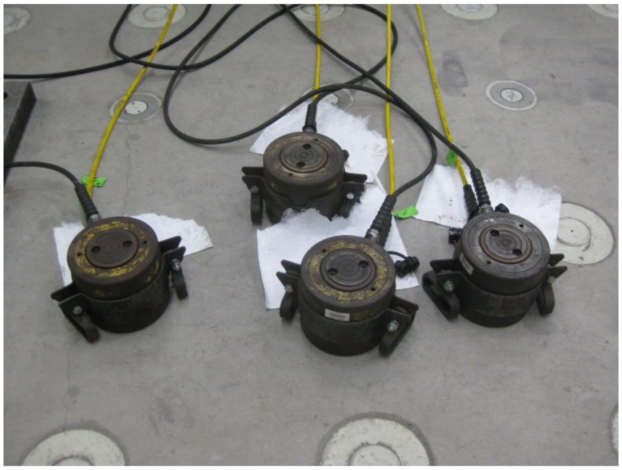


Figure 2: 150 Ton Enerpac Cylinders

Figure 3: Enerpac Hydraulic Pump

4.2. Loading of Piles

Pile sections were manually loaded using increments of 1500 psi of hydraulic pressure to 7500 psi, and then loaded to 8000 psi and 8700 psi. Pressure readings were taken from a calibrated dial gauge, as pictured in Figure 4, and matched to strain and deflection data using timestamps. The load was held for 5 seconds at each pressure increment to correlate data acquisition.

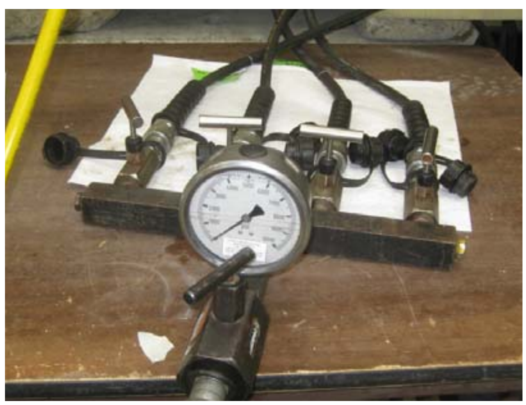


Figure 4: Dial Gauge Used for Pressure Readings

4.3. Instrumentation

Pile sections were instrumented with 3 longitudinal strain gages placed at the mid-height of the sample. Longitudinal gages were placed at intervals of 120 degrees around the circumference of the sample. Hoop strains were measured by 1 strain gage at the mid-height of the pile section and 1 strain gage located 1.25 feet (1/4 of the sample height) from the top of the pile section. Deflections were measured using 2 string potentiometers which were attached to the 3 inch steel loading plate. A sketch of the instrumentation can be seen in Figure 5. It should be noted that the diameter of the pile is 23.5 inches in this figure. While the nominal diameter of the piles is considered to be 24 inches, the piles actually have a diameter of 23.5 inches due to the tooling used in the manufacturing process.

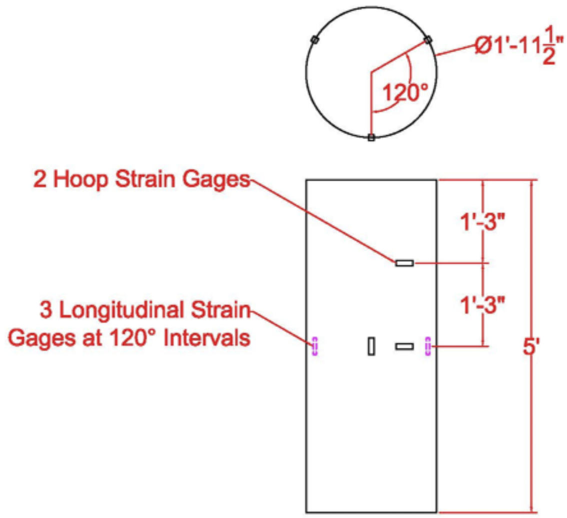


Figure 5: Instrumentation for Axial Testing

5. HOLLOW PILES

All hollow piles were constructed with 8 layers of reinforcing fabric. Testing was conducted on 3 baseline pile sections (cut from Pile K) and 3 driven pile sections (cut from Pile D).

Plots of test results for baseline and driven hollow piles can be seen in Figure 6, Figure 7, and Figure 8.

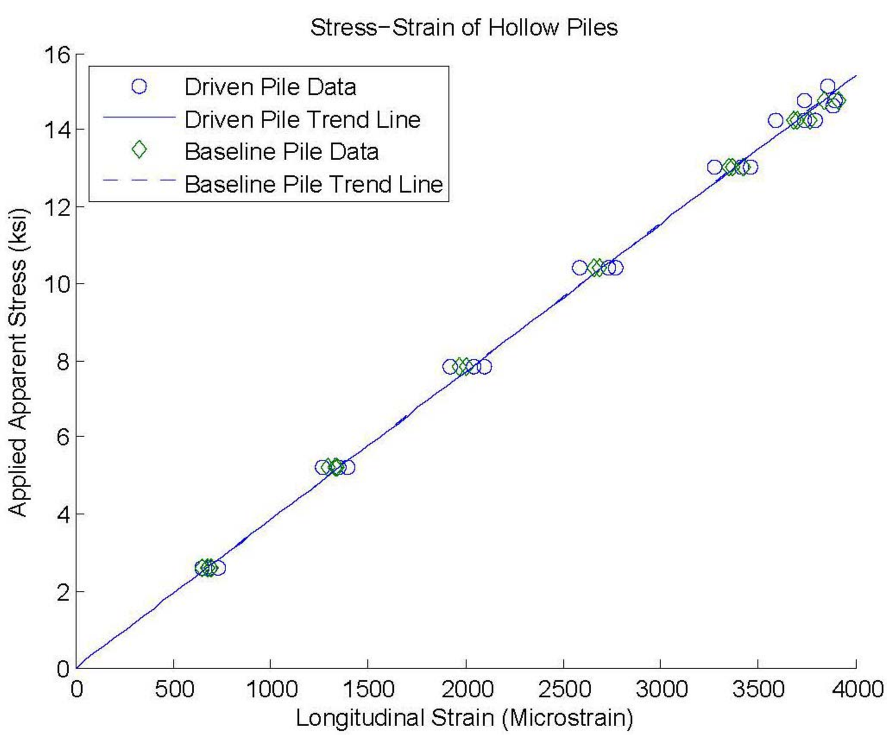


Figure 6: Applied Apparent Stress vs. Longitudinal Strain of Hollow Piles

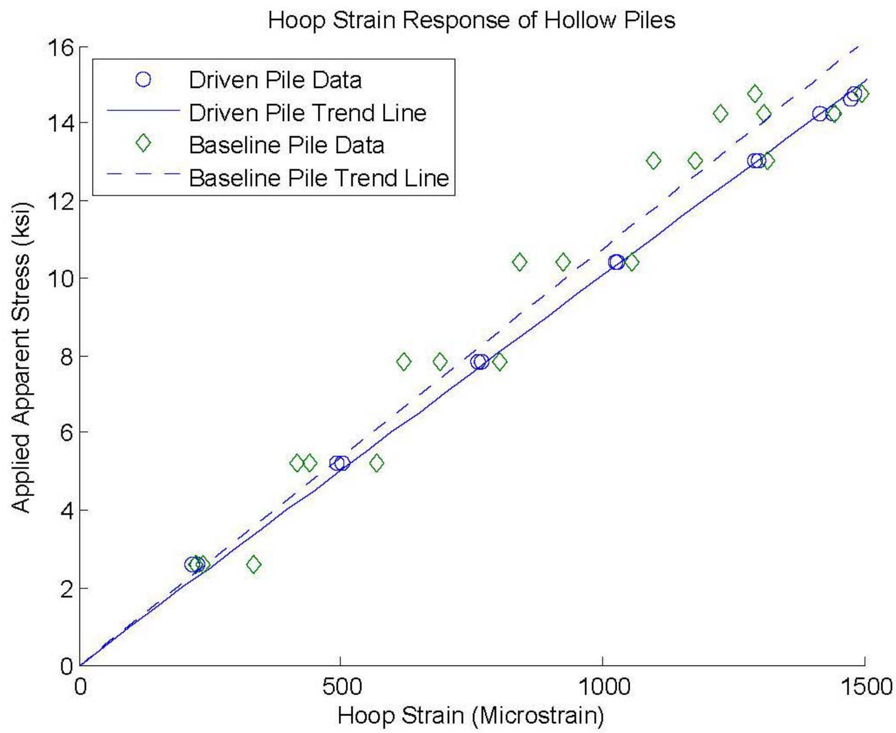


Figure 7: Applied Apparent Stress vs. Hoop Strain of Hollow Piles

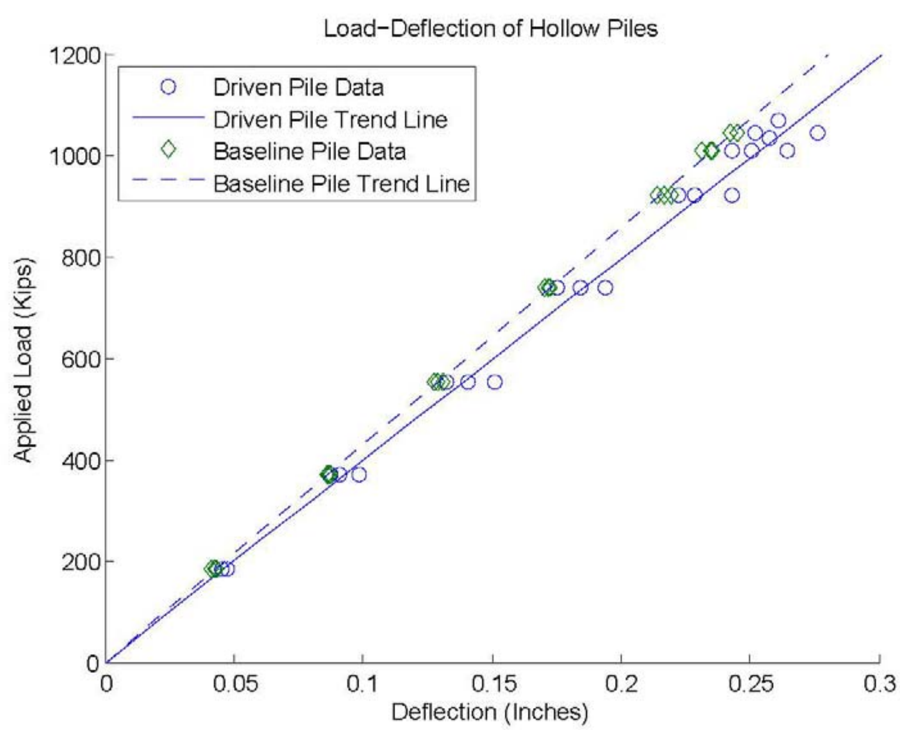


Figure 8: Applied Load vs. Deflection of Hollow Piles

A summary of pile longitudinal modulus and Poisson's ratios for baseline and driven piles can be seen in Table 1 and Table 2 respectively.

Table 1: Longitudinal Modulus and Poisson's Ratio of Baseline Hollow Piles

Test	Longitudinal Modulus (ksi)	Poisson' s Ratio
Pile K Specimen 1	3,890	0.350
Pile K Specimen 2	3,880	0.328
Pile K Specimen 3	3,810	0.388
Pile K All Data	3,860	0.356

Table 2: Longitudinal Modulus and Poisson's Ratio of Driven Hollow Piles

Test	Longitudinal Modulus (ksi)	Poisson's Ratio
Pile D Specimen 1	3,810	0.377
Pile D Specimen 2	3,750	0.374
Pile D Specimen 3	3,970	No Data
Pile D All Data	3,850	0.376

Individual test data for Pile D and Pile K can be seen in Appendix C: Test Results for Pile D and Appendix D: Test Results for Pile K, respectively.

6. CONCRETE-FILLED PILES

All concrete-filled piles were constructed using 4 layers of reinforcing fabric. Testing was conducted on 3 baseline pile sections (cut from Pile L) and 2 driven pile sections (cut from Pile A). The driven concrete-filled pile was previously tested in flexure (Pile A-4FB).

Plots of test results for baseline and driven concrete-filled piles can be seen in Figure 9, Figure 10, and Figure 11.

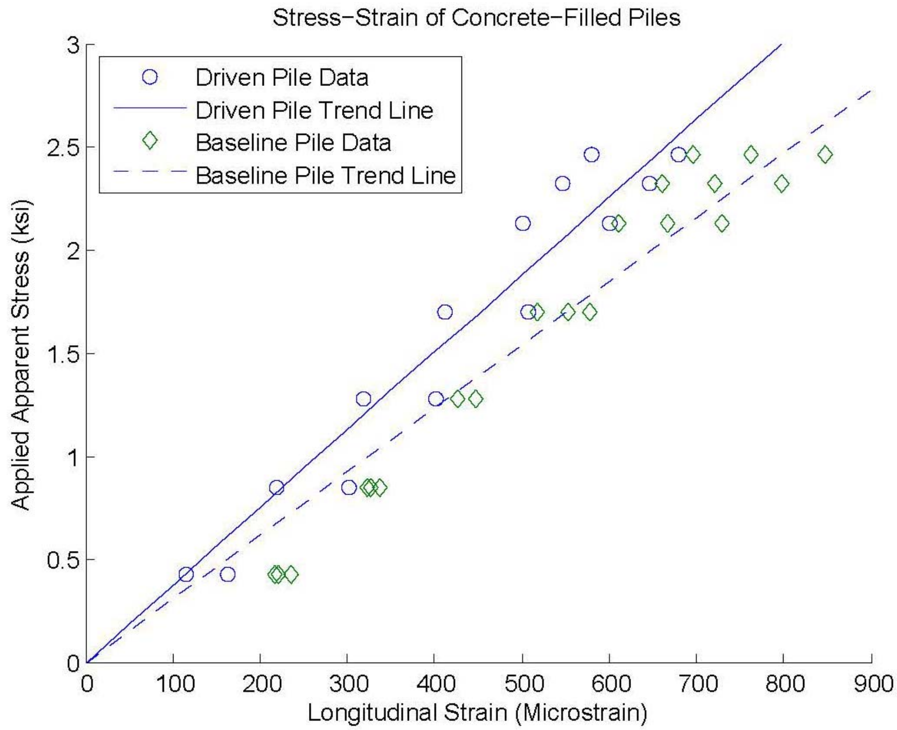


Figure 9: Applied Apparent Stress vs. Longitudinal Strain of Concrete-Filled Piles

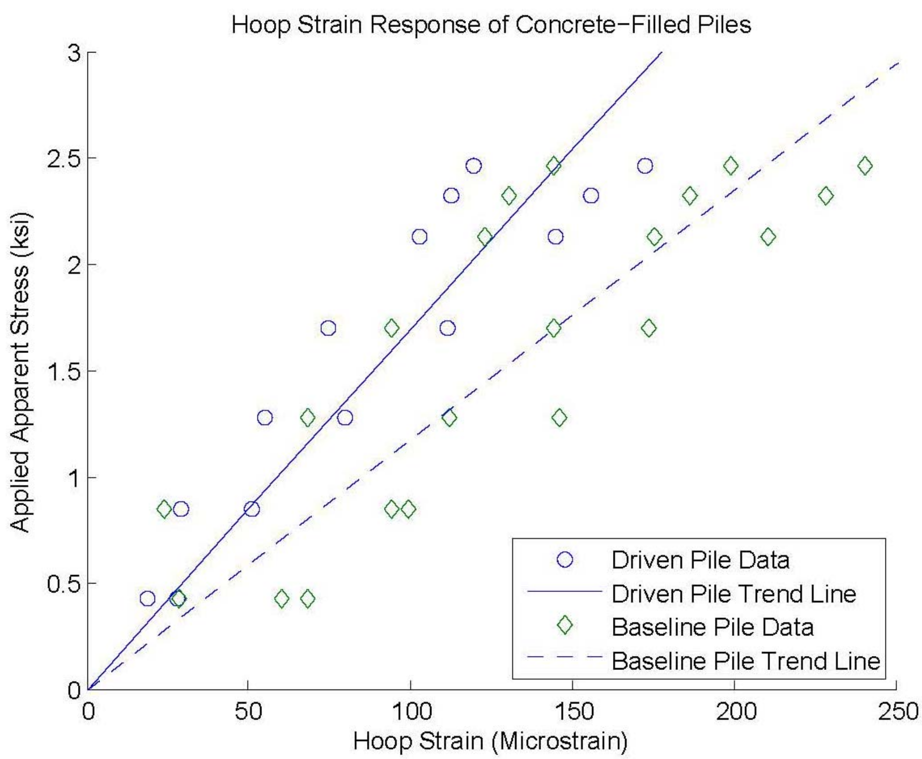


Figure 10: Applied Apparent Stress vs. Hoop Strain of Concrete-Filled Piles

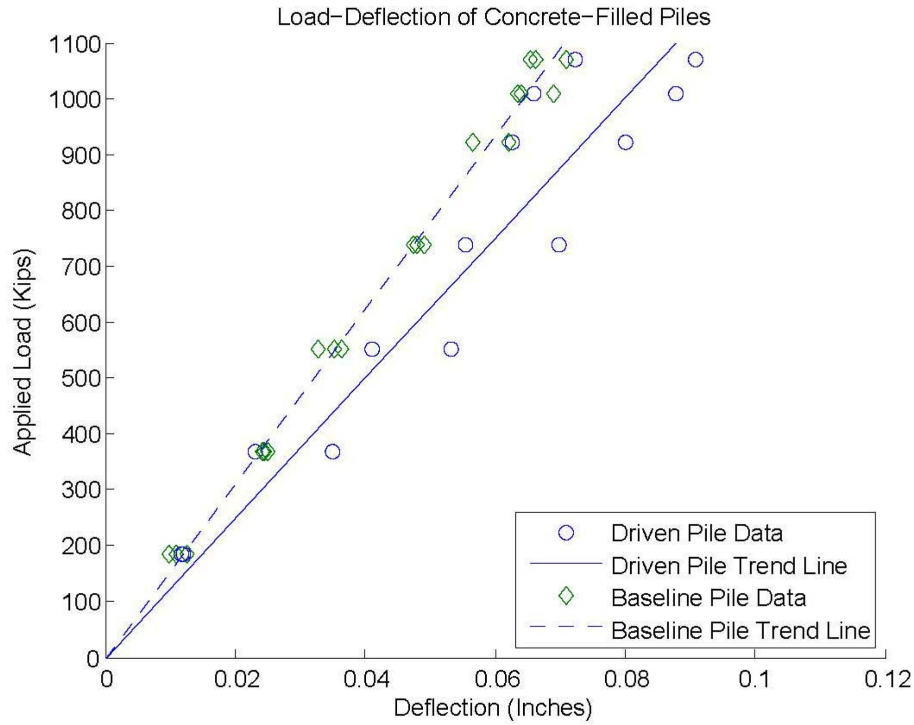


Figure 11: Applied Load vs. Deflection of Concrete-Filled Piles

A summary of apparent longitudinal modulus for baseline and driven piles can be seen in Table 3 and Table 4 respectively. Poisson's ratio values are considered unreliable for concrete-filled piles. This is discussed further in Section 8.

Table 3: Apparent Longitudinal Modulus of Baseline Concrete-Filled Piles

Test	**Apparent Longitudinal Modulus (ksi)**
Pile L Specimen 1	2,880
Pile L Specimen 2	3,340
Pile L Specimen 3	3,090
Pile L All Data	3,080

Table 4: Apparent Longitudinal Modulus of Driven Concrete-Filled Piles

Test	**Apparent Longitudinal Modulus (ksi)**
Pile A Specimen 1	3,460
Pile A Specimen 2	4,190
Pile A All Data	3,760

Individual test data for Pile A and Pile L can be seen in Appendix A: Test Results for Pile A and Appendix B: Test Results for Pile L, respectively.

7. DATA ANALYSIS METHODS

When manually loading pile sections, each hydraulic pressure interval was held for 5 seconds. Data points for strain and deflection were selected 3 seconds after the specified load was reached. This allowed potential inertial effects due to loading to dissipate and provide a more reliable correlation between manually and automatically recorded data.

To convert hydraulic pressure to load, the nominal area of the Enerpac cylinder was used. This value of 30.71 square inches was taken from the specifications for RR-Series Double-Acting Cylinders provided by Enerpac (Reference 3). Nominal pile thicknesses (1 inch for hollow piles and 1/2 inch for concrete piles) and diameter (23.5 inches for all piles) were used to compute the applied apparent stress as the applied load over the cross-sectional area.

All redundant measurements were averaged, and a trendline was fitted to the data using linear regression with an intercept of zero.

8. DISCUSSION

The longitudinal modulus of the baseline hollow pile sections did not show much variation from the longitudinal compression coupon tests. The baseline hollow pile sections have a longitudinal modulus of 3860 ksi and the coupon level tests showed a longitudinal compressive modulus of 3670 ksi. This 5.2 percent increase in longitudinal modulus is considered to be within the error of the tests.

Some error may be introduced into the data due to the manual loading of the pile sections. The dial gage used to monitor hydraulic pressure had a resolution of 100 psi. Pressure readings are believed to be within +/- 50 psi which is equivalent to +/- 6.1 kips. A maximum hydraulic pressure of 8700 psi (equal to 1068 kips) was selected to ensure all pile sections were loaded to a minimum of 1000 kips.

Thicknesses of piles were not individually measured prior to testing, so the data does not take into account variations in thickness of the piles. Pile thicknesses of 1 inch +/- 1/8 inch were measured on hollow piles used in flexural testing.

Differences in concrete are believed to have caused the driven concrete-filled piles to be stiffer than baseline piles. Concrete for driven piles was provided by Auburn Concrete, and concrete for baseline piles was provided by Owen J Folsom Inc. Both concrete mixes were proportioned to meet specifications for MaineDOT Class A concrete with a target 28 day compressive strength of 4350 psi.

Table 5: Summary of Concrete Cylinder Compressive Strength

	Baseline Piles	**Driven Piles**
Cure Time at Cylinder Test (Days)	35	12
f'_c of Cylinders (psi)	4,812	4,680
f'c Corrected to 28 Days (psi)	4,640	5,538
Cure Time at Axial Pile Compression Test (Days)	39	253
f'_c Corrected to Axial Pile Test Date (psi)	4,871	6,396

Concrete cylinder strengths were converted to 28 day strength and strength at the time of axial testing using Equation 1 (Reference 4). It should be noted that this correlation was developed for concrete using Type I cement and moist-cured at 70 degrees Fahrenheit.

$$f'_{c(t)} = f'_{c(28)} \left(\frac{t}{4 + 0.85t}\right) \qquad \text{Equation 1}$$

Poisson's ratio calculations for concrete-filled piles are not considered reliable due to the low stresses and strains seen during testing.

Some samples showed significant differences among longitudinal strain gages. This is believed to be a product of the cutting process for the piles and finishing of the concrete infill. An extensive effort was made to create a flat, square surface to load the piles, but these errors may be an appreciable percentage of the small deflections seen during testing (approximately 0.09 inches in concrete-filled piles). An example of the difference in strain data can be seen in Figure 12 and Figure 13. It should be noted that hollow pile sections were visibly more square than concrete-filled pile sections, because concrete-filled samples were much harder to sand/grind flat than hollow samples. It should also be noted that there is a large difference in the magnitude of strains presented in Figure 12 and Figure 13.

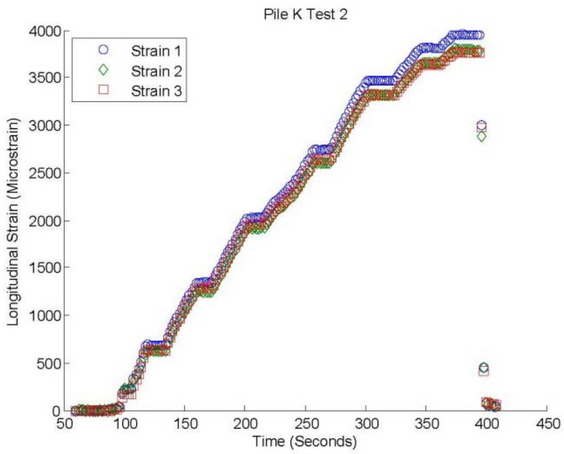


Figure 12: Consistent Strain Data (Hollow Pile)

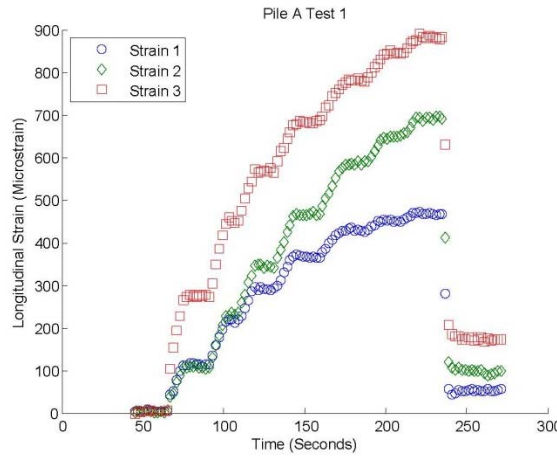


Figure 13: Inconsistent Strain Data (Concrete-Filled Pile)

Differences in tests may also be due to internal defects in FRP such as folds in the reinforcing fabric, areas of high resin content, and misaligned fibers. These defects are discussed further in Reference 5. It should be noted that none of these defects were visibly present in axial compression samples.

9. CONCLUSIONS

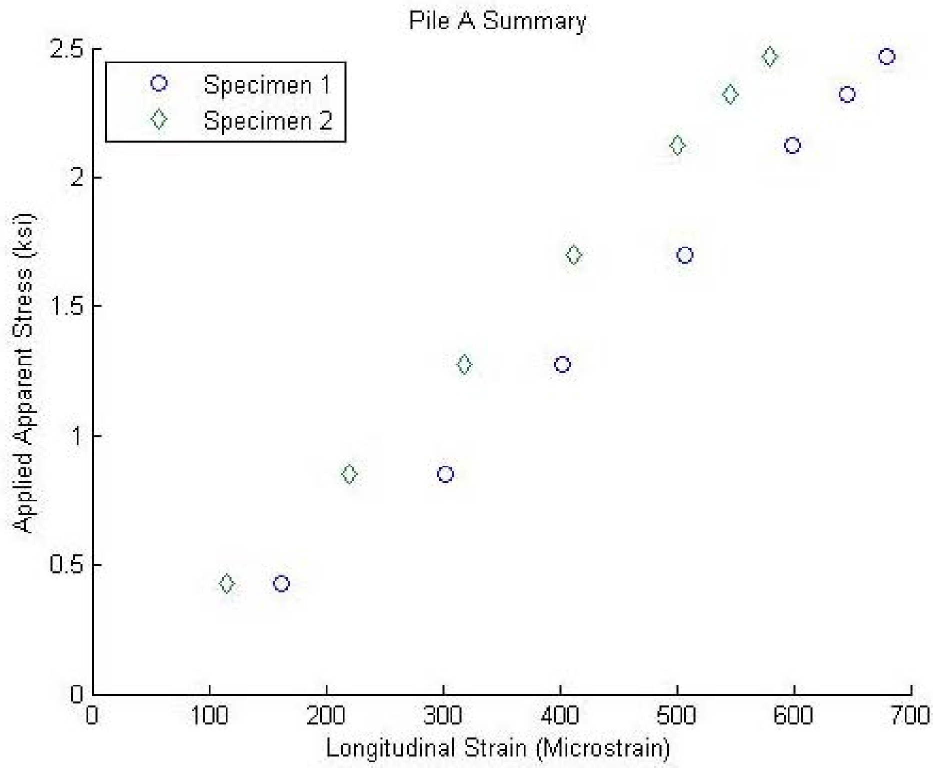
A summary of all modulus and Poisson's ratio values for hollow and concrete-filled piles can be seen in Table 6.

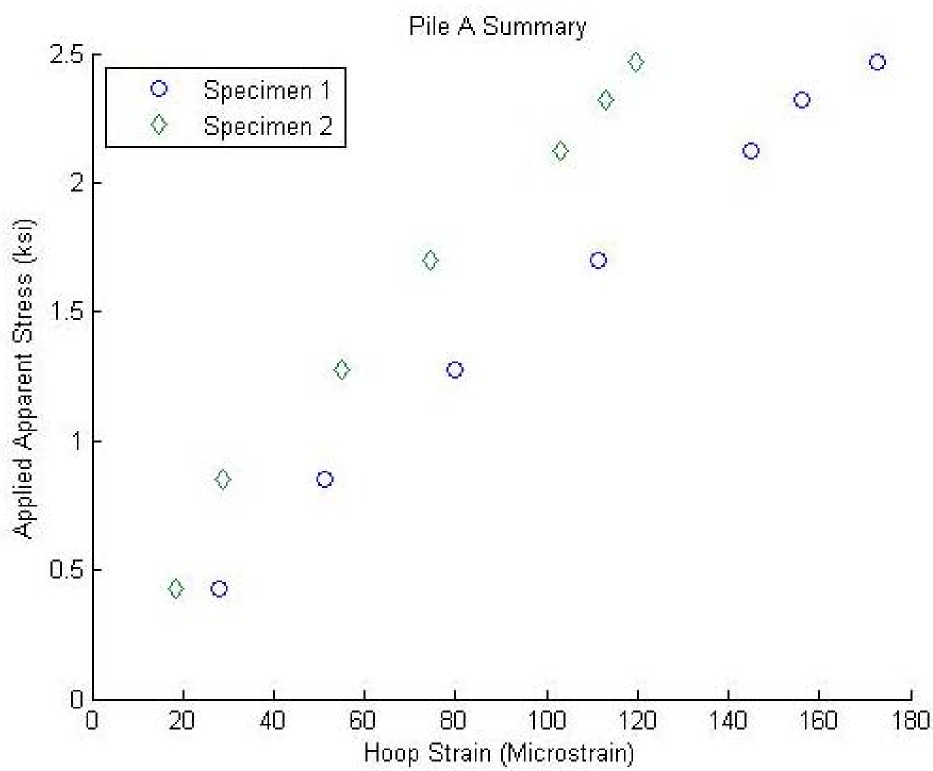
Table 6: Summary of Hollow and Concrete-Filled Pile Results

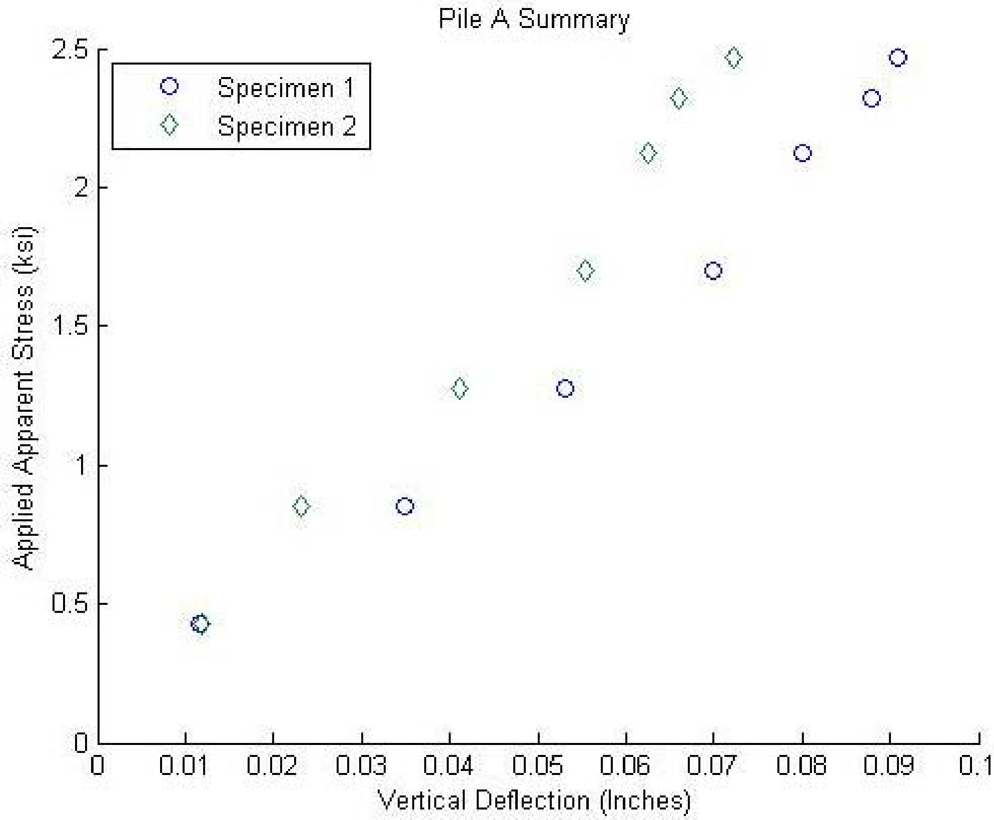
Pile Type	Condition	Longitudinal Modulus (ksi)	Apparent Longitudinal Modulus (ksi)	Poisson's Ratio
Hollow Piles	Baseline	3,860	–	0.356
	Driven	3,850	–	0.376
Concrete-Filled Piles	Baseline	–	3,080	–
	Driven	–	3,760	–

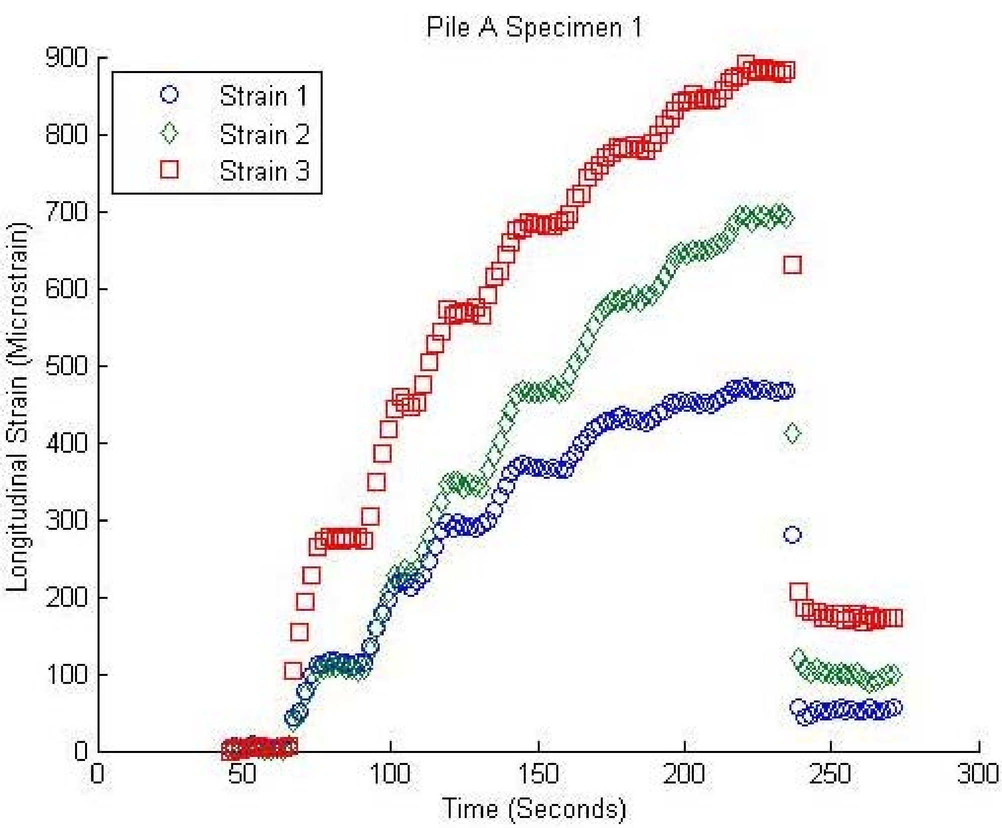
Testing showed that pile driving does not appear to affect the longitudinal modulus of hollow piles loaded in axial compression. Driven concrete-filled piles appear to have an apparent longitudinal modulus 22 percent higher than baseline concrete-filled piles. This is believed to be a result of differences in the concrete used in driven and baseline piles. The theoretical compressive strength of the concrete used in driven piles is 31 percent higher than theoretical compressive strength of concrete used in baseline piles at the time of testing.

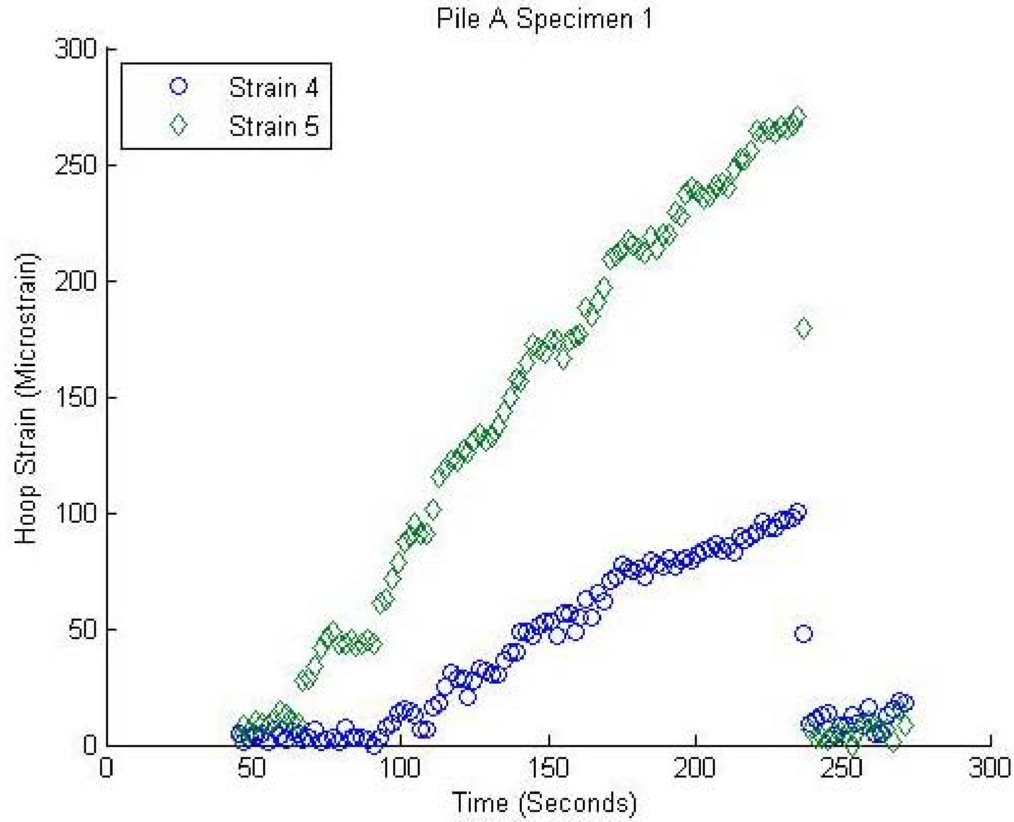
10. APPENDIX A: TEST RESULTS FOR PILE A

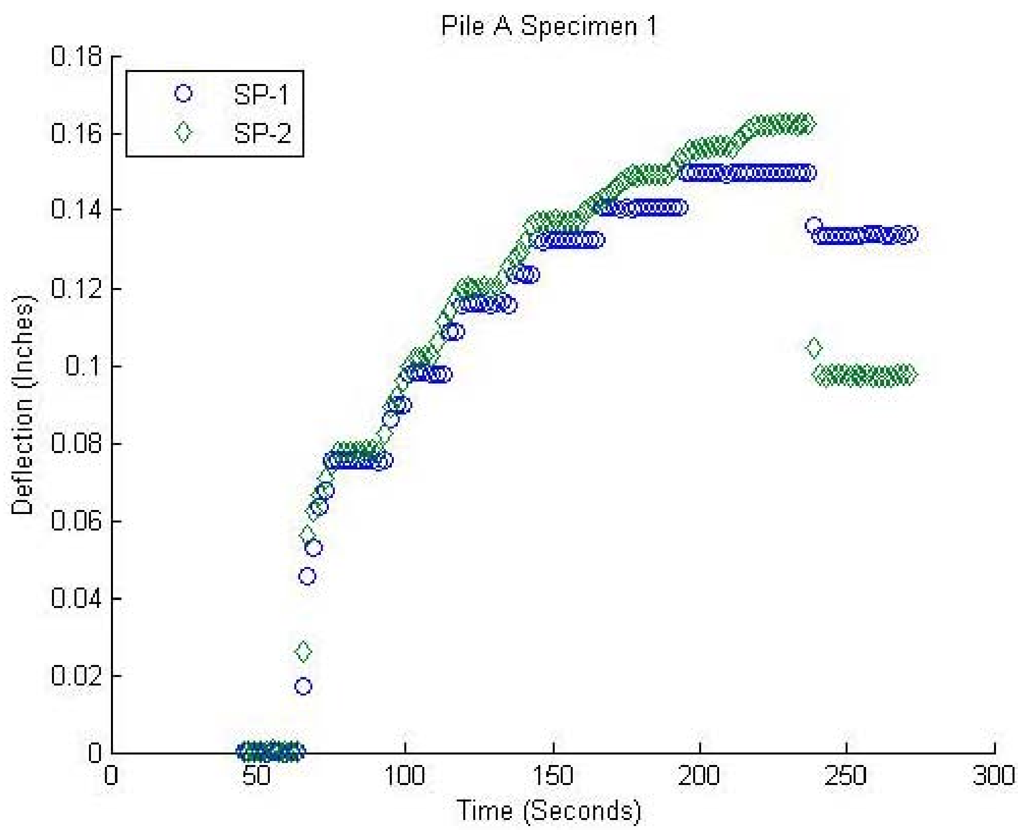


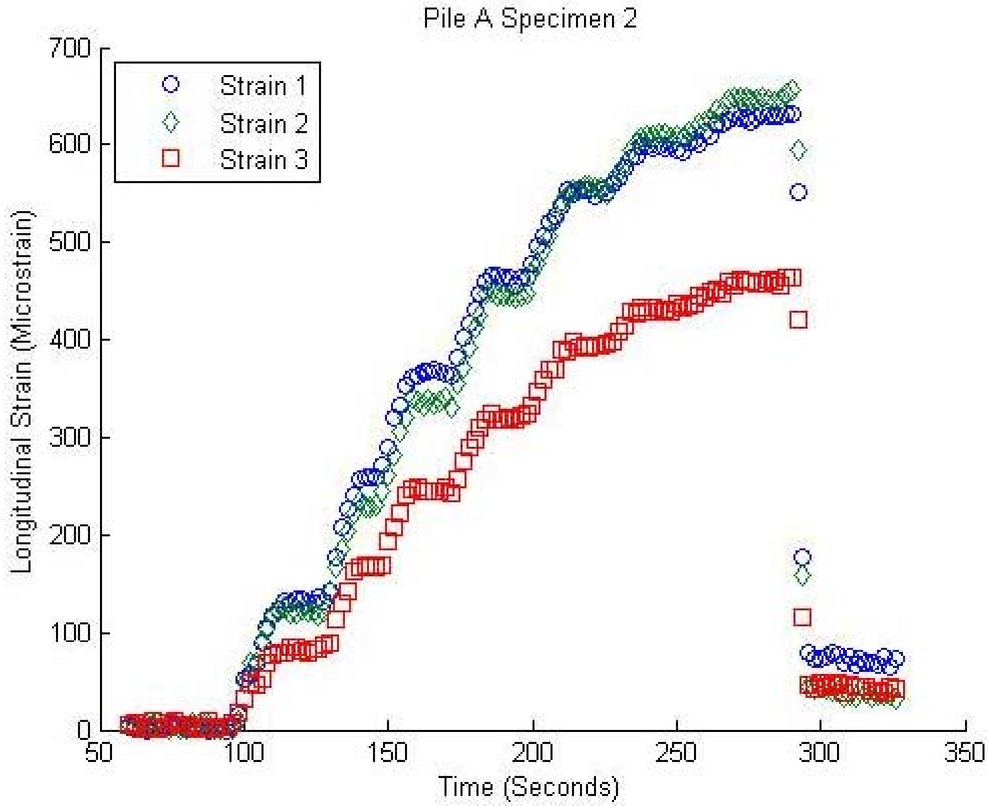



Pile A Summary
Specimen 1
Specimen 2
Applied Apparent Stress (ksi)
Vertical Deflection (Inches)
0
0.5
1
1.5
2
2.5
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1


Pile A Specimen 1
Strain 1
Strain 2
Strain 3
Longitudinal Strain (Microstrain)
Time (Seconds)
0
100
200
300
400
500
600
700
800
900
50
150
250


Pile A Specimen 1
Strain 4
Strain 5
Hoop Strain (Microstrain)
Time (Seconds)
0
50
100
150
200
250
300


Pile A Specimen 1
SP-1
SP-2
Deflection (Inches)
Time (Seconds)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
50
100
150
200
250
300


Pile A Specimen 2
Strain 1
Strain 2
Strain 3
Longitudinal Strain (Microstrain)
Time (Seconds)
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200
300
400
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700
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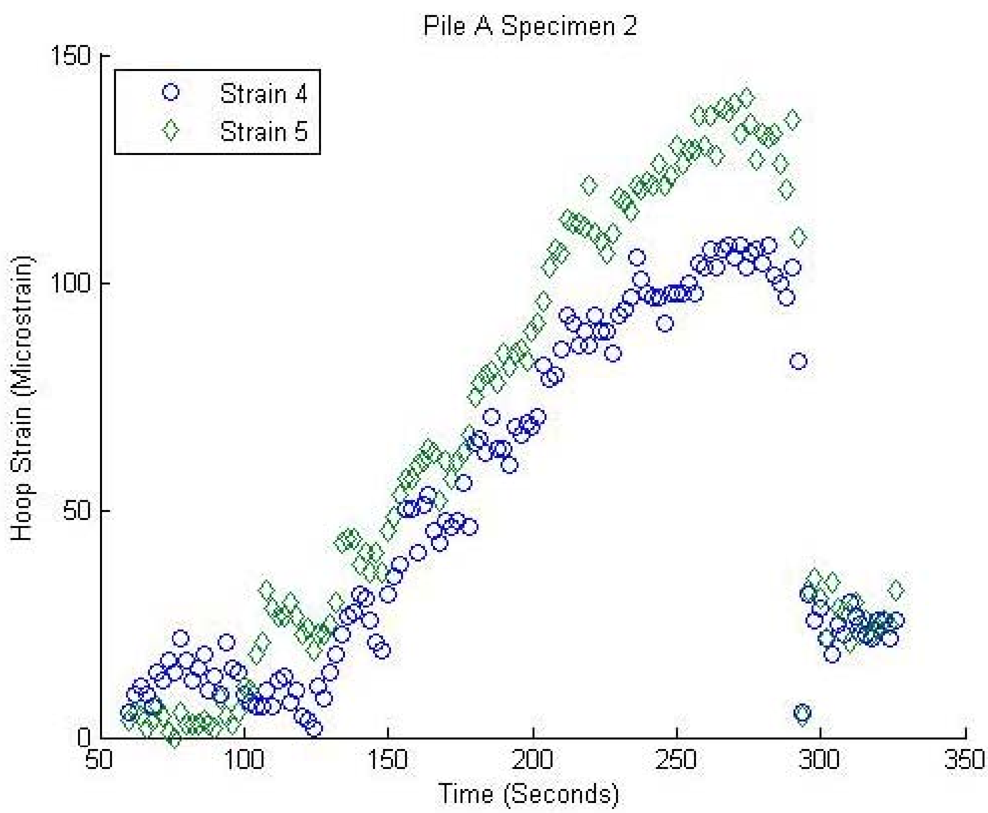
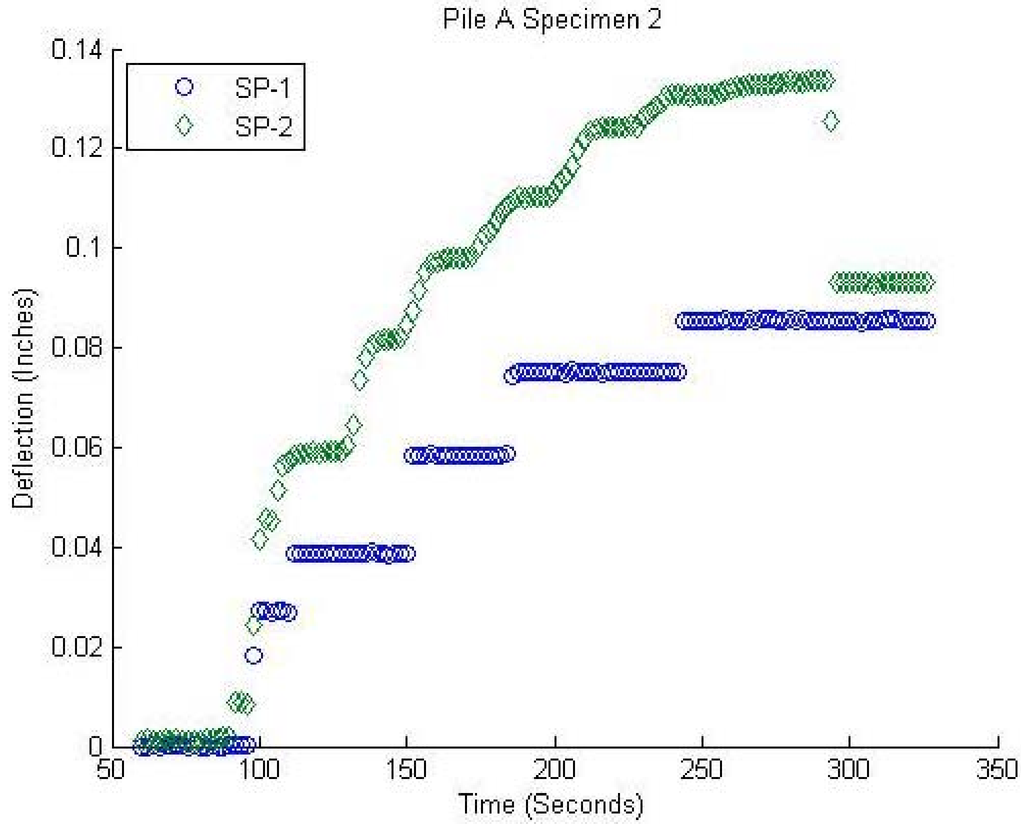
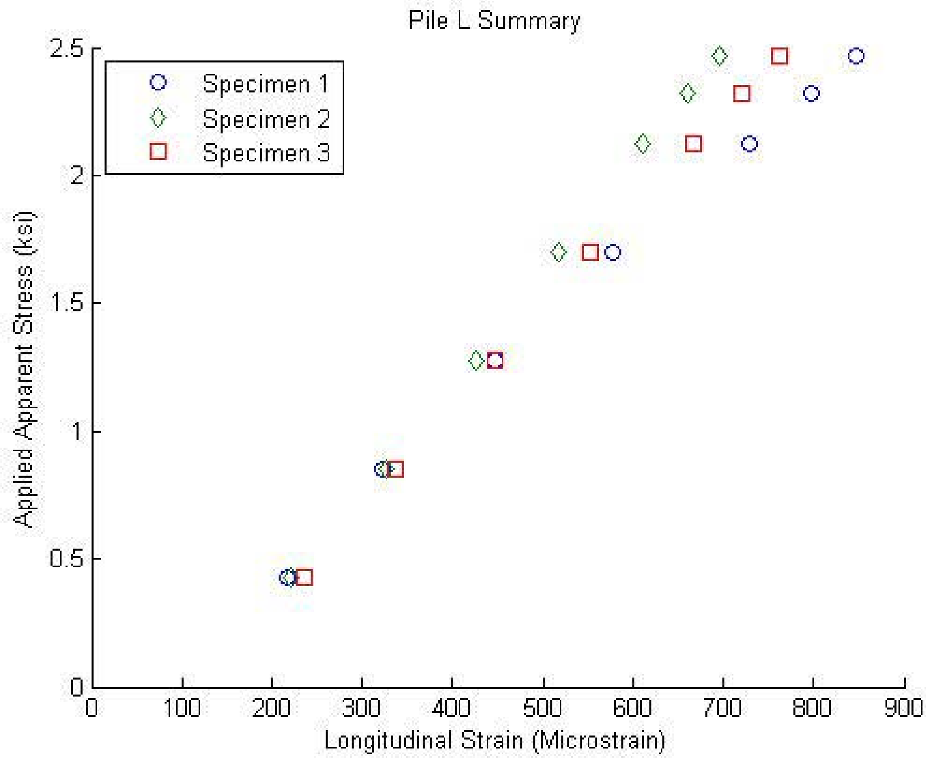
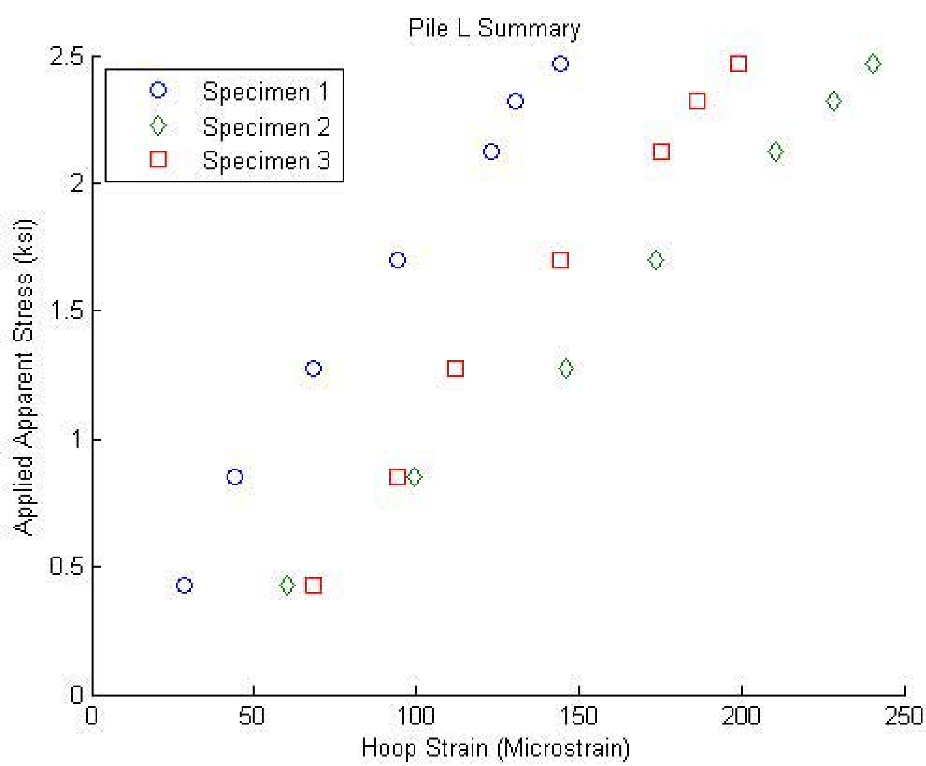
150
200
250
300
350

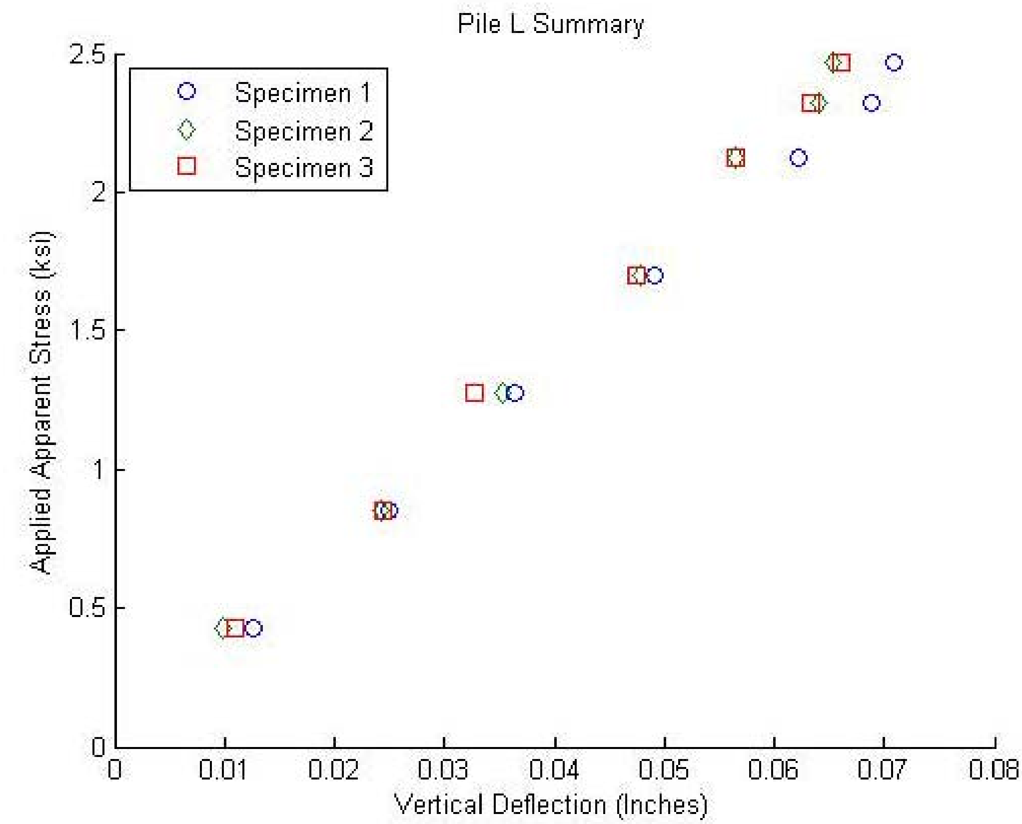

Pile A Specimen 2
Strain 4
Strain 5
Hoop Strain (Microstrain)
Time (Seconds)
0
50
100
150
50
100
150
200
250
300
350

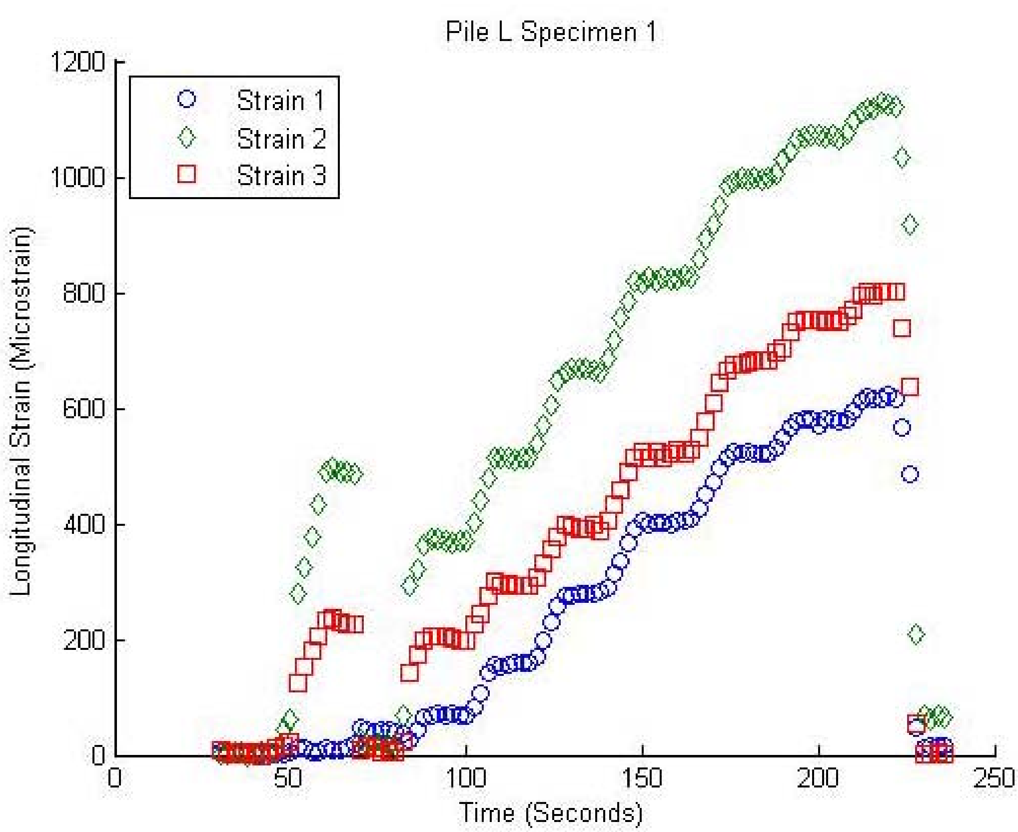

Pile A Specimen 2
SP-1
SP-2
Deflection (Inches)
Time (Seconds)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
50
100
150
200
250
300
350

11. APPENDIX B: TEST RESULTS FOR PILE L






Pile L Summary
Specimen 1
Specimen 2
Specimen 3
Applied Apparent Stress (ksi)
Vertical Deflection (Inches)
0
0.5
1
1.5
2
2.5
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08


Pile L Specimen 1
Strain 1
Strain 2
Strain 3
Longitudinal Strain (Microstrain)
Time (Seconds)
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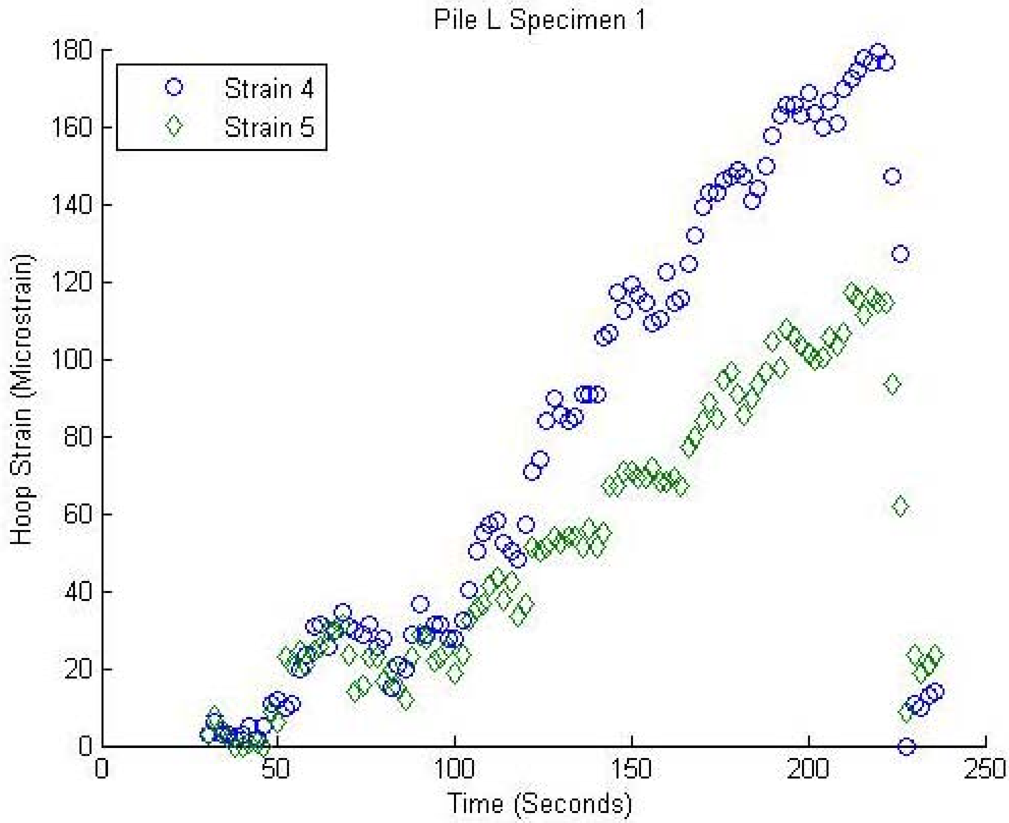
200
400
600
800
1000
1200
0
50
100
150
200
250


Pile L Specimen 1
Strain 4
Strain 5
Hoop Strain (Microstrain)
Time (Seconds)
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20
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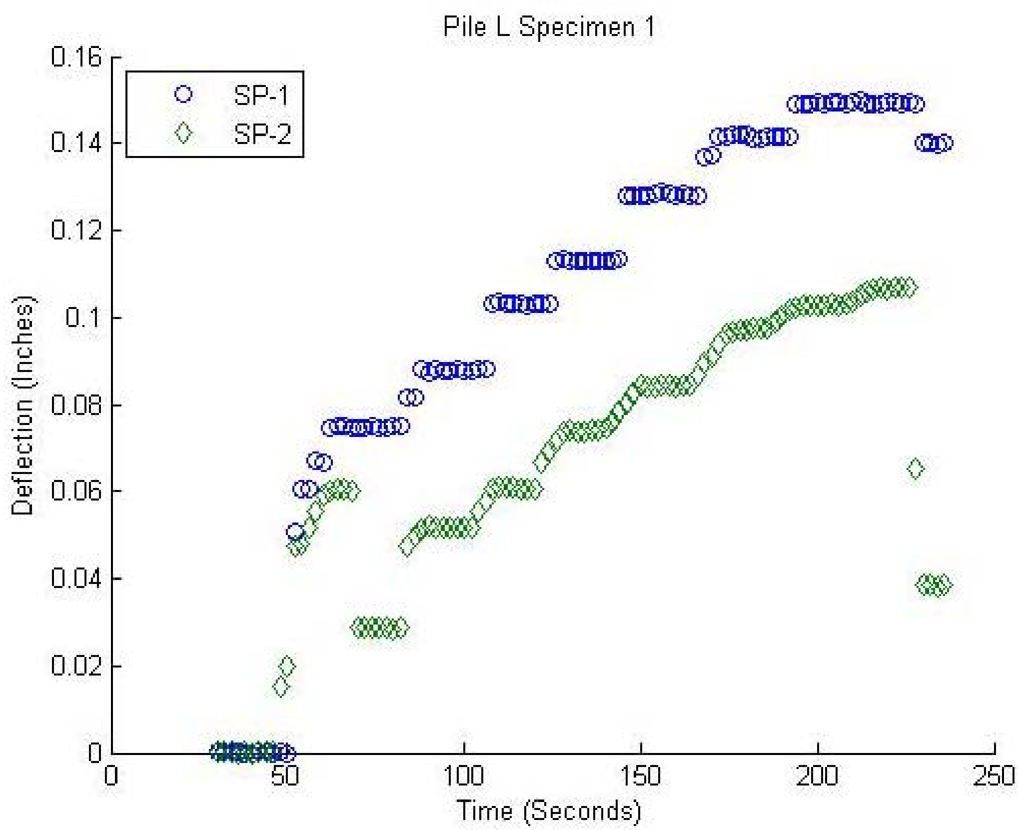
60
80
100
120
140
160
180
0
50
100
150
200
250


Pile L Specimen 1
SP-1
SP-2
Deflection (Inches)
Time (Seconds)
0
0.02
0.04
0.06
0.08
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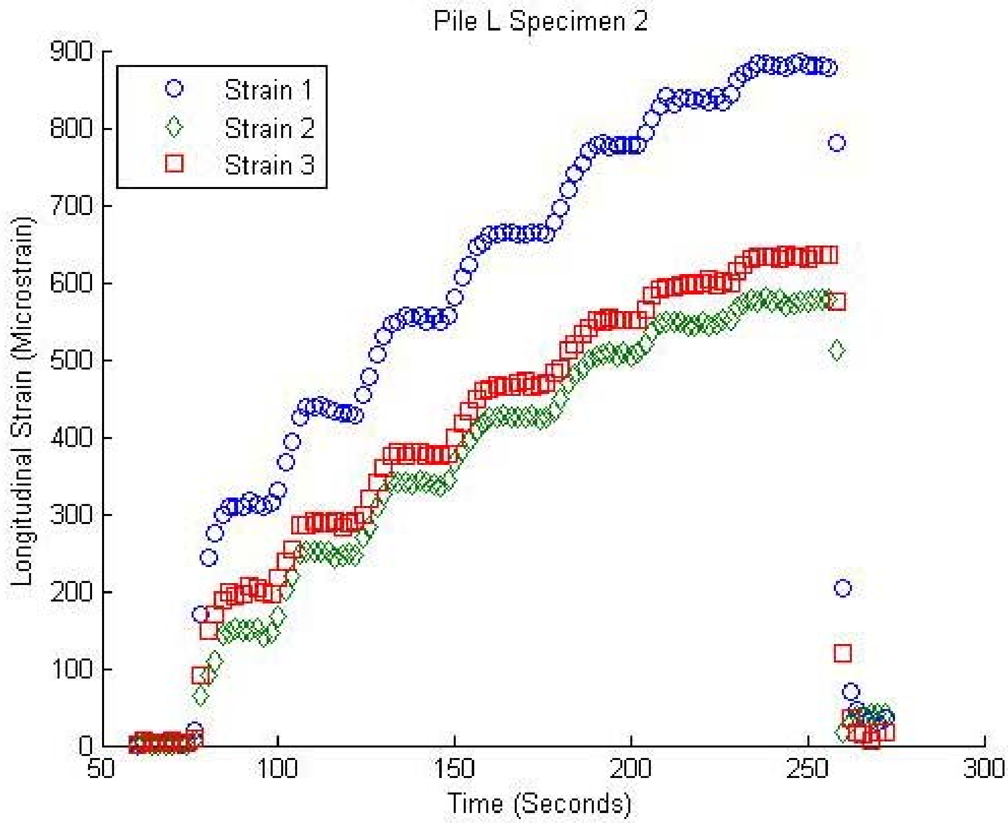
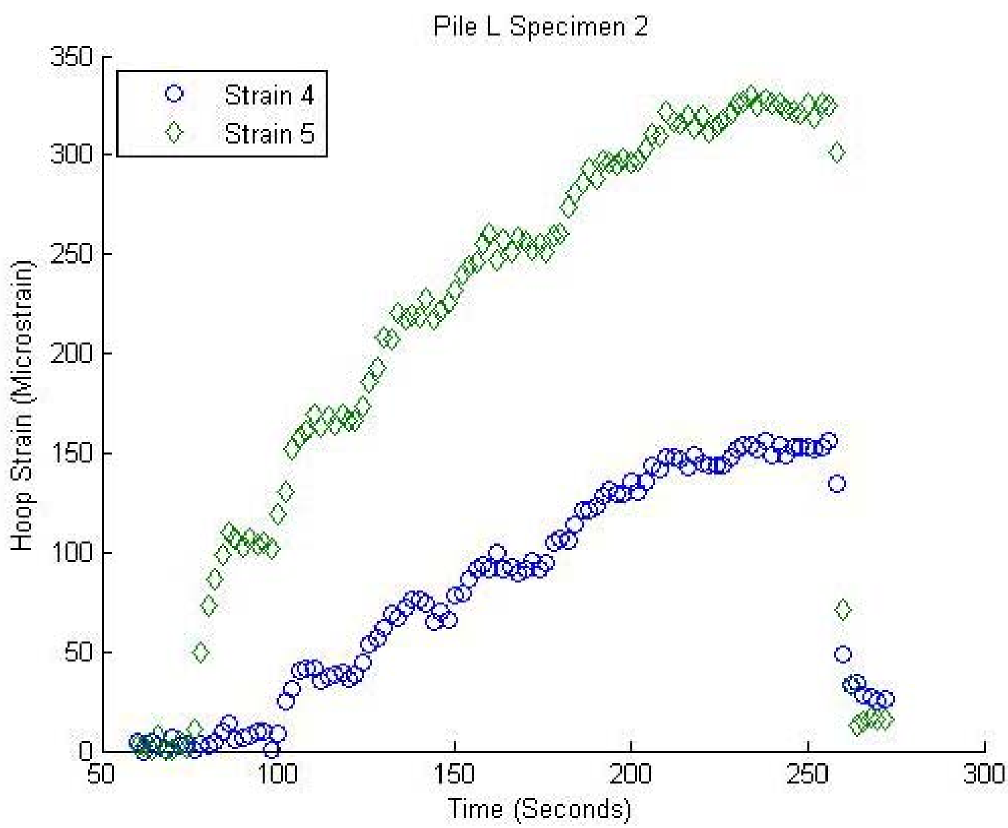
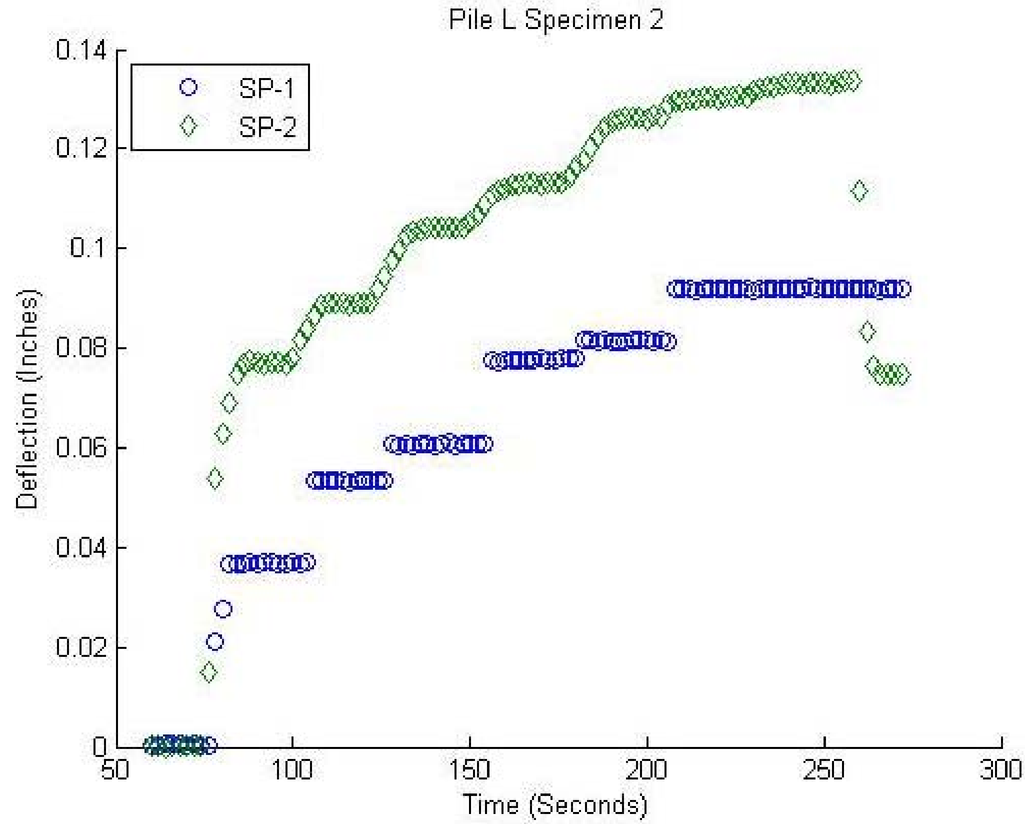
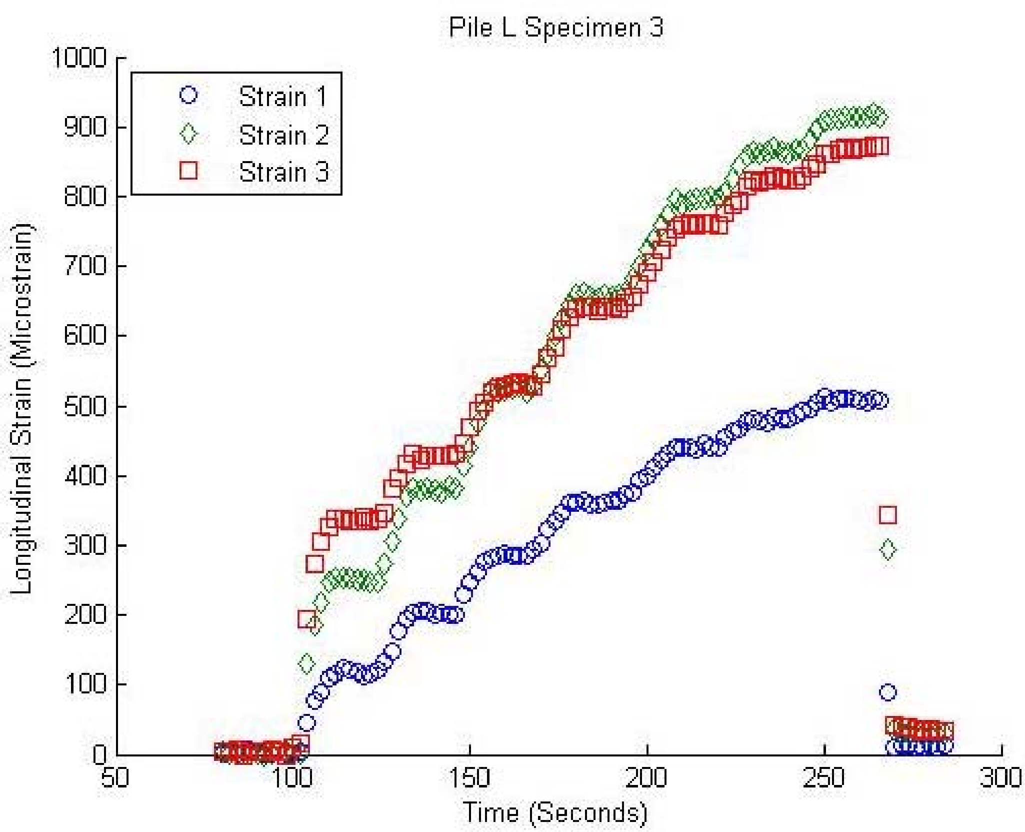
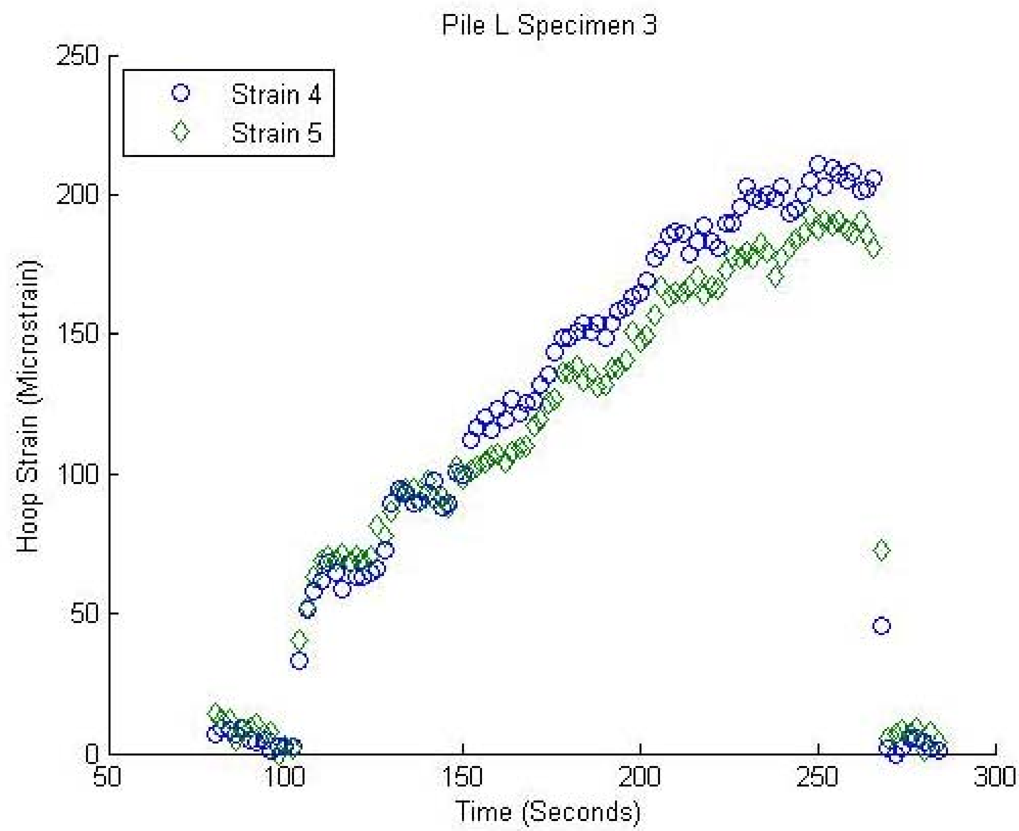
50
100
150
200
250

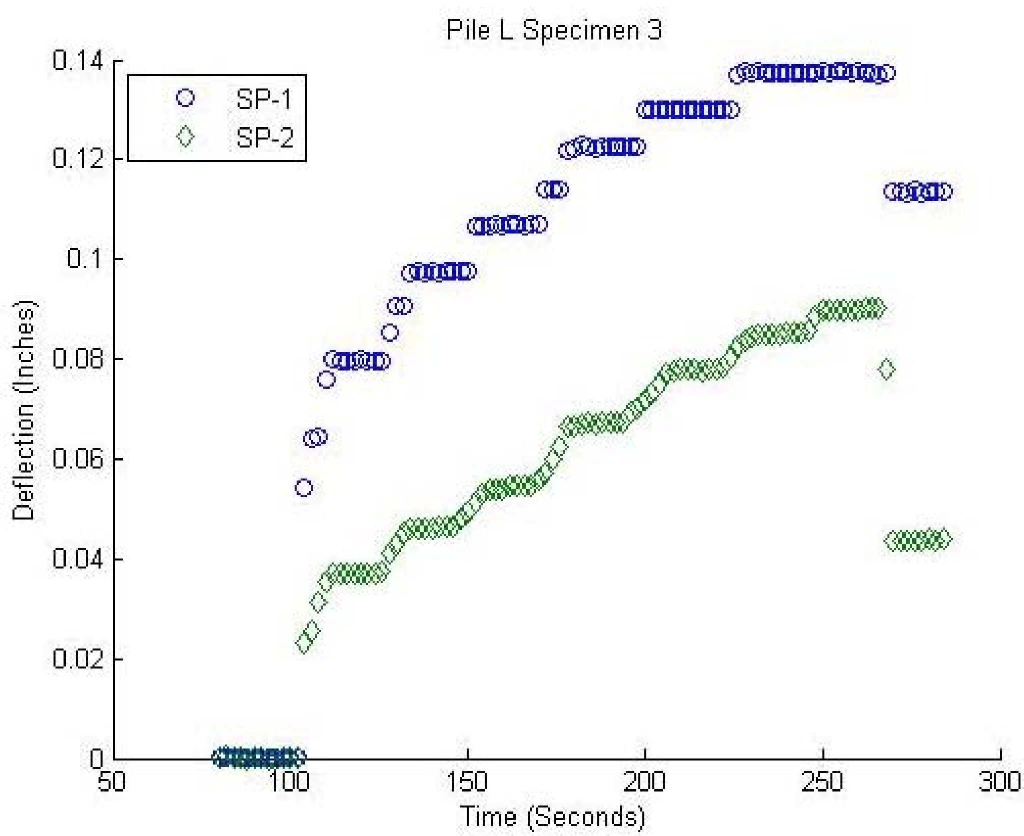

Pile L Specimen 2
Strain 1
Strain 2
Strain 3
Longitudinal Strain (Microstrain)
Time (Seconds)
0
100
200
300
400
500
600
700
800
900
50
100
150
200
250
300


Pile L Specimen 2
Strain 4
Strain 5
Hoop Strain (Microstrain)
Time (Seconds)
0
50
100
150
200
250
300
350
50
100
150
200
250
300

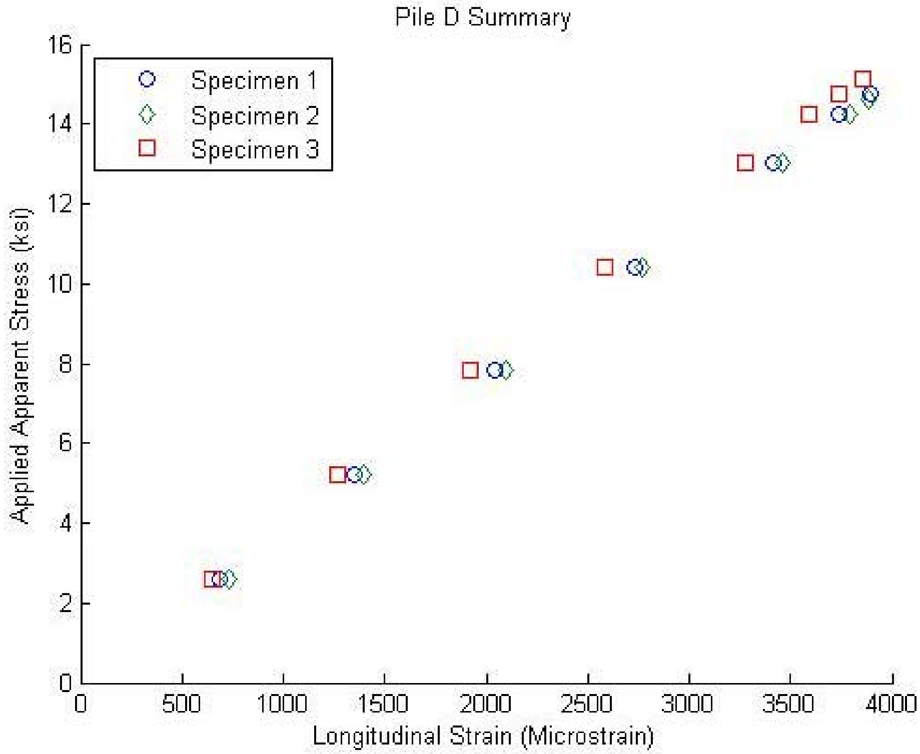

Pile L Specimen 2
SP-1
SP-2
Deflection (Inches)
Time (Seconds)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
50
100
150
200
250
300

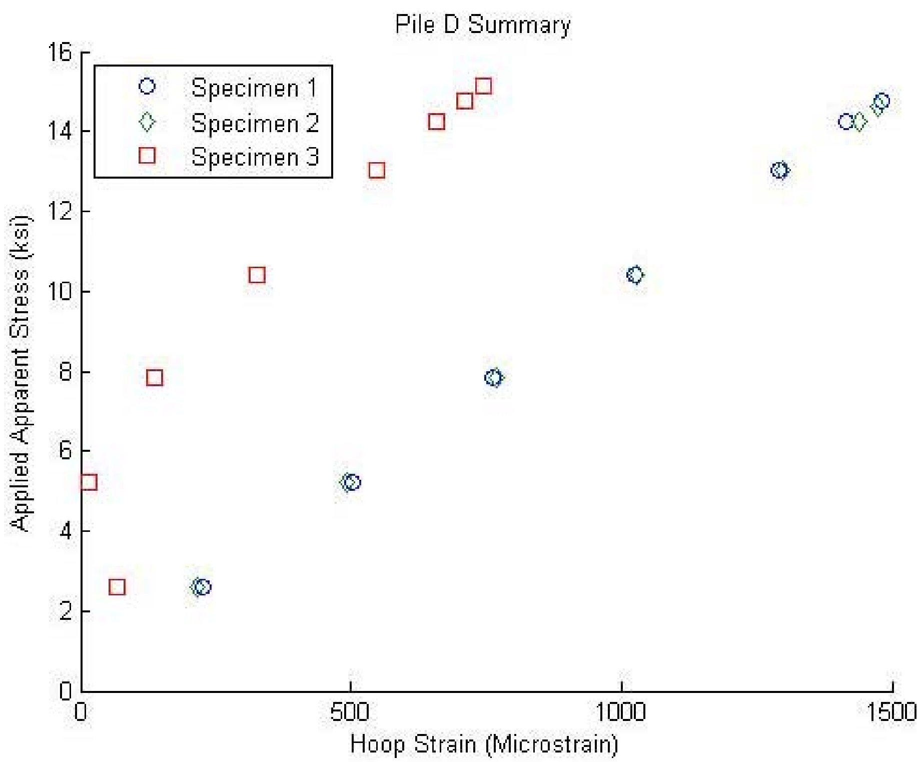

Pile L Specimen 3
Strain 1
Strain 2
Strain 3
Longitudinal Strain (Microstrain)
Time (Seconds)
1000
900
800
700
600
500
400
300
200
100
0
50
100
150
200
250
300

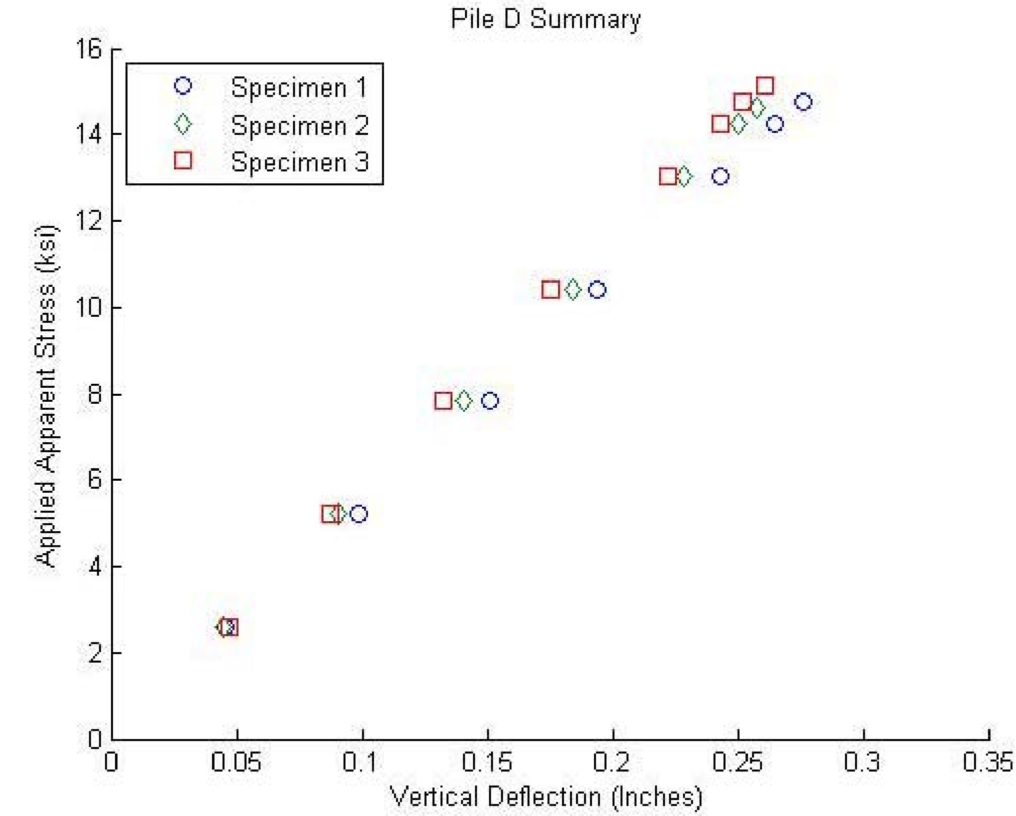

Pile L Specimen 3
Strain 4
Strain 5
Hoop Strain (Microstrain)
Time (Seconds)
0
50
100
150
200
250
300

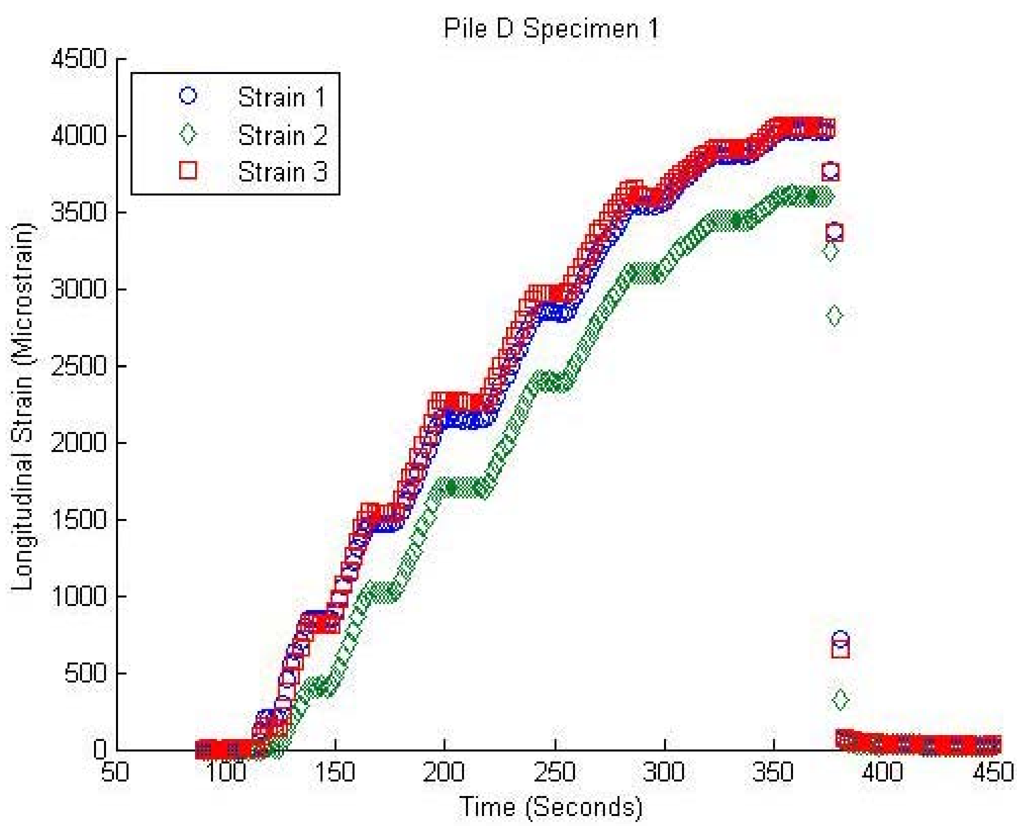

Pile L Specimen 3
SP-1
SP-2
Deflection (Inches)
Time (Seconds)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
50
100
150
200
250
300

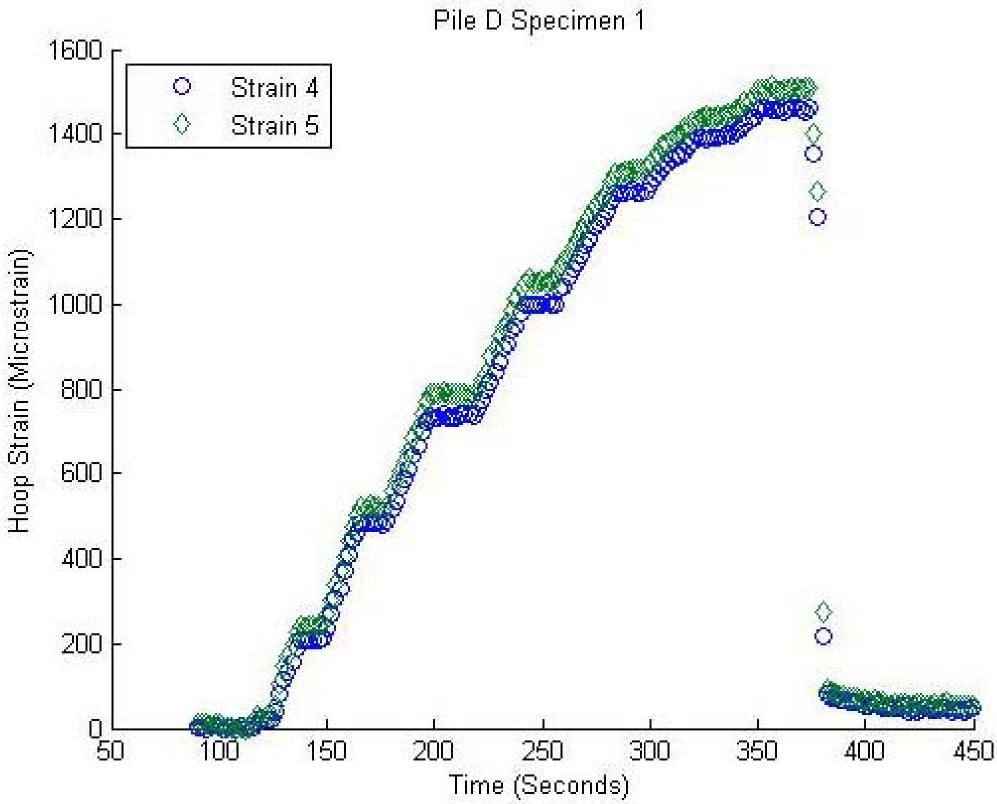
12. APPENDIX C: TEST RESULTS FOR PILE D

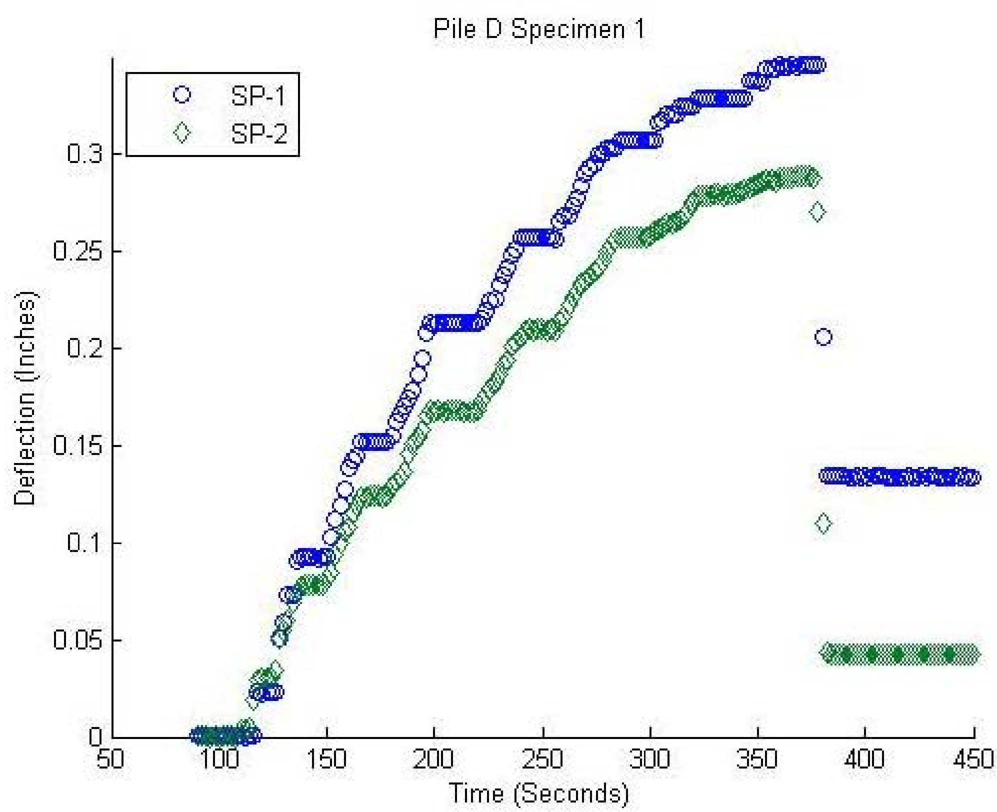


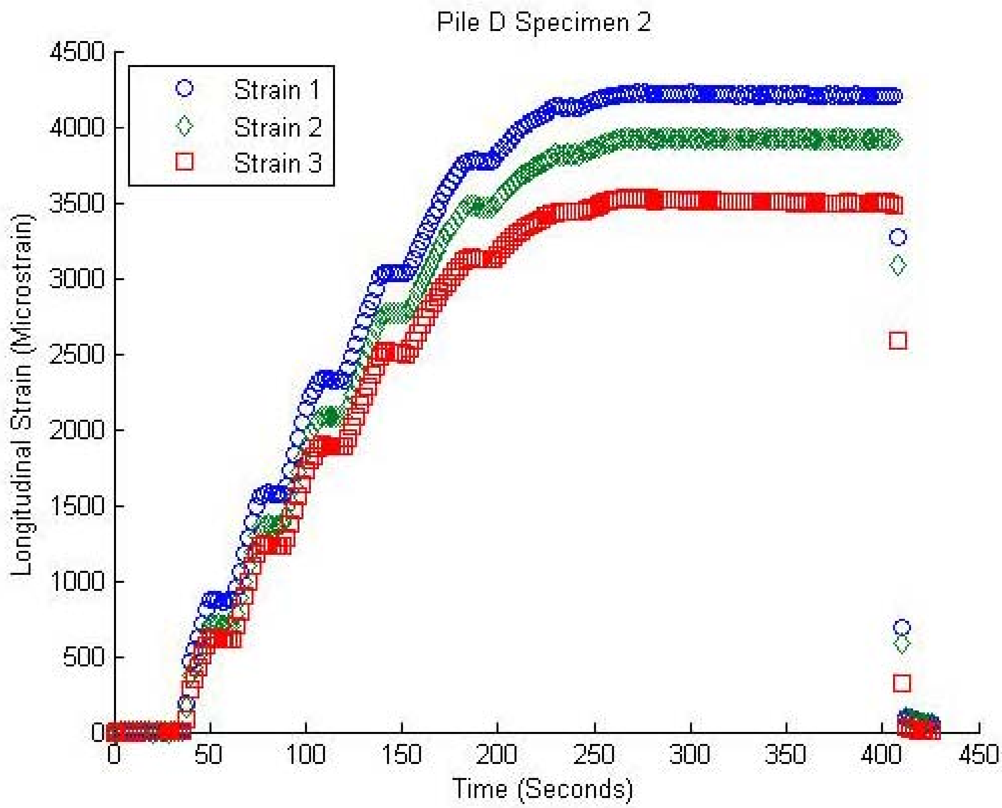


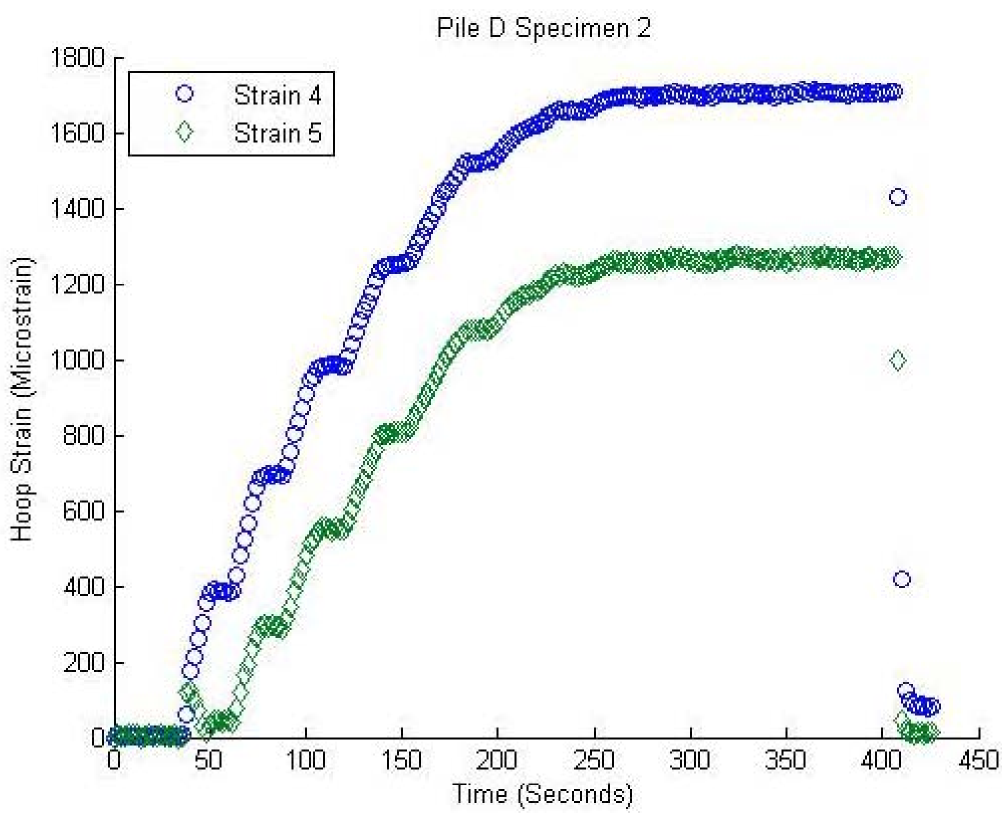

Pile D Summary
Specimen 1
Specimen 2
Specimen 3
Applied Apparent Stress (ksi)
Vertical Deflection (Inches)
0
2
4
6
8
10
12
14
16
0.05
0.1
0.15
0.2
0.25
0.3
0.35

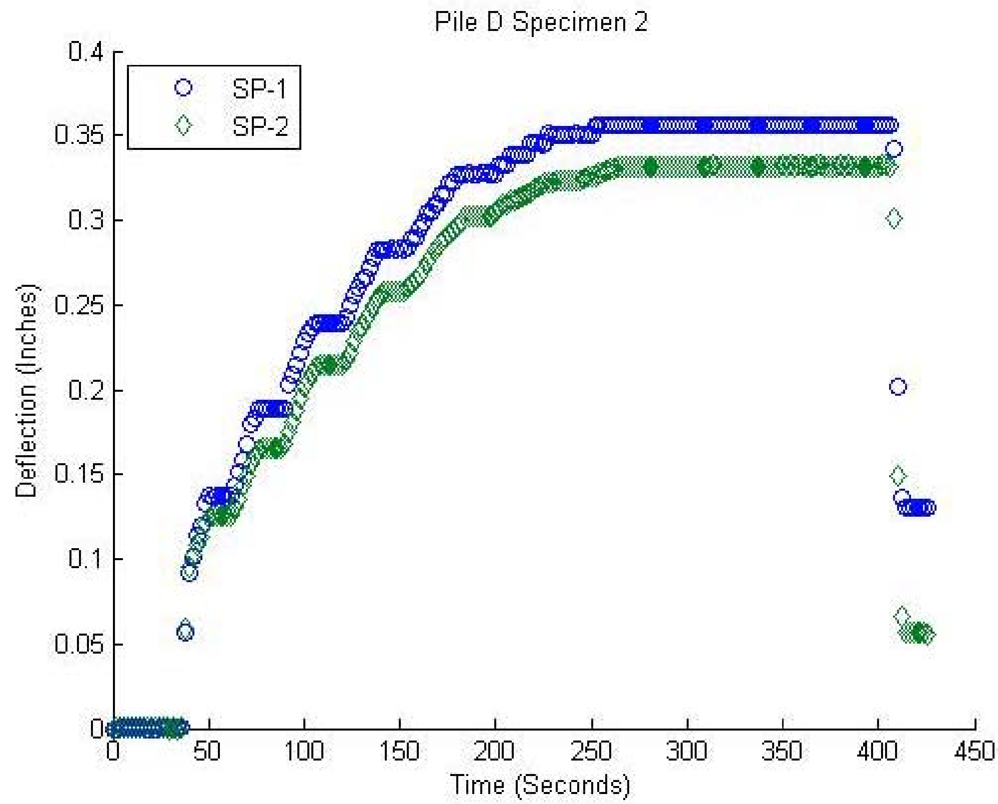

Pile D Specimen 1
Strain 1
Strain 2
Strain 3
Longitudinal Strain (Microstrain)
Time (Seconds)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
50
100
150
200
250
300
350
400
450

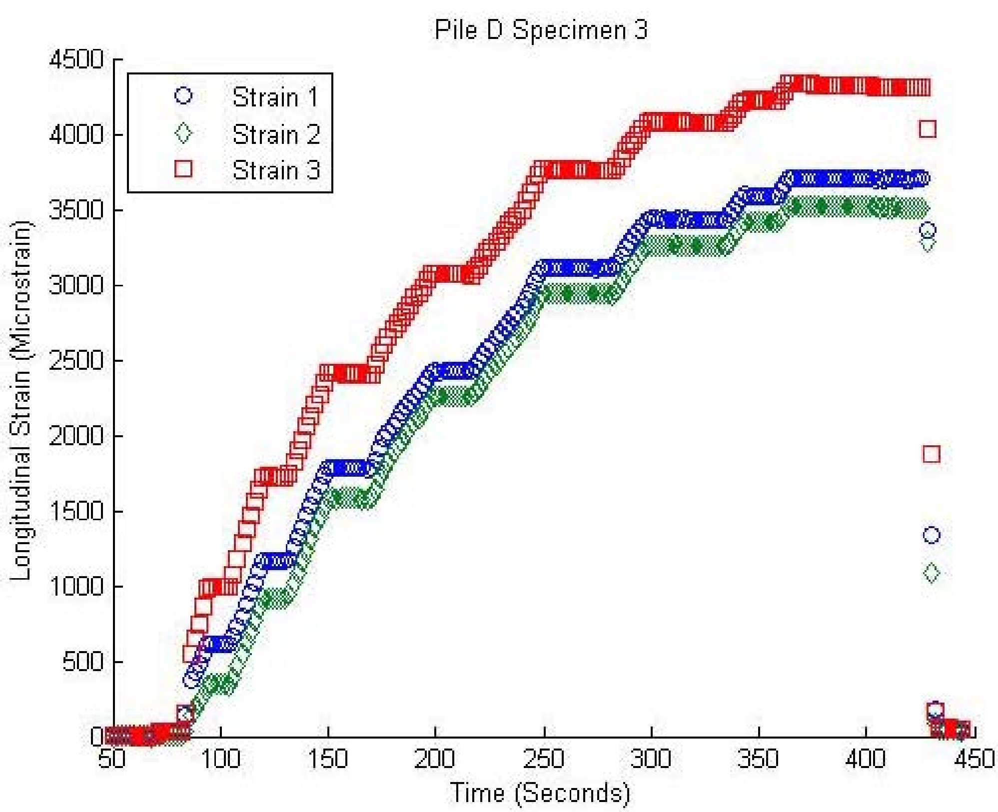

Pile D Specimen 1
Strain 4
Strain 5
Hoop Strain (Microstrain)
Time (Seconds)
0
200
400
600
800
1000
1200
1400
1600
50
100
150
200
250
300
350
400
450

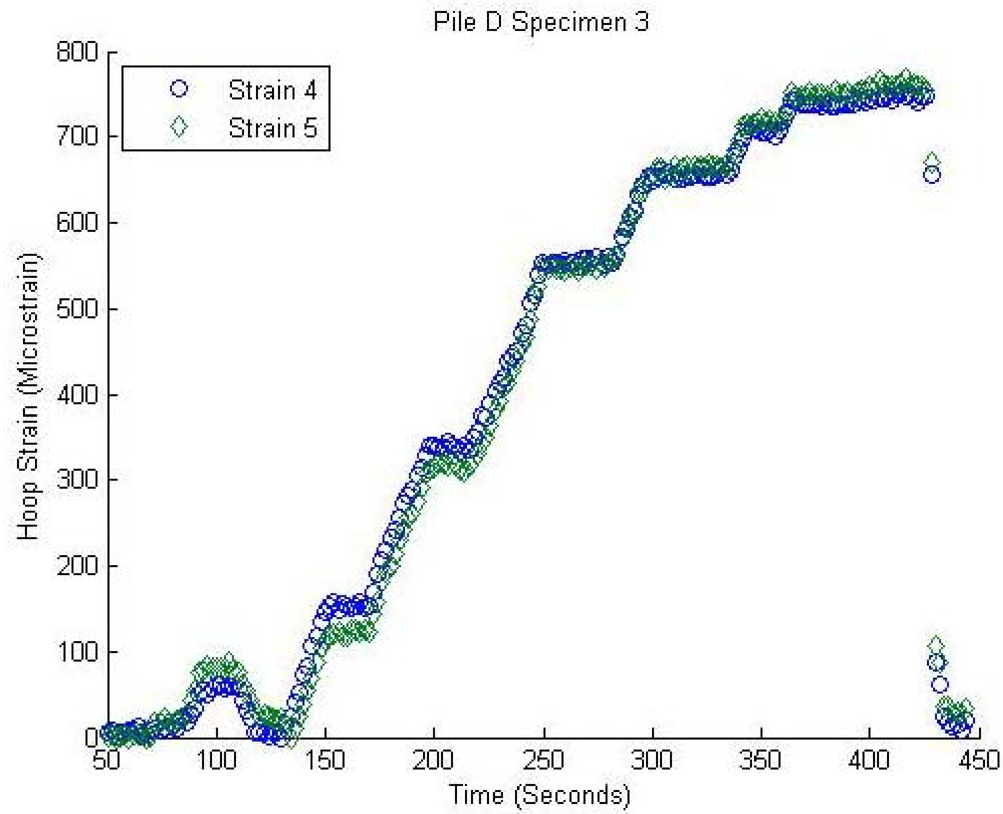

Pile D Specimen 1
SP-1
SP-2
Deflection (Inches)
Time (Seconds)
0
0.05
0.1
0.15
0.2
0.25
0.3
50
100
150
200
250
300
350
400
450

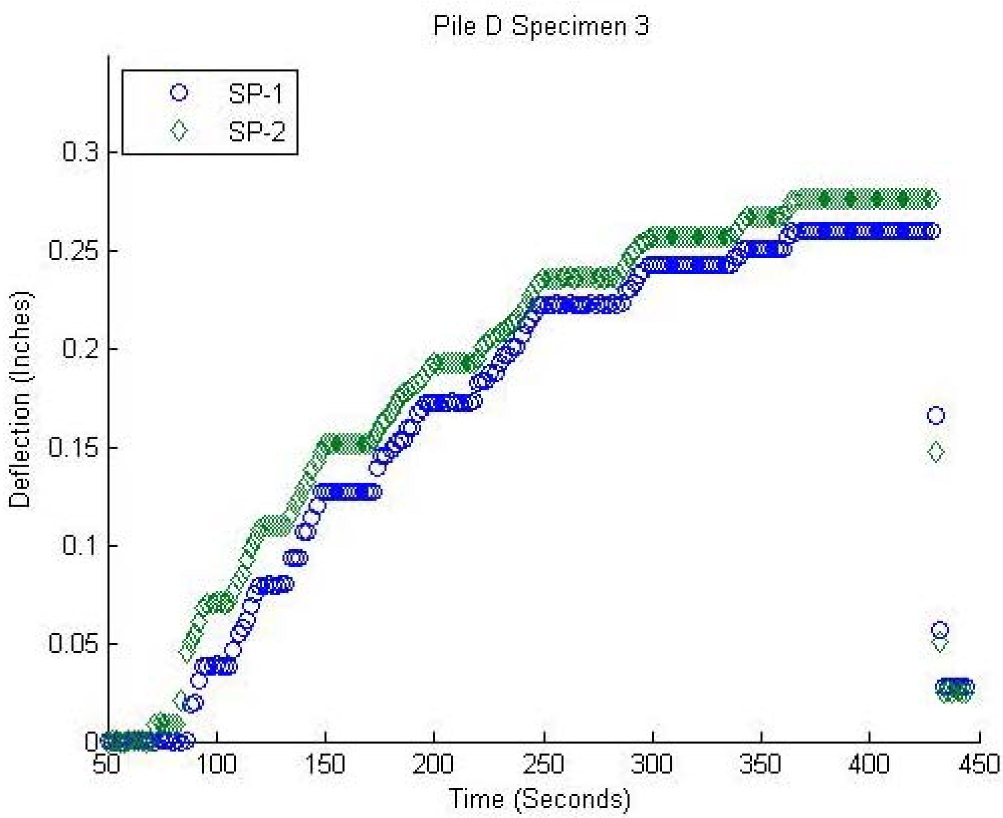

Pile D Specimen 2
Strain 1
Strain 2
Strain 3
Longitudinal Strain (Microstrain)
Time (Seconds)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
0
50
100
150
200
250
300
350
400
450


Pile D Specimen 2
Strain 4
Strain 5
Hoop Strain (Microstrain)
Time (Seconds)
0
200
400
600
800
1000
1200
1400
1600
1800
0
50
100
150
200
250
300
350
400
450

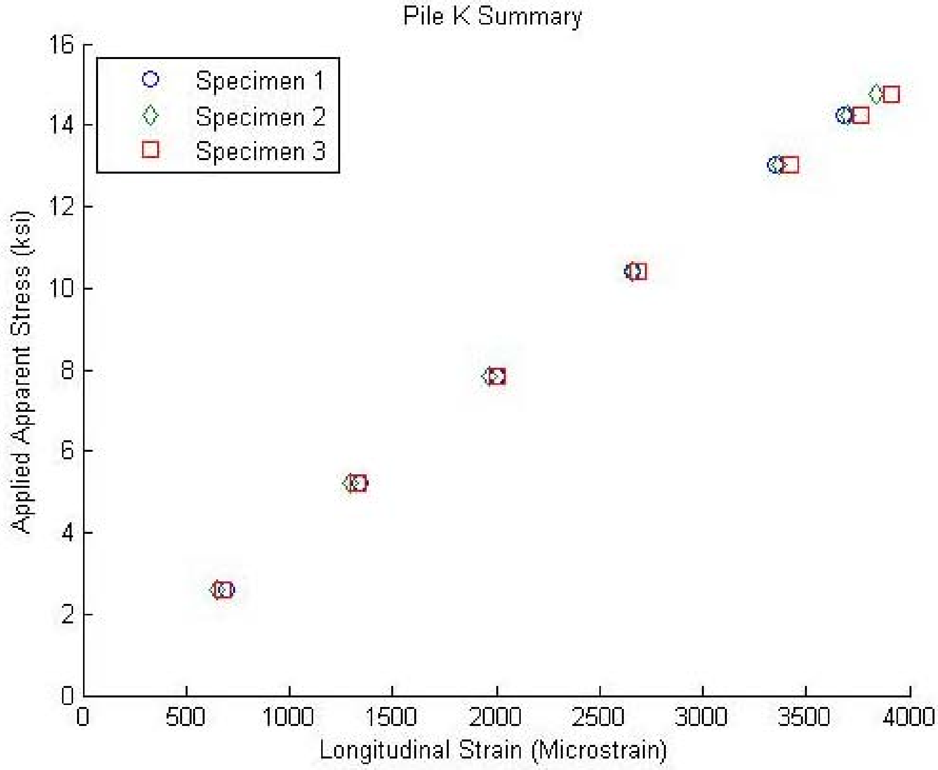

Pile D Specimen 2
SP-1
SP-2
Deflection (Inches)
Time (Seconds)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0
50
100
150
200
250
300
350
400
450

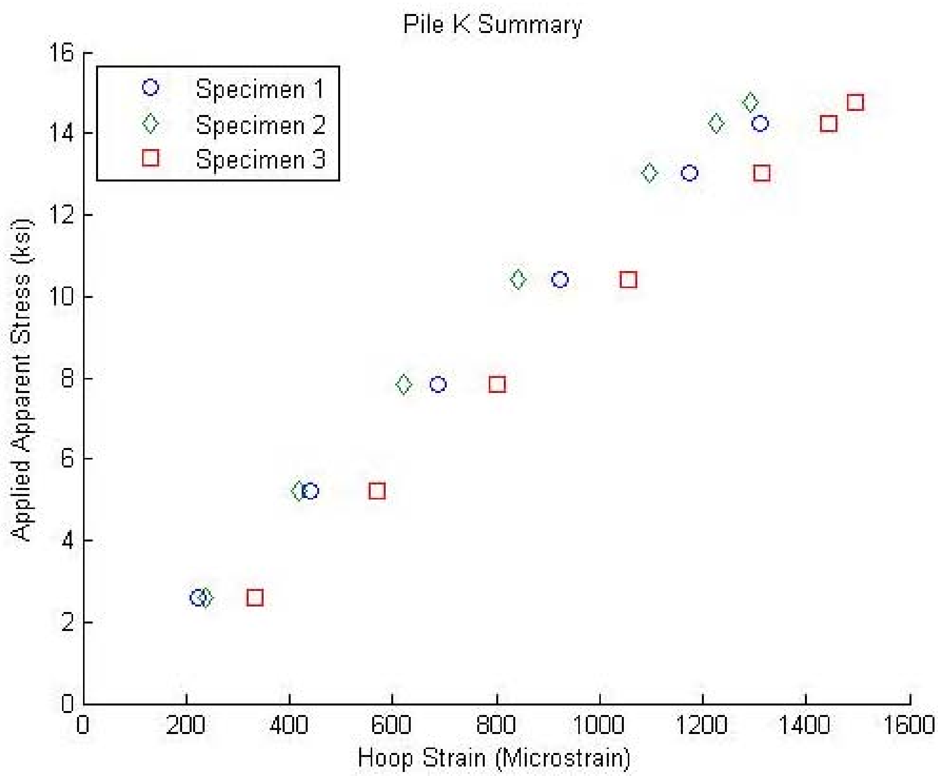

Pile D Specimen 3
Strain 1
Strain 2
Strain 3
Longitudinal Strain (Microstrain)
Time (Seconds)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
50
100
150
200
250
300
350
400
450

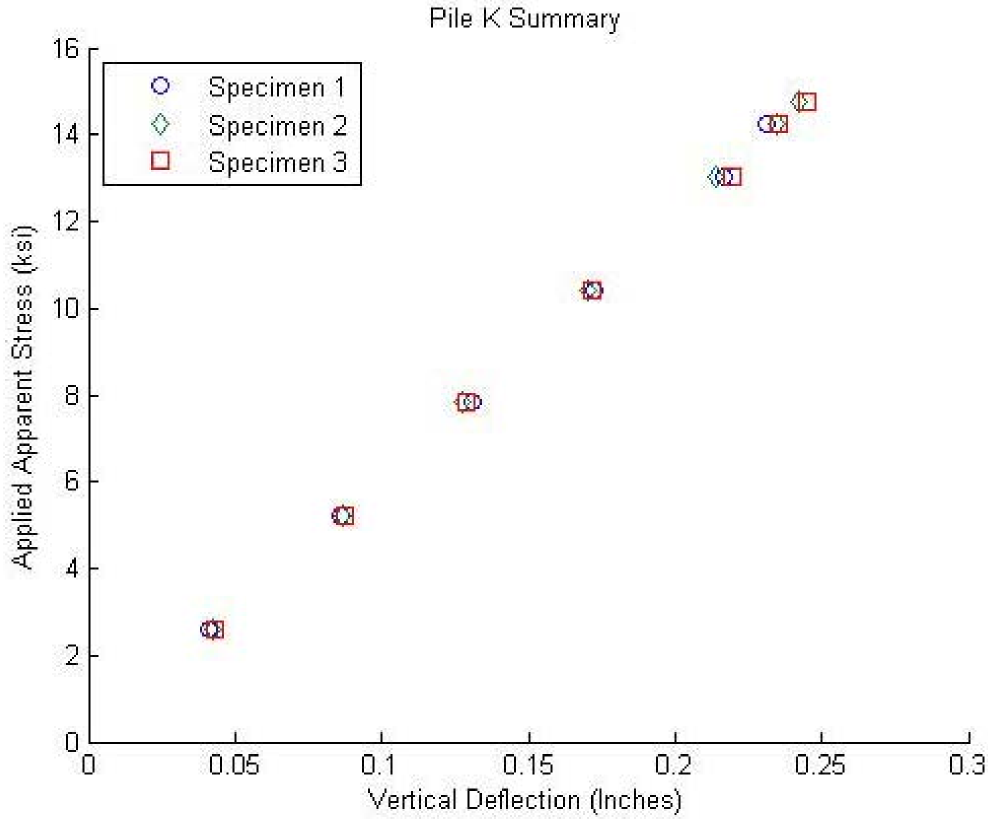

Pile D Specimen 3
Strain 4
Strain 5
Hoop Strain (Microstrain)
Time (Seconds)
0
100
200
300
400
500
600
700
800
50
100
150
200
250
300
350
400
450

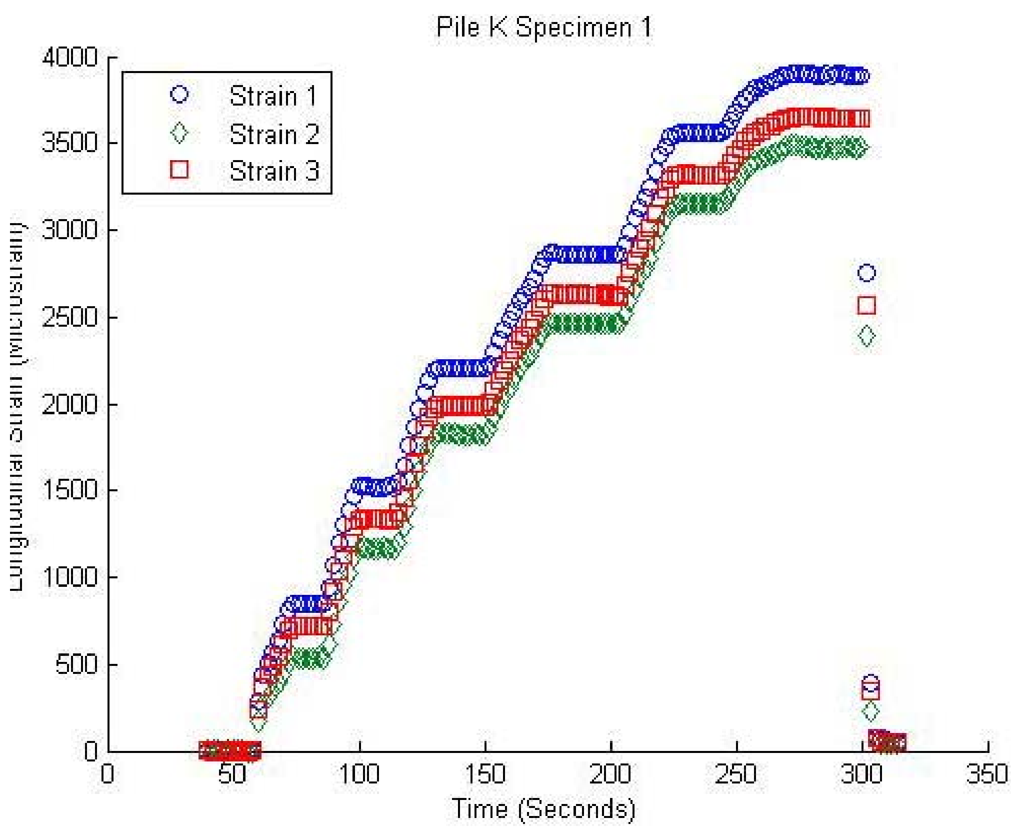

Pile D Specimen 3
SP-1
SP-2
Deflection (Inches)
Time (Seconds)
0
0.05
0.1
0.15
0.2
0.25
0.3
50
100
150
200
250
300
350
400
450

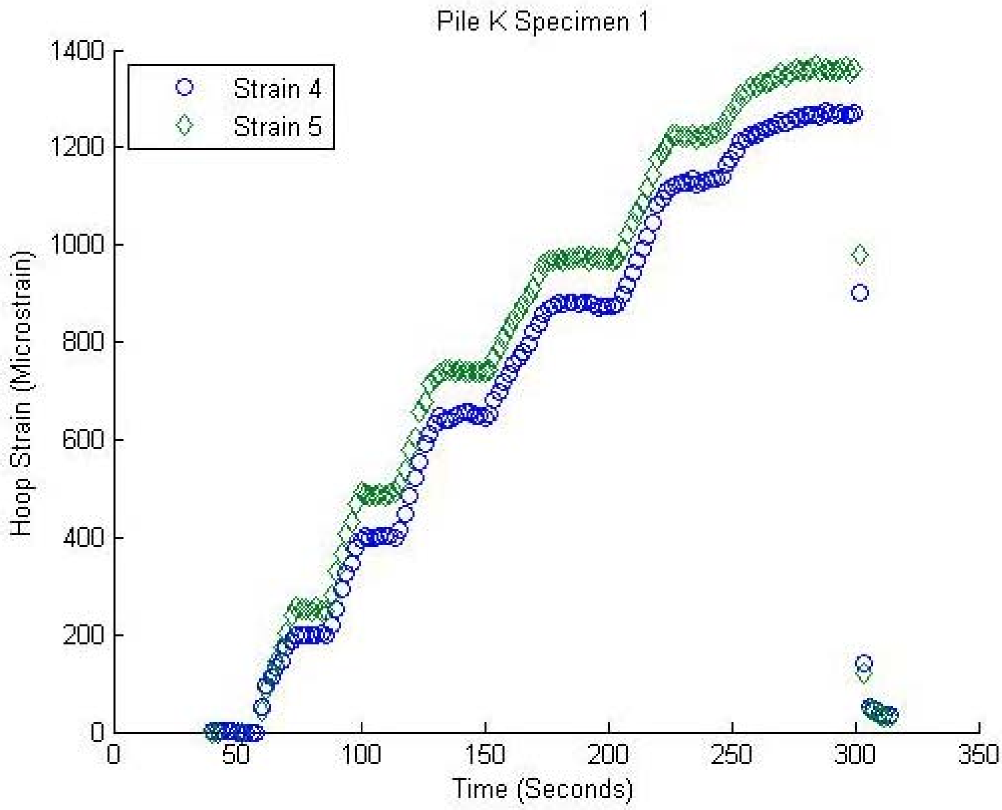
13. APPENDIX D: TEST RESULTS FOR PILE K

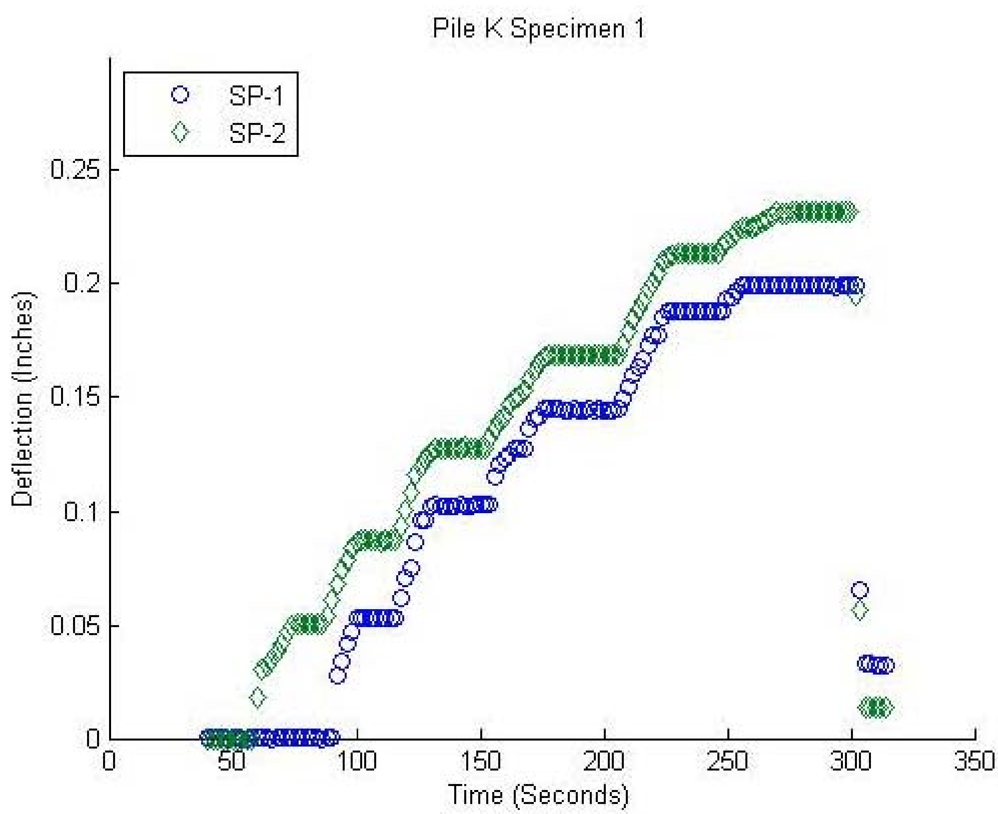


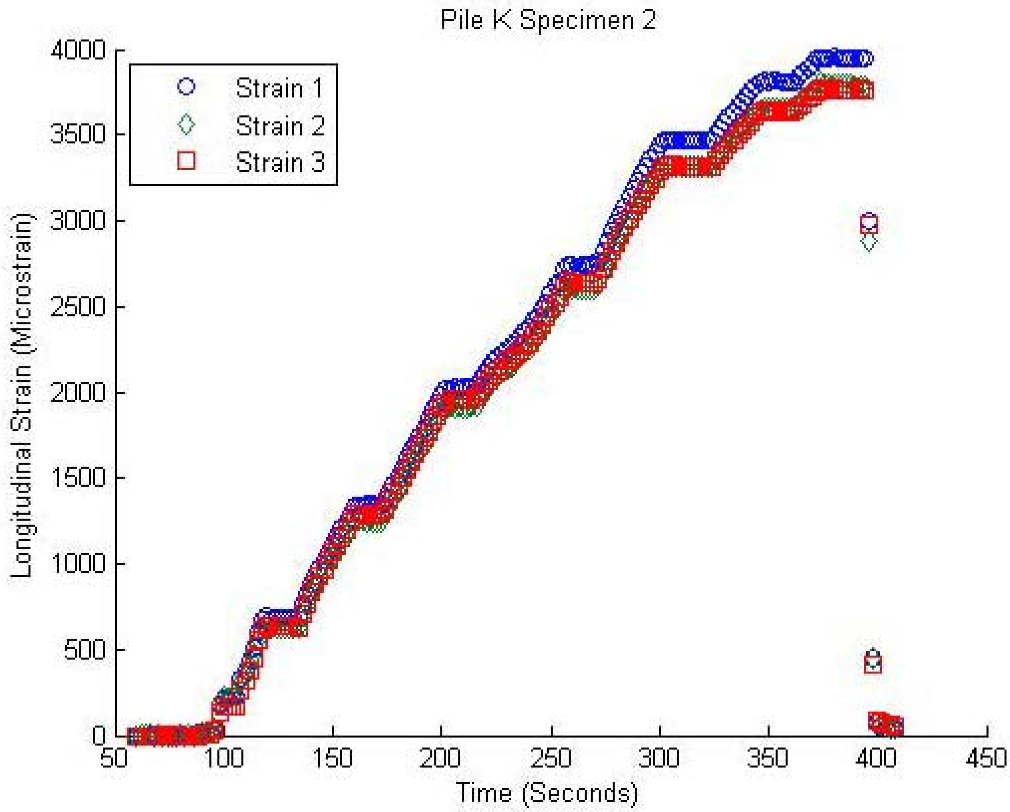


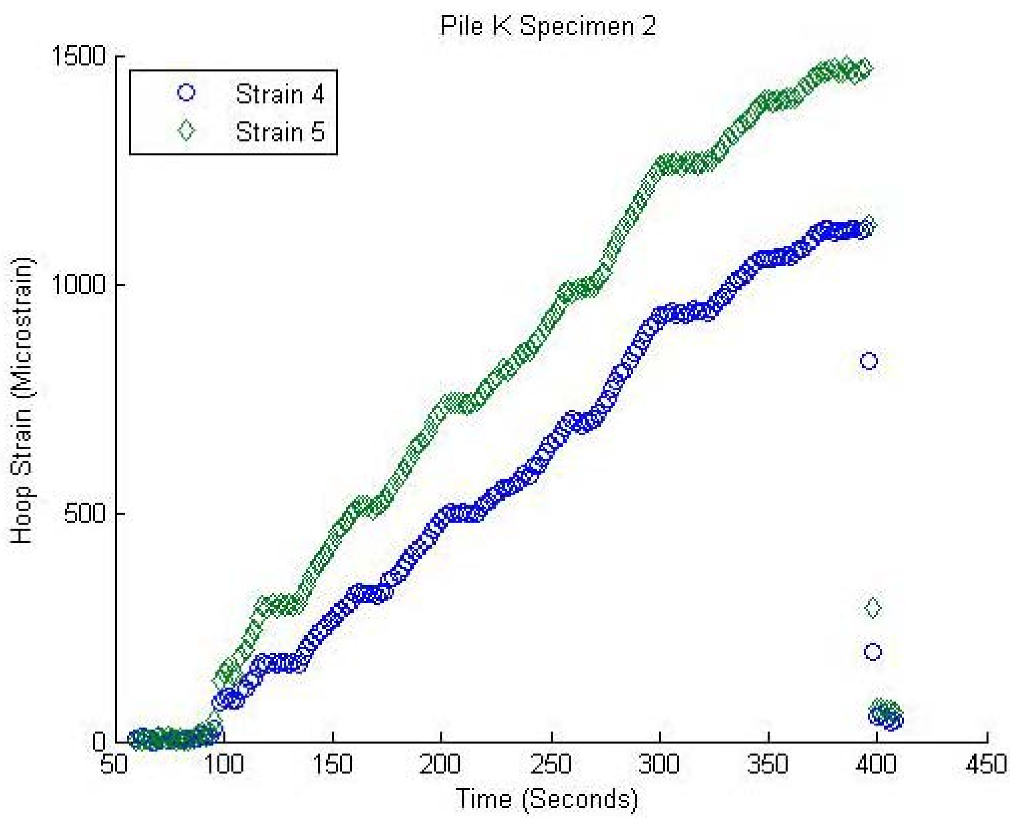

Pile K Summary
Specimen 1
Specimen 2
Specimen 3
Applied Apparent Stress (ksi)
Vertical Deflection (Inches)
0
2
4
6
8
10
12
14
16
0
0.05
0.1
0.15
0.2
0.25
0.3

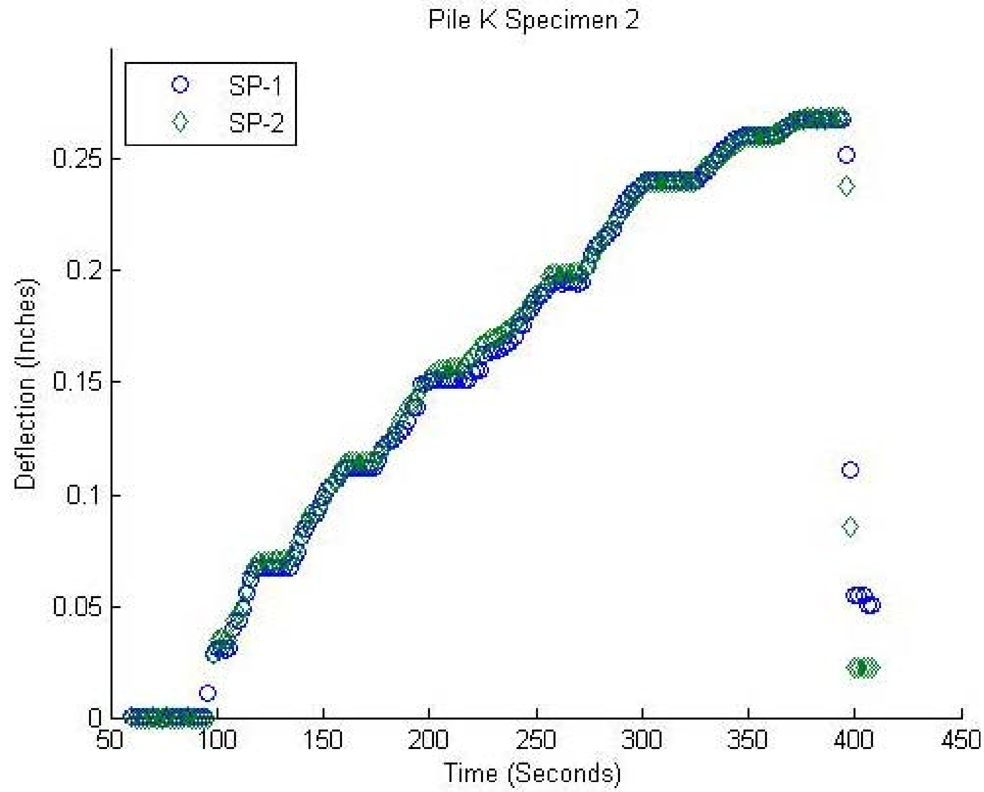

Pile K Specimen 1
Strain 1
Strain 2
Strain 3
Time (Seconds)
0
500
1000
1500
2000
2500
3000
3500
4000
0
50
100
150
200
250
300
350

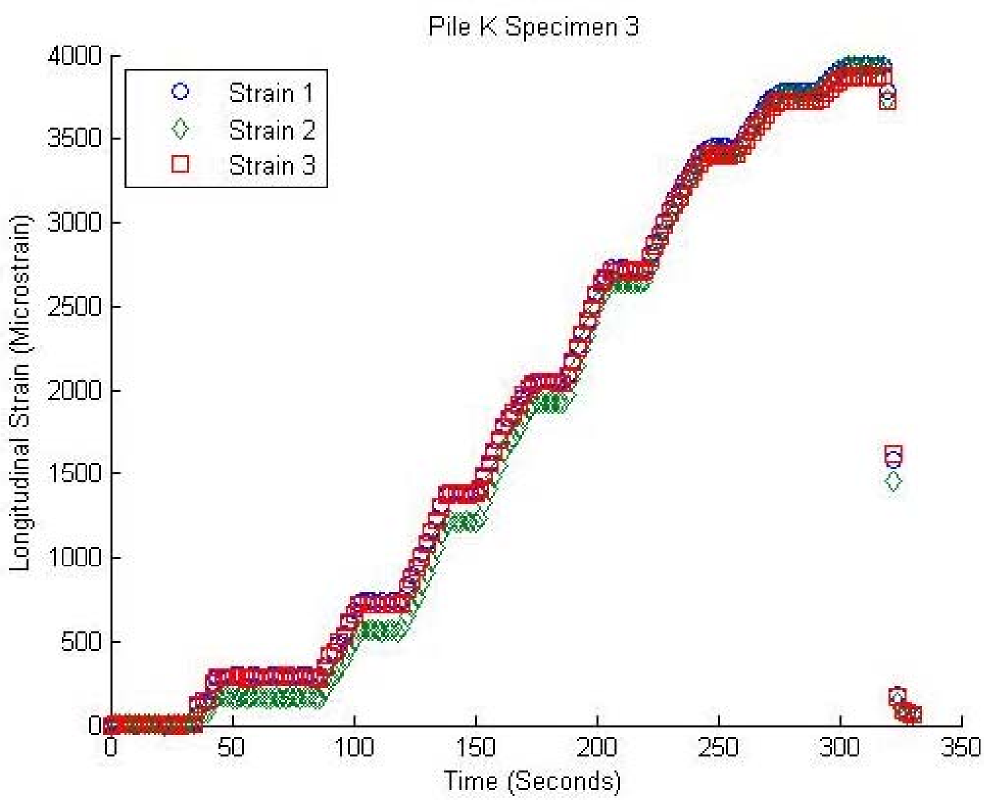

Pile K Specimen 1
Strain 4
Strain 5
Hoop Strain (Microstrain)
Time (Seconds)
0
200
400
600
800
1000
1200
1400
0
50
100
150
200
250
300
350

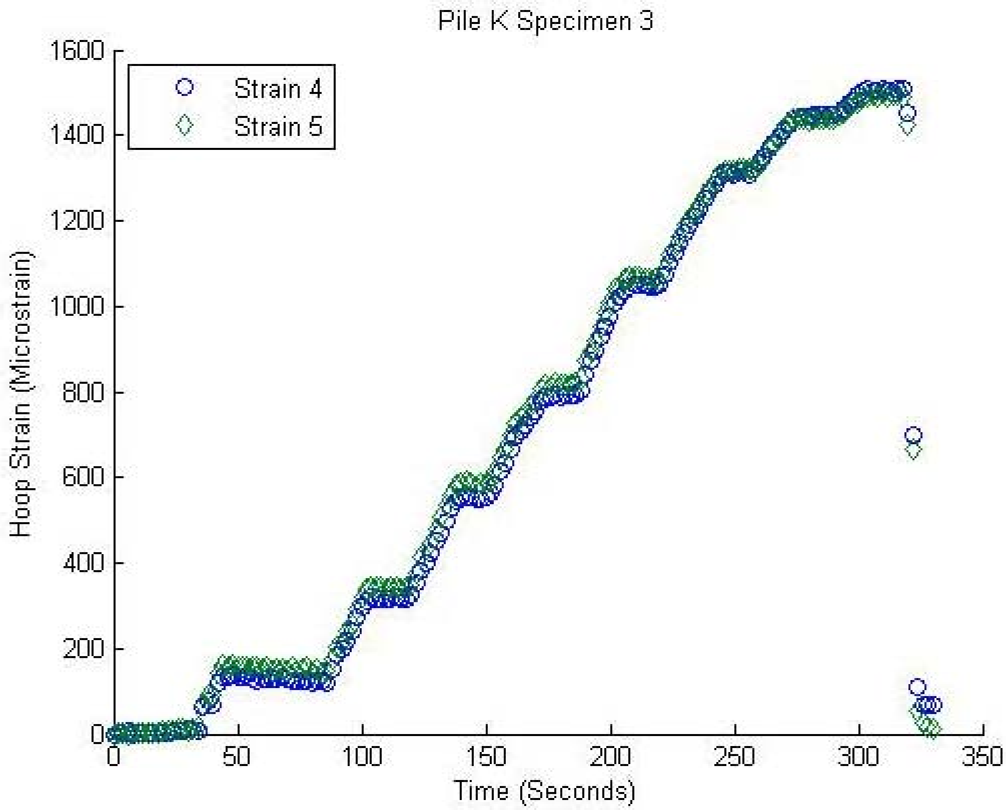

Pile K Specimen 1
SP-1
SP-2
Deflection (Inches)
Time (Seconds)
0
0.05
0.1
0.15
0.2
0.25
0
50
100
150
200
250
300
350

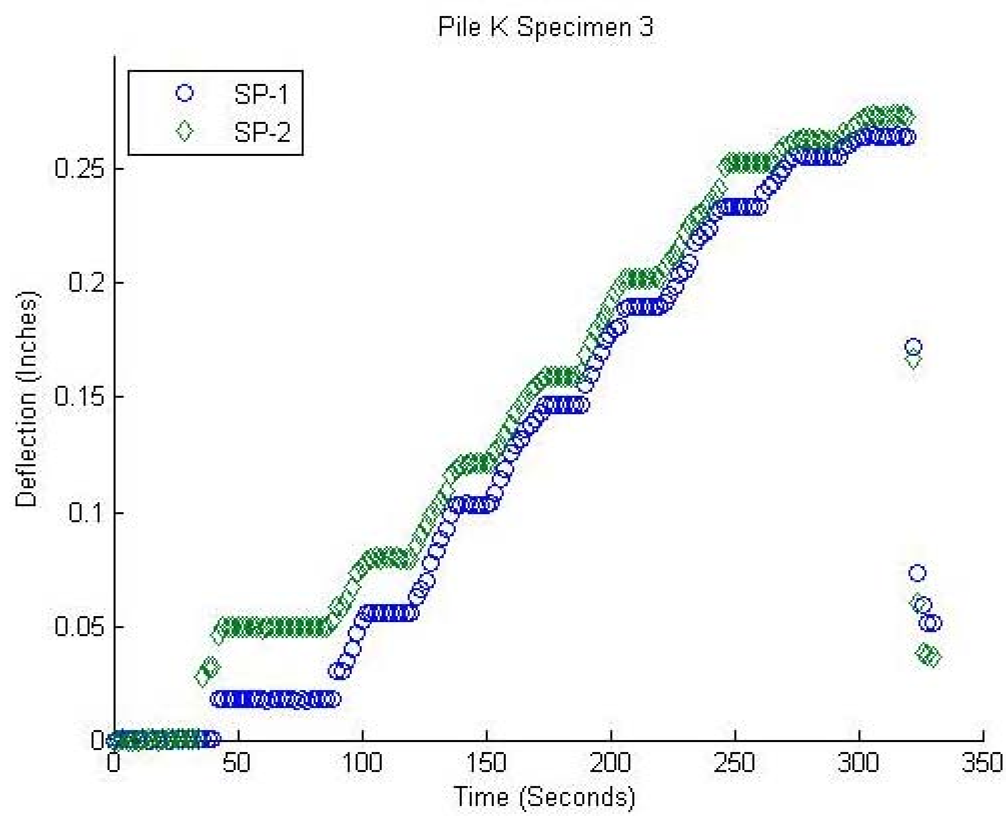

Pile K Specimen 2
Strain 1
Strain 2
Strain 3
Longitudinal Strain (Microstrain)
Time (Seconds)
4000
3500
3000
2500
2000
1500
1000
500
0
50
100
150
200
250
300
350
400
450


Pile K Specimen 2
Strain 4
Strain 5
Hoop Strain (Microstrain)
Time (Seconds)
1500
1000
500
0
50
100
150
200
250
300
350
400
450


Pile K Specimen 2
SP-1
SP-2
Deflection (Inches)
Time (Seconds)
0
0.05
0.1
0.15
0.2
0.25
50
100
150
200
250
300
350
400
450


Pile K Specimen 3
Strain 1
Strain 2
Strain 3
Longitudinal Strain (Microstrain)
Time (Seconds)
0
500
1000
1500
2000
2500
3000
3500
4000
0
50
100
150
200
250
300
350


Pile K Specimen 3
Strain 4
Strain 5
Hoop Strain (Microstrain)
Time (Seconds)
0
200
400
600
800
1000
1200
1400
1600
0
50
100
150
200
250
300
350


Pile K Specimen 3
SP-1
SP-2
Deflection (Inches)
Time (Seconds)
0
0.05
0.1
0.15
0.2
0.25
0
50
100
150
200
250
300
350