

ASSESSING THE EFFECTS OF VIBRATORY LOADING ON PIPELINES USING ANALYSIS AND MONITORING TECHNIQUES

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ABSTRACT

This paper provides the methods and results associated with an engineering assessment for a project involving pile driving adjacent to an active 6-inch (152 mm) nominal diameter gas pipeline. The pile driving was associated with the expansion of the I-95 Highway located in Daytona Beach, Florida. The work involved analysis, metallurgical field evaluation, and measurement of strain and acceleration in the pipe during the pile driving. The analysis involved using finite element methods to predict stresses in the pipe using acceleration loads provided during a previous pile driving exercise. Using a range of soil stiffness values, the calculated bending stresses in the pipeline ranged from 50 to 2,000 psi (0.3 to 13.8 MPa). Even with the most compliant soils, the stress was relatively low compared to the hoop stress created by an internal pressure of 500 psi (3.4 MPa). The metallurgical field investigation involved careful inspection of the pipe quality, including field replication and determining the carbon content of one weld. The strain measurements indicated that the stress levels in the pipe were below design stress limits and that the short-term pile driving loads did not inflict serious injury to the line.

Findings of the investigation indicated that the pipe had been well-maintained over its 40 year life and that no measurable corrosion was present. This project demonstrates the benefits derived in using a range of engineering disciplines and capabilities to ensure safety in conducting potentially-damaging activities adjacent to active gas pipelines.

INTRODUCTION

The tasks performed in assessing the effects of vibratory loading involved three distinct phases of work:

- Stress analysis of pipeline using finite element methods
- Field evaluation of actual pipeline using metallurgical techniques
- In situ evaluation of strain in the pipe during pile driving.

The work effort was progressive in the sense that each phase of the program built upon lessons learned in the previous phase of work. Had the analysis and field evaluation efforts not provided positive indications about the quality of the pipeline, installing strain gages and recording high speed data during the actual driving of a pile adjacent to the active gas pipeline would not have taken place.

The following sections of the paper provide specific information on the three phases of the project. *A Recommendations for Industry*

section has also been prepared that can be used by the pipeline industry when performing vibratory activities adjacent to pipelines.

FINITE ELEMENT ANALYSIS

A stress analysis of the pipeline using finite element methods was performed to determine stresses generated in the gas pipeline system considering loads developed by pile driving. The objective of the analysis was to consider seismic-type acceleration loads developed by pile driving and their impact on stresses in the pipeline. The beam finite element model was constructed to include soil boundary conditions, internal pressure, and localized acceleration loads.

Modeling Techniques

A finite element model was constructed and analyzed using the ABAQUS finite element program. The pipeline was modeled using beam elements that permitted internal pressure loading as well as integration of acceleration loads. A total length of 100 feet (30.5 meters) was modeled and acceleration loads were applied to elements located at the center of this span. Although acceleration loads were provided from previous field data [1] that ranged from 0.1 up to 0.9 g's, a worst case condition of 1.0 g loading was modeled.

In conducting the analysis, a bounded approach was taken to address the effects of the following variables:

- Soil stiffness ranging from 0.5 lbs/in per linear inch (0.003 N/mm per linear mm) up to 500 lbs/in per linear inch (3.4 N/mm per linear mm)
- Zone of acceleration (ranged from centerline of the pile out to a minimum of +/-2 feet (0.61 meters) and out to a maximum of +/-20 feet (6.10 meters)
- Acceleration of 1.0 g and internal pressure of 700 psi (4.8 MPa) for all load cases

The pipe geometry and material properties are 6.625-in x 0.188-in (168.3 mm x 4.8 mm), Grade B (35,000 psi (241.3 MPa) specified minimum yield strength). Soil stiffness was assumed to act in all directions (x, y, and z). The units for soil stiffness were modeled as lbs/inch per linear inch. Clay-type soils have effective stiffness values on the order of 1,000 lbs/in per linear inch (6.9 N/mm per linear mm) [2]. The loosely-compacted sand-type soil associated with the problem at hand is assumed to a stiffness of 500 lbs/in per linear inch (3.4 N/mm/ per linear mm), although the range of stiffness values for

compacted sand are between 5,000 and 50,000 lbs/in per linear inch (34.4 and 343.9 N/mm per linear mm) [2]. Soils that have less stiffness provide reduced resistance to external loads and will consequently permit pipelines to be subjected to higher loads that result in elevated stresses.

The concept in bounding the problem is that any lack of certainty in the assumptions will not result in failing to adequately capture stresses that might result from the actual load state. As will be demonstrated, even with extremely low soil stiffness assumptions, the bending stresses in the model are low. Issues not addressed in the analysis were wall losses due to corrosion, strength of welds, or metallurgical issues such as hydrogen embrittlement.

Modeling Results

The bounded approach in this study permits us to address a range of possible stresses. For each of the possible boundary and loading conditions, maximum displacements and accelerations were calculated.

Table 1 provides a summary of the displacement and stress results based upon the selected loading matrix. As noted in **Table 1**, the worst case scenario is when the largest acceleration zone is considered with the least stiff soil conditions. It is highly unlikely that soil stiffness values as low as this actually exist; however, the results clearly demonstrate that even with such assumptions the bending stresses are relatively low. The 0.001-inch (0.03 mm) and 0.002-inch (0.05 mm) displacements correspond to displacement measurements obtained during prior pile driving exercises [1].

The analysis results clearly demonstrated that the acceleration loads do not generate stresses that pose imminent danger to the gas pipeline. The results presented are based upon extreme boundary and loading conditions. A case in point is the wide variations that were considered for the soil stiffness (i.e. three orders of magnitude). Even with an internal pressure of 700 psi (4.8 MPa), the combined stress intensity in the pipe including bending stresses due to acceleration loads is less than the 17.5 ksi (120.7 MPa) corresponding to Maximum Allowable Operating Pressure (MAOP) stress for this respective gas pipeline.

Additional Thoughts and Considerations

At the completion of the stress analysis work, a list of questions was posed to develop a greater understanding about the integrity of the line. These bulleted items are listed below and are based upon experience in pipeline studies and reflect insights considering mechanical, civil, and metallurgical engineering.

- When was the last time the pipeline was hydrotested?
Hydrotesting is useful for several purposes including the detection of serious defects and indicating the level of reserve strength.
- What is the manufacturing process for the pipe in question (e.g. seamless, ERW, lap weld, etc.)?
- Where are the closest girth welds located relative to the pile driving locations?
- What information is available regarding the quality of the welds? Specific concerns are hardness, ductility, and the potential for existing partial cracks.
- Has the pipeline been protected by a cathodic protection system and what historical information is available regarding its performance?

- Where are the anode ground beds relative to the pile driving locations and are there any potentials that would create hydrogen charging?
- Has the coating disbonded in any areas and if so, are there any chances that corrosion under the disbonded coating exists?
- Where are the closest valves relative to the pile driving locations?

An outgrowth of the proposed question list was that a field evaluation of the excavated pipeline focusing on metallurgy be performed. Issues such as addressing hardness in the base pipe and heat affected zone were primary areas of focus. It was also recommended that monitoring be conducted using strain gages and accelerometers to ensure that the gas pipeline would not be loaded to levels that exceeded prudent allowable stresses.

FIELD INSPECTION WORK

Presented are findings for the metallurgical inspection of the 6-inch nominal diameter pipeline. The evaluation of the pipeline indicated that no detectable levels of corrosion were present and the coating was in good condition. From a metallurgical standpoint the carbon content of the weld region was relatively low and there were no obvious indications of gross defects in the areas that were examined from the grain structure replicas.

The sections that follow provide specific details from the field inspection work that include findings relative to the visual inspection, observed metallurgy, and chemistry of the weld material.

Field Inspection Notes

An on-site inspection near the junction of U.S. Interstate 95 and Florida State Highway 92 was performed along the west bound shoulder of Highway 92. Prior to the inspection a plan of action was developed and all involved parties were briefed relative to activities to be conducted during the pile driving efforts. The pipe was found 3 feet beneath the road bed/shoulder. The gas pipeline was located approximately 7 feet (2.1 meters) west of the Highway 92 pavement. Excavation continued by hand once the gas pipeline was uncovered. Total excavation continued to where the girth weld was found. Data points for the ultrasonic (UT) and portable hardness tests were utilized at locations where coating was chipped away by the shovel work.

Ultra Sonic Thickness Results. A handheld Ultrasonic meter was used to record wall thickness measurements in the pipe base material and weld region. Data are presented in **Table 2** showing the results and **Figure 1** provides diagrams detailing selected measurement locations. Nominal wall thickness was specified as 0.188 inches (4.8 mm) per Florida Gas Transmission Company.

Portable Hardness Test Results. A *TIME* portable hardness tester was used to determine local hardness values in the pipeline base material and weld region. Ultimate tensile strengths (UTS) for the carbon steel pipe and girth weld were obtained from the hardness values using known calibration values. The UTS values are important for assessing the overall strength of the pipe material as well as determining if any significant variations exist between the strength of the pipe and weld material. **Table 3** provides results from the portable hardness tests.

As noted from the data presented in **Table 3**, ultimate tensile strengths ranged from 57,800 psi (398.5 MPa) to 73,500 psi (506.8 MPa). Significant variations in UTS measurements were not noted in the weld and heat affected zone (HAZ) when compared to the pipe base material. The UTS values are consistent with what would be expected for the pipe material designated by Florida Gas as Grade B pipe (per API Spec 5L [3] the minimum UTS is specified to be 60 ksi (413.7 MPa)).

Metallurgical Evaluation

Six metallurgical replicas were taken from two locations across one of the girth welds. The location corresponded to the 12:00-1:00 o'clock position of the pipe. The areas that were examined included the upstream pipe's base metal and heat affected zone (HAZ) and the downstream pipe's base metal, HAZ and weld.

The base metal of the upstream pipe section showed a relatively fine-grained structure. Ferrite grains were prominent in the base metal where lamellar pearlite colonies were also evident. A very small area of the HAZ was visible on this metallurgical replica, but appeared typical of a HAZ in line pipe steel.

The base metal of the downstream pipe showed a ferrite and lamellar pearlite microstructure. Relatively small grains were also evident; however, select areas did show relatively coarser grains within the fine-grained region consisting primarily of ferrite. The HAZ and weld were easily observed on this set of replicas. The weld microstructure was typical of a normalized structure (air-cooled) in carbon steel pipe. A typical heat affected zone for this material was also observed.

From the steel shavings taken from the weld zone, a chemical composition analysis was performed. The results indicate that the carbon content was on the order of 0.14 percent and the sulfur content was approximately 0.03 percent (both less than the specified values per API Spec 5L [3] that are 0.27 percent for Carbon and 0.05 percent for Sulfur).

Field Inspection Closing Comments

The primary purpose of the field investigation was to assess the metallurgical integrity of the pipeline. Assuming that the inspected regions of the pipeline and the girth weld were representative of conditions along the length of the pipeline, the line was of good quality and well-preserved in the 40 years since its installation. From an overall standpoint, there were no obvious indications of gross defects in the areas of the pipeline that were examined.

Based upon the previous analytical work as well as the field inspection efforts, the integrity of the line appeared to be sufficient to withstand the anticipated loading conditions generated by the pile driving process.

At the completion of the field investigation, it was recommended that strain gages and accelerometers be installed and used to monitor stresses and acceleration levels during the actual pile driving process.

FIELD MONITORING DURING PILE DRIVING

Strain gages and accelerometers were installed on the active gas pipeline. Data were recorded during the pile driving process. The objective was to determine the maximum levels of stress that were

developed in the pipe. There was also an interest to determine the levels of acceleration relative to the values used in the analysis. The sections that follow provide greater details on the test set-up and results from the monitoring tests.

Set-up for Testing

Prior to installing instrumentation and making measurements on the pipeline, efforts were taken to predict the behavior of the pipeline during pile driving. While some of this involved calculations and finite element analysis, other efforts involved a common-sense approach to making the measurements to ensure that the maximum strains and accelerations were recorded.

Figures 1 through **Figure 4** are photographs from the site of the pile driving. The steps involved in the installation of the electronic equipment included:

- Excavating around the pipe to ensure adequate clearance for installing the equipment
- Removing the coating by scraping and polishing the surfaces of the steel pipe in areas where strain gages were installed
- Installing weldable strain gages to the pipe at four (4) locations around the pipe. Two gages (one axial and one hoop) were installed at positions 90 degrees apart.
- Wiring up the strain gages to the cables for connection to the data acquisition system (DAQ)
- Connecting accelerometers using the mounting blocks and brackets. Two accelerometers were used, one vertical and the other horizontal
- Enclose all connections and equipment to prevent moisture penetration
- Completing the connection of cables and running out of the excavation hole up to the computers in the back rented-vehicle
- Check out no-load measurements and make sure all components of the system work properly.

Installation of the strain gages and accelerometers were completed in one day. No problems were encountered and a successful installation was made.

To provide additional background on the instrumentation that was used, the following sections of this paper are provided. The information presented is not intended to be exhaustive.

Strain Gages. Weldable strain gages were used to measure strain in the pipe, both axially and circumferentially. The weldable gage types have a thin gage steel backing that permits their attachment directly to the pipe. The welding used in this context involves nothing more than a series of extremely small spot welds around the outer perimeter of the gage.

When the strain gages were loaded the wires within the gages changed length, accompanied by a change in electrical resistance of the wiring. It is this change in electrical resistance that was measured and used to determine how much the pipeline was loaded. As long as the strains remained elastic, stresses were calculated by multiplying the strain measurements by the elastic modulus for the pipe (30×10^6 psi (206.4 GPa)).

Accelerometers. Accelerometers were used to measure the amount of acceleration that was imparted to the pipe during the pile driving process. The accelerometer is a sensor that incorporates a piezoelectric

material that is sensitive to acceleration loads. In quantifying the level of acceleration, often expressed as a function of the acceleration of gravity, one can assess the overall dynamic loading on the pipeline.

Data Acquisition System. The data acquisition (DAQ) system is vital to making measurements. The DAQ system is responsible for converting the electrical signals retrieved from various sensors into a format that can be used by engineers. The DAQ system incorporates several pieces of equipment that are responsible for providing excitation voltage to the instrumentation, retrieving the data, converting the data into useful information, and even involves computer programs that can plot results real-time. The modern-day DAQ systems involve high-speed computers with large storage devices that permit data to be recorded at rates exceeding 100,000 scans per second. To capture the acceleration and strain measurements in the pipeline, a rate of 10,000 scans per second was selected.

Test Results

Prior to driving piles, a framework was fabricated to serve as a template during the auger and pile driving processes. During the pile driving process, strain gage and accelerometer readings were taken at a rate of 10,000 scans per second per data channel. Based upon acceleration readings provided from a previous pile driving effort [1], a scan rate of 10,000 scans per second was selected to properly capture the excitation from the pile driving. The results obtained indicated that this was an appropriate scan rate.

Figure 5, 6, and 7 are plots showing the strain gage readings. Results for one test showing the accelerometer readings are shown in **Figure 8**. The total cycle time appears to be approximately 0.002 seconds per cycle. With the scan rate of 10,000 scans per second, 20 data points were collected for each measurement device (e.g. strain gages and accelerometers) during each cycle.

In reviewing the plots there are several significant trends. The sections that follow provide specific details on these important observations.

Strain Magnitude. During testing, the strain and accelerometer results were displayed on a computer screen. The apparent peak-to-peak magnitude of the strain appeared to be on the order of 30 microstrain, which was well below the pre-calculated allowable axial strain for the pressurized gas pipeline. When converting strains to stresses, the strain is multiplied by the modulus of elasticity for the pipe material. The carbon steel pipe has an approximate modulus of 30 million. Consequently, 30 microstrain multiplied by a modulus of 30 million psi (206.4 GPa) results in a calculated stress of 900 psi (6.2 MPa). As shown in the following section, the calculated axial stress limit for the pipeline was 8,400 psi (57.8 MPa). The peak-to-peak stresses generated by the pile driving process were approximately one-tenth of the allowable value.

Increasing Strain During Initial Stages of Driving. After the first pile had been driven, a trend was observed in the strain gage results that was concerning. Prior to starting the pile driving, the strain gages were zeroed and no strain was measured in the pipe. Once the first pile started moving into the ground, the strain gage readings clearly indicated that the pipe was being moved away from the pile. With Gages #1 and #4 indicating tension and Gages #2 and #3

showing compression, it was clear that the pipe was being subjected to a bending load. Although not completely obvious in the plotted data, the results for all three pile drives show that in Gage #1 a maximum nominal strain on the order of 250 microstrain (stress of 7,500 psi (51.6 MPa)) was reached. Fortunately, even this value was less than the calculated allowable axial stress of 8,400 psi (57.8 MPa). However, it was noted that each time the pile driving process was completed the strains returned to approximately zero microstrain.

After all three piles were driven, the pipeline was visually inspected. **Figure 9** is a photograph showing what was discovered. As shown in this figure, a wood beam and a piece of plywood were installed to protect the pipe from outside forces. Due to the relative rigidity of these members, as the piles were driven the displaced soil in conjunction with the position of the timber forced the pipeline upward. The fact that Gages #1 and #4 (located on top of the pipe) are in tension throughout the recording process indicates the upward direction of loading.

It was recommended that future pile driving efforts create a space barrier between protection members and the pipeline. Having a buffer zone between the pipe and timber will prevent loads from being transferred to the pipe during the pile driving process and permit the soil to be displaced more freely and not load the pipeline.

Acceleration Readings. The primary reason that the accelerometers were installed was to determine the maximum acceleration levels that were imparted to the pipeline during the pile driving process. As shown in **Figure 8**, the maximum acceleration level was less than 0.5 g. This measured value is well below the 1.0 g value that was assumed in the analysis work.

Detailed Calculations. Calculations were performed to determine the allowable axial stress for the 6-inch (152.4) gas pipeline using the methodology outlined in ASME B31.8 [4]. The data for one of the typical readings showed that during the pile driving process the average axial stress was 2,018 psi (13.9 MPa), while the maximum bending stress at 0 degrees is 6,086 psi (41.9 MPa).

The calculations also showed that the maximum bending stress in the pipe did not exceed the allowable axial stress of 8,400 psi (57.8 MPa). These calculations had been made prior to making measurements to determine the maximum axial stress limit that would be permitted. During the monitoring process, the process would have been halted if measured strains had exceeded this allowable value.

Field Monitoring Closing Comments

The strain gage results indicated that the maximum axial bending strains due to pile driving were on the order of 20 microstrain. For the steel pipeline this translates to approximately 600 psi. As a point of comparison, the hoop stress in the pipe due to pressure alone (i.e. reported to be 500 psi (3.4 MPa) internal pressure at the time of the pile driving) was approximately 8,800 psi (60.5 MPa). When comparing the hoop and axial values, it was clear that the stresses induced by the pile driving nearby were almost one-tenth the stresses created by pressure alone. As discussed previously, pipeline engineers should calculate an allowable stress limit using an appropriate design code such as ASME B31.8 prior to driving piles. If measured stress

values exceed the pre-determined limit, the pile driving process should be stopped and additional investigations be conducted.

The monitoring results confirmed the previous analysis efforts indicating that strains induced by driving piles were relatively low. With this information, the construction company was able to complete the additional pile driving efforts associated with the highway expansion project without incident.

RECOMMENDATIONS FOR INDUSTRY

The efforts associated with the work reported herein are clear examples of how analysis, field inspection, and real-time monitoring can be used to assist engineers and construction companies in characterizing the interdependent behavior of pile driving and gas pipelines. In many instances, engineers are called upon to make difficult and challenging decisions without having sufficient details and information. It is important for engineers to develop the ability to determine what critical information is needed before making decisions that impact the safety and well-being of engineered systems.

As a result of the lessons learned in completing this project, the following recommendations are provided for others who are assessing the effects of pile driving adjacent to live pipelines. It is recognized that not every situation will permit the extensive level of evaluation permitted in the work reported herein.

- Gather detailed information about the pipeline including geometric data, material grade, and operating history. Information on the pile driver and its operating characteristics is also recommended.
- Determine the type of soil and obtain boring data if possible (important for assessing soil stiffness).
- If possible, obtain accelerometer readings from a previous pile driving process using the same pile driving equipment and soil types.
- Perform an analysis using a method such as finite elements to determine strain levels based upon a range of soil stiffness values and acceleration levels created by a pile driver.
- Excavate the pipeline in question and perform a field inspection on the base material and at least one weld. As a minimum this effort should involve visual inspection and ultrasonic measurements to verify wall thickness. A more rigorous, but recommended, evaluation will involve field replication work and obtaining filings from the pipe to determine chemistry (i.e. levels of carbon content).
- Compile and assess the combined results from the stress analysis and the field inspection work.
- If possible, install strain gages and accelerometers on the pipeline prior to actually driving piles. Data should be recorded at a rate that is high enough to capture all possible transients. Prior to performing the field tests, engineers should calculate beforehand the permissible levels of stress using an applicable code such as ASME B31.4 for liquid pipelines and ASME B31.8 for gas pipelines.
- If measured stress levels exceed acceptable limits, the pile driving process should be terminated immediately. Engineers should formulate options for providing greater isolation to prevent damage to the pipeline from the pile driver.

REFERENCES

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Table 1 Displacement and Stresses for Analysis Matrix

Soil Stiffness (lbs/in per linear inch)	Region of Acceleration (total longitudinal span in feet)	Maximum Displacement (inches)	Maximum Bending Stress (psi)
0.50 (0.003 N/mm/mm)	4 (1.2 meters)	0.206 (5.2 mm)	500 (3.4 MPa)
0.50 (0.003 N/mm/mm)	40 (12.2 meters)	1.722 (43.7 mm)	2010 (13.8 MPa)
500 (3.4 N/mm/mm)	4 (1.2 meters)	0.001 (0.03 mm)	50 (0.3 MPa)
500 (3.4 N/mm/mm)	40 (12.2 meters)	0.002 (0.05 mm)	60 (0.4 MPa)

Table 2 – UT Wall Thickness Measurements from Field Testing

Longitudinal Position (feet)	Circumferential Orientation	Location on pipe	Wall thickness Readings (inches)
27 (8.2 meters)	12 O'clock	Base pipe	0.194 (4.9 mm)
37 (11.6 meters)	11 O'clock	Base pipe	0.196 (5.0 mm)
46 (14 meters)	9 O'clock	Base pipe	0.196 (5.0 mm)
54 (16.5 meters)	12 O'clock	Upstream base Pipe	0.196 (5.0 mm)
		HAZ (upstream)	0.199 (5.1 mm)
		Weld	0.202 (5.1 mm)
		HAZ (downstream)	0.196 (5.0 mm)
54 (16.5 meters)	3 O'clock	Downstream base pipe	0.200 (5.1 mm)
		Upstream base Pipe	0.185 (4.7 mm)
		HAZ (upstream)	0.183 (4.6 mm)
		Weld	0.199 (5.1 mm)
54 (16.5 meters)	6 O'clock	HAZ (downstream)	0.197 (5.0 mm)
		Downstream base pipe	0.195 (5.0 mm)
		Upstream base Pipe	0.190 (4.8 mm)
		HAZ (upstream)	0.189 (4.8 mm)
54 (16.5 meters)	9 O'clock	Weld	0.200 (5.1 mm)
		HAZ (downstream)	0.195 (5.0 mm)
		Downstream base pipe	0.200 (5.1 mm)
		Upstream base Pipe	0.185 (4.7 mm)
54 (16.5 meters)	9 O'clock	HAZ (upstream)	0.184 (4.7 mm)
		Weld	0.207 (5.3 mm)
		HAZ (downstream)	0.195 (5.0 mm)
		Downstream base pipe	0.197 (5.0 mm)

Note: Random scanning close to the Upstream side of weld at 11 O'clock produced the lowest reading of .172-in (4.4 mm) which could not be reproduced. When rescanned readings of 0.174-in (4.4 mm), 0.175-in (4.4 mm), 0.178-in (4.5 mm), and 0.177-in (4.5 mm) were found in this region.

Table 3 – Hardness Measurements from Field Testing

Longitudinal Position (feet)	Circumferential Orientation	Readings	HLDL Average	UTS (converted from HLDL Average)
27 (8.2 meters)	12 O'clock	608, 597, 590	598	60.9 ksi (418.9 MPa)
37 (11.6 meters)	11 O'clock	589, 624	607	64.5 ksi (443.6 MPa)
46 (14 meters)	9 O'clock	583, 602, 590	592	57.8 ksi (397.5 MPa)
54 (16.5 meters)	12 O'clock	634, 637, 612 (upstream base)	628	73.5 ksi (505.5 MPa)
54 (16.5 meters)	12 O'clock	603, 602, 587 (downstream base)	597	60.1 ksi (413.3 MPa)
54 (16.5 meters)	Random	613, 608, 616, 607, 619 (weld)	613	67.5 ksi (464.2 MPa)
54 (16.5 meters)	Random	612, 607, 613 (upstream HAZ)	611	66.6 ksi (458.0 MPa)
27 (8.2 meters)	Random	587, 593, 598 (downstream HAZ)	593	58.2 ksi (400.3 MPa)



Figure 1 - Excavating pipe adjacent to highway



Figure 2 - Installing strain gages on pipe



Figure 3 - Location of gages on pipe in exposed ditch



Figure 4 - Location of exposed pipe relative to I-95 overpass

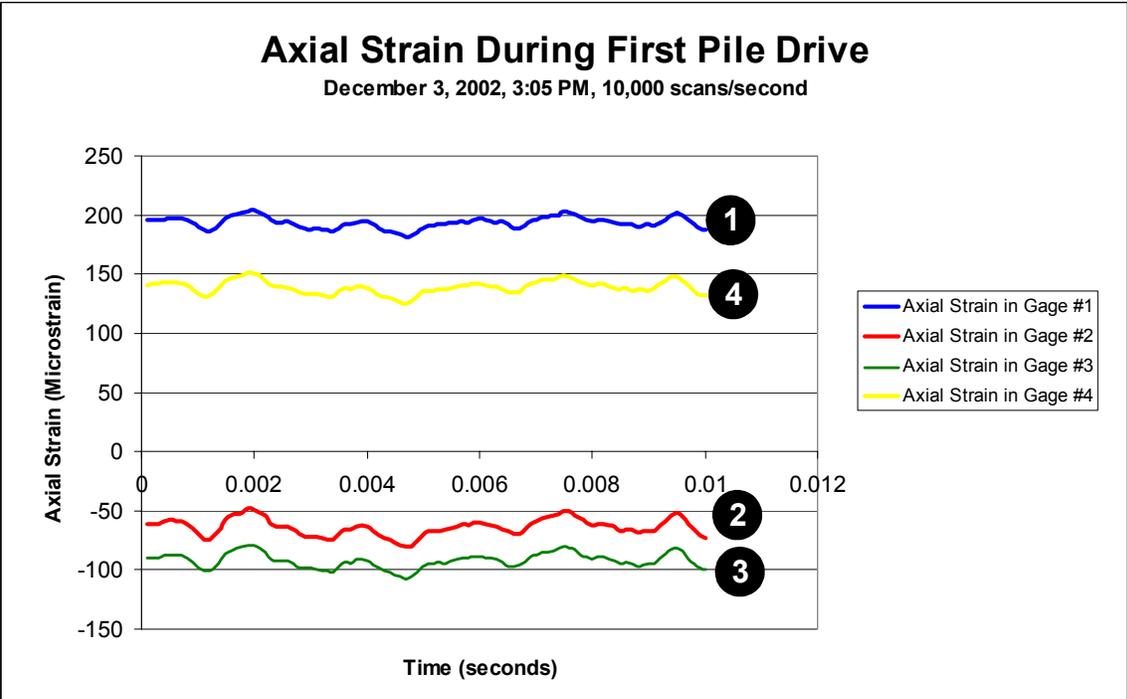


Figure 5 – Strain gage measurements recorded during first pile drive

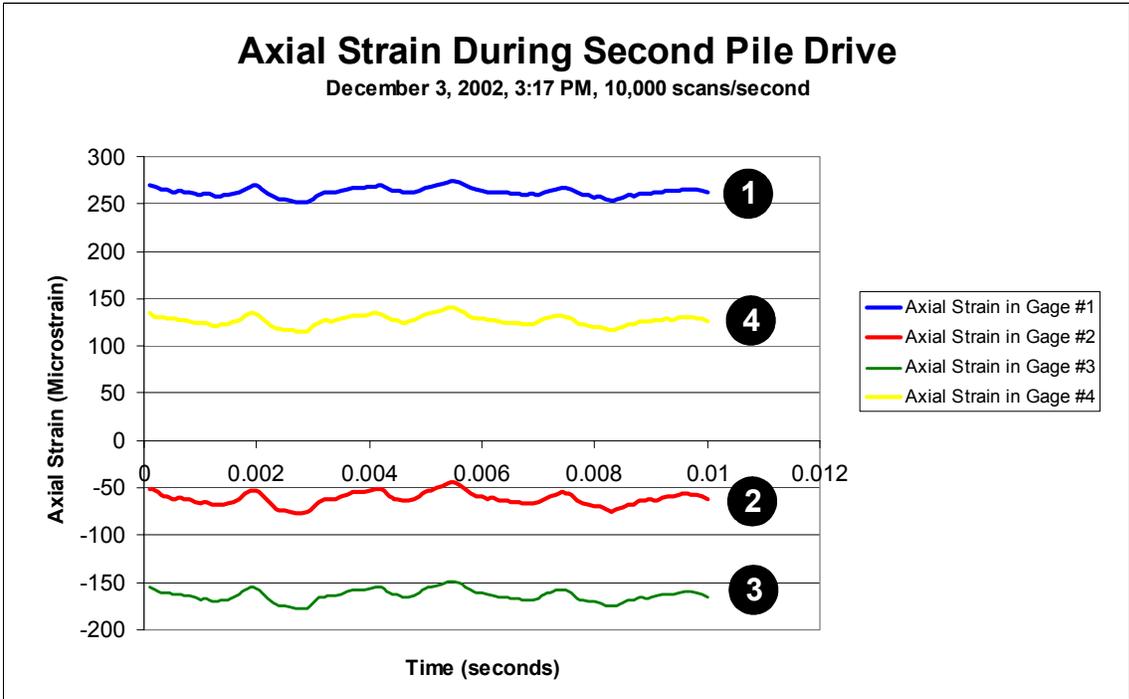


Figure 6 – Strain gage measurements recorded during second pile drive

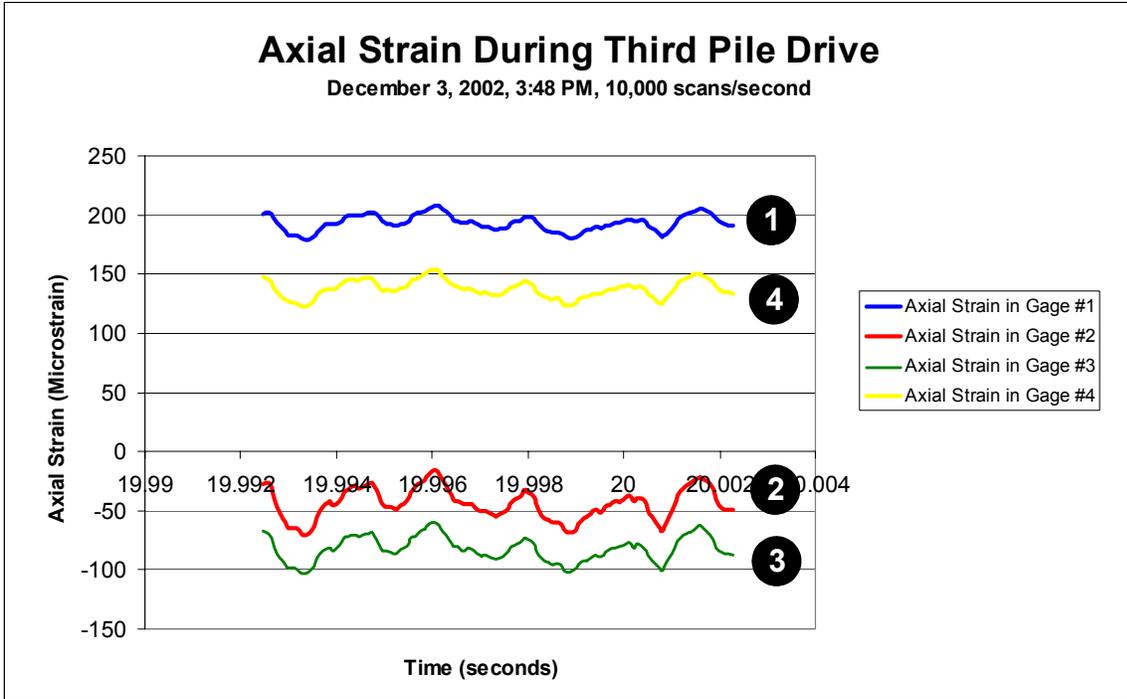


Figure 7 – Strain gage measurements recorded during third pile drive

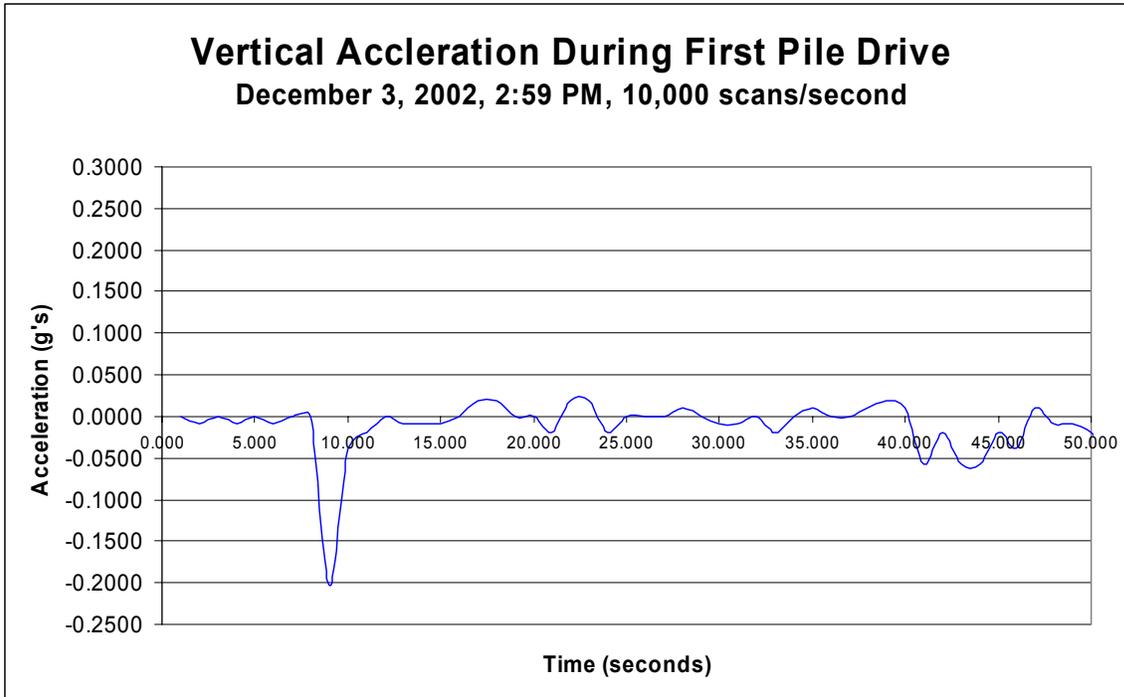


Figure 8 – Strain gage measurements recorded during first pile drive



Figure 9 - Position of wood beam adjacent to pipe