Final Report on Vibrations Due to Pile Driving at the Mobile River Bridge Site

Research Project 930-839R

INVESTIGATION OF PILE SETUP (FREEZE) IN ALABAMA

Development of a Setup Prediction Method and Implementation into LRFD Driven Pile Design

Addendum:* *Pile Driving Vibration Monitoring of the Future Mobile River Bridge Project

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DISCLAIMER

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ABSTRACT

All projects have some amount of inherent risk; one such risk associated with construction projects is the potential for ground vibrations that could damage nearby structures. Research has been conducted on the effects of vibrations on structures; however, the expected levels of vibration are dependent on several factors including the soil conditions at the construction site. Therefore, site specific investigations are often required.

After concerns were raised by the Alabama Department of Transportation (ALDOT) about damage potential at a project site in South Alabama, an addendum was added to a research project related to investigating pile setup in Alabama soils. The purpose of the addendum was to investigate ground vibrations from pile driving at a project site near the Mobile River in Mobile, Alabama.

An investigation and vibration monitoring program was developed for four pile sizes that are often used by the Alabama Department of Transportation (ALDOT). The piles included thirty-six inch square and twenty-four inch square concrete piles, as well as, two steel H-Piles. The piles were driven using typical installation techniques and the vibration levels at various distances from the piles were monitored.

The investigation found that the largest vibrations were observed while driving the thirty-six inch concrete pile. The maximum vibrations observed had a magnitude of 0.82 inches per second at fifty feet from the pile. The vibrations at 150 feet from the pile had dissipated to 0.15 inches per second. The results of the monitoring program and a literature review determined that an allowable vibration level of 0.5 inches per second for modern structures and 0.1 inches per second for potentially sensitive structures should be established for construction activity at or near the location of the project site. Additionally, a survey distance of 150 feet for modern structures and 250 feet for potentially sensitive structures is recommended.

INTRODUCTION

Background

The following report contains the analysis of ground vibrations generated during a pile driving research study located at the Mobile River Bridge Project Site. The project site, owned by the Alabama Department of Transportation (ALDOT), is located on the Mobile River just south of the Alabama Cruise Terminal, Figure 1. The study consisted of monitoring ground vibrations during the installation of four driven piles; two precast concrete piles and two steel H-piles. The study was conducted in response to concerns raised by ALDOT related to possible damage of nearby structures from ground-borne vibrations. The primary objective of this project was to determine the distance that pile driving operations can be conducted with minimal risk to nearby structures. To accomplish this, the vibration levels at various distances from the driven piles were determined and a prediction equation for other distances was developed. This study was conducted by researchers from the Department of Civil Engineering at the University of South Alabama between August 15, 2013 and August 27, 2013.

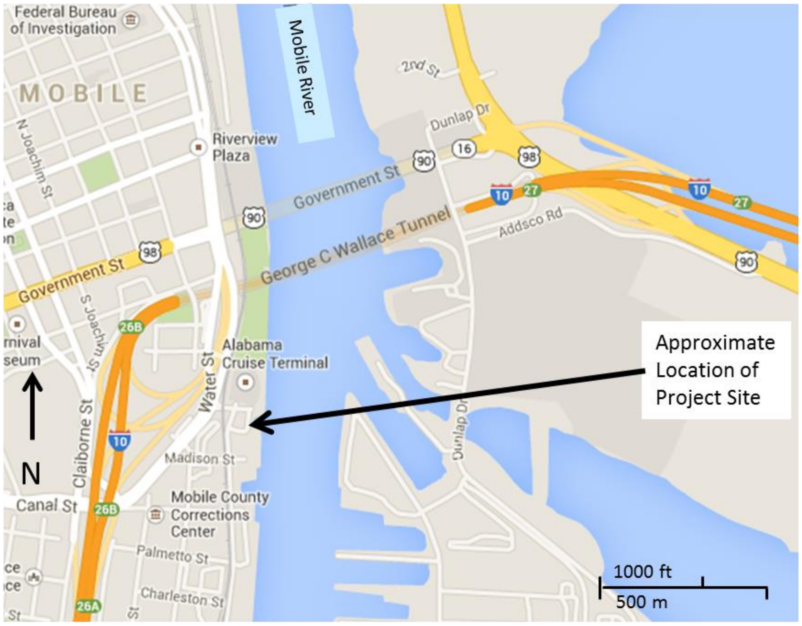

Figure 1: Location of project site, Mobile, AL **(Google 2013)**

Objective

This project consisted of several objectives. The first was to determine the vibration levels from typical piles used by ALDOT. The second objective was to develop a methodology to predict vibrations at any distance from the pile. The third and final objective of the project was to develop guidelines on allowable vibrations for the project site.

Scope

The scope if this report is limited to the vibrations portion of the larger project: *Investigation of Pile Setup (Freeze) In Alabama: Development of a Setup Prediction Method and Implementation into LRFD Driven Pile Design; Addendum: Pile Driving Vibration Monitoring of the Future Mobile River Bridge Project* (Research Project 930-839R).

The vibrations portion of the project was limited to the aforementioned location near the Mobile River. The project included monitoring vibrations during pile installation and restrikes, analysis of vibration data, development of vibration prediction methodology, and vibration limit recommendations.

Report Organization

The report is organized into five main sections: Introduction, Literature Review, Experimental Design, Results, and Conclusions. Each section contains sub sections as needed.

LITERATURE REVIEW

Construction Vibrations

Ground vibrations are commonly generated from several sources including roadway traffic, railroad traffic, and construction activity. Vibrations can be measured and quantified using several different parameters including: displacement, velocity, and acceleration. Ground vibrations are typically measured by the velocity of the ground surface and reported as Peak Particle Velocity or PPV. Typical units of PPV are inches per second (in/sec) in the US system or millimeters per second (mm/sec) in the SI system of units. Typical construction activity that generates vibrations includes: pile driving, heavy equipment operation, concrete breaking (jackhammers), and truck/equipment traffic. Although the level of vibrations generated from these sources can vary widely, some typical vibration levels have been included in Table 1.

Table 1: Typical ground vibrations from construction equipment **(Hanson, Towes and Lance 2006)**

Equipment		**PPV (in/sec)** (Distance = 25 ft.)
Pile Driver (impact)	upper range	1.518
	typical	0.644
Pile Driver (vibratory)	upper range	0.734
	typical	0.170
Bulldozer	large	0.089
	small	0.003
Caisson Drilling		0.089
Loaded Trucks		0.076
Jackhammer		0.035

Table 1 shows that under typical conditions, pile driving has the potential to create large vibration levels. The pile installation method, however, can affect the level of vibrations. Displacement piles are typically driven using an impact hammer and non-displacement piles are often driven using a vibratory hammer. Research has shown that vibratory hammers typically create less vibration than impact hammers. Additionally, installation techniques such as pre-boring and jetting can reduce vibration levels from impact pile driving (Woods 1997).

The mechanism of vibration formation is the transfer of energy from the pile driving hammer to the pile and then to the surrounding soil. The transfer of energy comes from two main sources. The first is the skin friction that is developed along the surface of the pile and the second is the displacement of the soil at the pile tip. For displacement piles, the main source of energy transfer is at the pile tip. Several factors can affect the magnitude of vibrations including pile size, pile type, soil type, and the hammer energy. The most important factor in determining vibration levels is the distance from the pile, since vibrations will mitigate or dampen with distance from the source (Dowding 1996).

Structural Damage

Vibrations generated from construction activity can cause several concerns at adjacent structures that range from annoyance to structural damage. Several studies have been conducted to determine the relationship between vibration levels, human perception, and structural damage. Table 2 contains a summary of one study conducted by the California Department of Transportation (Caltrans) for continuous vibrations. The study concluded that vibration levels that are large enough to "annoy people" are at threshold levels for architectural damage to structures that contain plaster walls or ceilings. Since these levels are below levels of even minor structural damage, the perception of building occupants can sometimes lead to discrepancies in the effects of vibrations. It should also be noted that the tables are generally conservative when compared to pile driving vibrations since they were developed for continuous vibrations. Pile driving operations develop vibrations that are discontinuous which can reduce the damage potential (Hendriks 2002).

Table 2: Continuous vibration levels and effects **(Hendriks 2002)**

Vibration Level (Peak Particle Velocity)	Human Reaction	Building Effects
0.006-0.019 in/sec	Threshold of perception; possibility of intrusion	Vibrations unlikely to cause damage of any type
0.08 in/sec	Vibration readily perceptible	Recommended upper level to which ruins and ancient monuments should be subjected
0.1 in/sec	Level at which continuous vibrations begin to annoy people	Virtually no risk of "architectural" damage to normal buildings
0.2 in/sec	Vibrations annoying to people in buildings	Threshold at which there is a risk of "architectural" damage to normal dwelling- houses with plaster wall and ceilings
0.4-0.6 in/sec	Vibrations considered unpleasant by people subjected to continuous vibrations	Vibrations at a greater level than normally expected from traffic, but would cause "architectural" damage and possible minor structural damage

In addition to the many studies that have been conducted to determine the effect of vibrations on structures, several State and Federal Agencies, as well as, International Organizations have developed guidelines on permissible vibration levels due to construction activity. Much of the early work related to vibrations was performed by the United States Bureau of Mines (USBM) in the 1970's and 80's (Siskind, et al. 1980). This research focused on vibrations from blasting operations. Figure 2 shows the recommended vibration limits for blasting as a function of frequency. The limits range from 0.2 to 2.0 inches per second (in/sec).

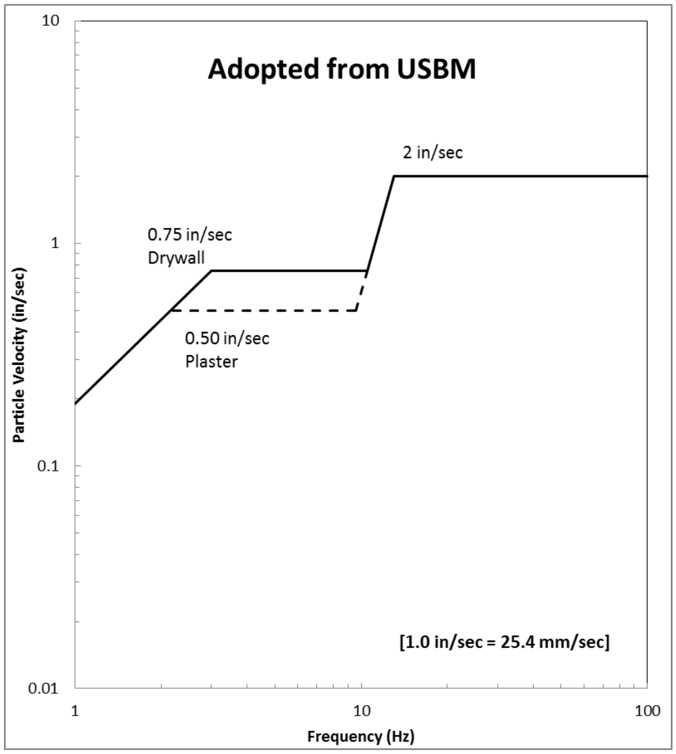

Figure 2: Vibration limits from the USBM **(Siskind, et al. 1980)**

A wide range of vibration limits have been developed for vibrations from pile driving and other construction activity. These limits range from as low as 0.08 in/sec to as high as 1.0 in/sec. There are several reasons for the broad range in limits including the structure type, human perception, and the amount of conservatism applied by the study authors.

A review of construction vibration limits can be found in several reports including: (Tao and Zhang 2012), (Wilson Ihrig & Associates 2012), and (Cleary 2013). A brief overview of vibration limits will be included here.

As previously mentioned several State and Federal Agencies have developed guidelines for vibration limits including the American Association of State Highway and Transportation Officials (AASHTO) and the Federal Transit Administration (FTA). The recommended vibration limits from AASHTO and FTA range from 0.1 to 1.5 in/sec depending on the structure type as shown in Table 3.

Table 3: AASHTO and FTA criteria for construction vibrations

Organization/Jurisdiction	Comments	PPV (in/sec)
American Association of State Highway and Transportation Officials (AASHTO 1990)	Residential buildings, plastered walls	0.2-0.3
	Residential buildings in good repair with gypsum board walls	0.4-0.5
	Engineered structures, without plaster	1.0-1.5
	Historic sites or other critical locations	0.1
Federal Transit Administration (FTA 2006)	Reinforced-concrete, steel or timber	0.5
	Engineered concrete and masonry	0.3
	Non-engineered timber and masonry	0.2
	Buildings extremely susceptible to vibration damage	0.12

The vibration criteria developed by the various states also have a wide range of values as shown in Table 4. If the table is carefully analyzed, the vibration limits can be divided into several categories including: modern structures, sensitive structures, and miscellaneous structures. The range of vibration limits for modern structures is from 0.4 to 1.0 in/sec and sensitive structures have a range of 0.08 to 0.2 in/sec. These vibration limits correlate well to the AASHTO and FTA limits.

Table 4: State criteria for construction vibrations

Organization/Jurisdiction	Comments	PPV (in/sec)
California Department of Transportation (Caltrans 2002)	Upper level for possible damage	0.4-0.6
	Threshold for damage to plaster	0.20
	Ruins and ancient monuments	0.08
Florida DOT (FDOT 2010)	All construction	0.5
	Fresh concrete	1.5
Iowa DOT (Iowa DOT n.d.)	Project specific specification	0.2
Louisiana Department of Transportation and Development (Tao and Zhang 2012)	General scenario	
	- New requirements	0.5
	- Old requirements	0.2
	Historic structures or loose sandy soil	0.1
New Hampshire DOT (NHDOT 2010)	Modern Homes	0.75
	Older Homes	0.50
New York City DOT (New York City DOT 2009)	Piles driven adjacent to subway structures (may be lowered)	0.5
Rhode Island DOT (RIDOT 2010)	Lower limits may be applied by engineer	1.0

Dynamic Settlement

In addition to structural damage and human perception, dynamic settlement can occur due to construction vibrations. Research has shown that if loose cohesionless soils (loose sands) are present, relatively low vibration levels can cause densification (Dowding 1996). This densification can lead to settlement related damage in adjacent structures. Loose sands are typically defined as having a relative density less than 40% (Tao and Zhang 2012). Vibration levels as low as 0.1 in/sec have been shown to cause dynamic settlement in some soils. If loose sands are located on or near a project site, then special considerations for construction vibrations need to be made.

Vibration Prediction

Since it is typically unrealistic for most construction projects to conduct full scale testing to determine the expected levels of vibrations and since only a discrete number of locations are measured during testing, several methods have been developed to predict vibration levels. The first prediction equations were developed as early as 1912 by Golitsin who developed a simple equation to predict the peak particle displacement of ground vibrations from earthquakes. The equation, as reported by (Bayraktar, et al. 2013) is as follows:

Equation 1: $$A_2 = A_1 \sqrt{r_1/r_2}\, e^{-\gamma(r_2 - r_1)}$$

Where A_1 = peak particle displacement of ground vibrations at a distance r_1 from the source, A_2 = peak particle displacement of ground vibrations at a distance r_2 from the source, and γ = attenuation coefficient.

More recently, several methods have been developed to predict the peak particle velocity (PPV) from construction activity, pile driving in particular. Hendriks (2002) developed an equation to predict the propagation of transportation related vibrations with the following (Hendriks 2002):

Equation 2: $$V = V_o (D_o/D)^{0.5} e^{\alpha(D_0 - D)}$$

Where V = peak particle velocity at distance D, V_o = peak particle velocity at reference distance D_o, and α = a soil parameter that must be determined experimentally.

Hendriks also developed a simplified equation for pile driving vibrations as follows (Hendriks 2002):

Equation 3: $$V = V_o (D_o/D)^k$$

Where V = peak particle velocity at distance D, V_o = peak particle velocity at reference distance D_o, and k = a soil parameter that must be determined experimentally.

Several researchers have found that a better correlation with predicted and measured vibrations could be determined by including the energy of the pile driving hammer in the equation. This approach is often referred to as the "scaled-distance" approach. One commonly used equation was developed by Wiss and reported by (Bayraktar, et al. 2013):

Equation 4: $$v = k\left[D/\sqrt{W_t}\right]^{-n}$$

Where W_t = energy of the source, v = peak particle velocity at distance D, k = intercept value of the peak particle velocity at a scaled distance of $D/(W_t)^{1/2}$, and n = a soil parameter that must be determined experimentally.

The previous equations are relatively accurate at predicting ground vibrations when compared to experimental data, however, they all require testing to determine the soil parameters. Jones & Stokes (2004) performed an extensive literature review and determined that the following equation, with the assumed values shown, could be used to predict pile driving vibrations without experimental evaluations.

Equation 5: $$PPV_{Impact\ Pile\ Driver} = PPV_{Ref}(25/D)^n\left(E_{equip}/E_{ref}\right)^{0.5}$$

Where $PPV_{Impact\ Pile\ Driver}$ = peak particle velocity at distance D in feet, PPV_{Ref} = 0.65 in/sec for a reference pile driver at 25 feet, E_{ref} = 36,000 ft-lb (rated energy of reference pile driver), E_{equip} = rated energy of impact pile driver in foot-pounds, and n = soil parameter with a recommended value of 1.1.

Jones and Stokes also provided a table, Table 5, with suggested "n" values based on the soil type.

Table 5: Suggested "n" values based on soil class: Adopted from **(Jones & Stokes 2004)**

Soil Class	Description of Soil	Suggested Value of "n"
I	Weak or soft soils: loose soils, dry or partially saturated peat and muck, mud, loose beach sand, and dune sand, recently plowed ground, soft spongy forest or jungle floor, organic soils, top soil. (shovel penetrates easily)	1.4
II	Competent soils: most sands, sandy clays, silty clays, gravel, silts, weathered rock. (can dig with shovel)	1.3
III	Hard soils: dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rock. (cannot dig with shovel, need pick to break up)	1.1
IV	Hard, competent rock: bedrock, freshly exposed hard rock. (difficult to break with hammer)	1.0

EXPERIMENTAL DESIGN

Overview

The main objective of this research was to determine the distance that pile driving operations can be conducted with minimal risk to nearby structures. It is important to note that these guidelines were developed for typical piles used by ALDOT at the project site. The project was divided into two phases, collecting data during pile driving and analyzing the data. The information related to the project site, the test piles, the pile driving equipment, and the data collection equipment is located below.

Project Site

The project site is located on the west bank of the Mobile River, just south of the Alabama Cruise Terminal. The soil profile at the site consists primarily of sandy soils to a depth of 90 feet below the ground surface with a clay layer located at an approximate depth of 90 to 110 feet. Table 6 contains a summary of the soil layers that were defined by a standard penetration test (SPT) conducted at the project site. Appendix A contains the details of the soil investigations conducted by an ALDOT drill crew and Southern Earth Sciences.

Table 6: Soil profile at site location

Depth (ft.)	Basic Material	Average Blow Count (N)	Consistency
0-23.5	Sand	12	Loose to Medium
23.5-89.5	Sand	31	Medium to Dense
89.5-108.5	Clay	28	Stiff to Very Stiff
108.5-115	Sand	27	Medium

Figure 3 contains a plan view of the project site. The dashed line in the figure represents the approximate property boundary. Note that the pile locations are approximate and the drawing is not to scale. The arc lines shown in the drawing represent the approximate distance from the piles to where the monitoring equipment was located.

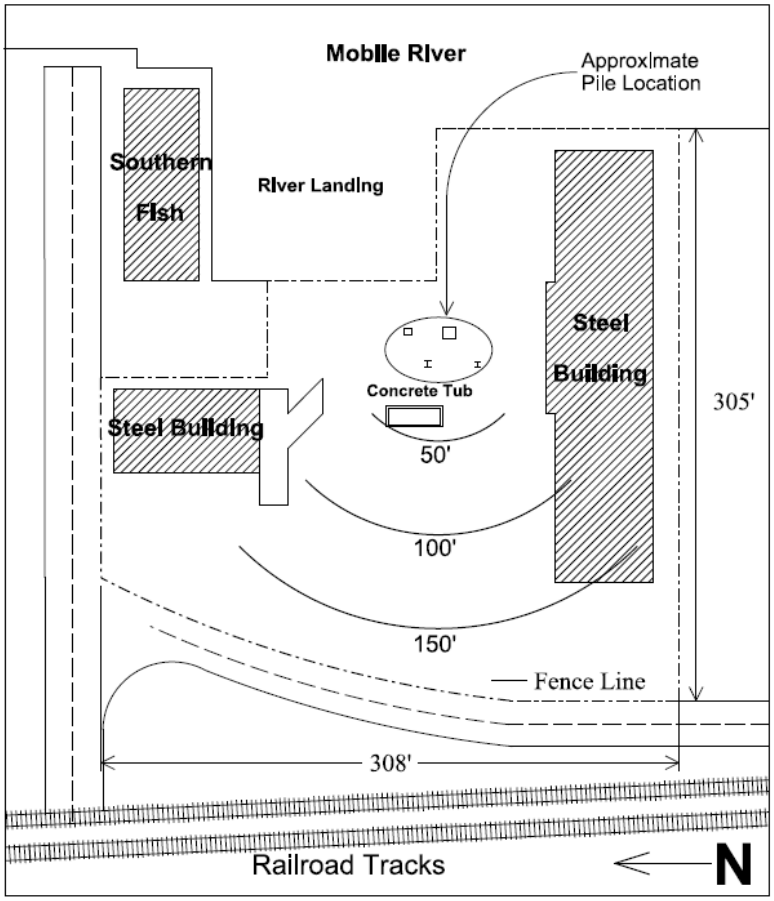

Figure 3: Plan view of Mobile River Bridge Project Site

Four test piles were driven for this project, two concrete piles (PCP) and two steel H-Piles. Table 7 contains descriptions of the piles and Appendix B contains the details of the two pile driving hammers utilized on this project. The piles were installed using typical techniques including pile jetting or vibration followed by driving with a diesel hammer. The concrete piles were jetted to a depth of approximately 30 feet and driven to the final elevation using a Delmag Model D-62-22 diesel hammer. A vibratory driver was used to drive the steel HP 14 to 55 feet and the HP 12 to 15 feet. The steel piles were then driven to the final elevation using an APE Model D30-42 diesel hammer.

Table 7: Pile descriptions

Pile	Cross Section	Material	Length
#1	24" Square	Precast Concrete	81 ft
#2	36" Square	Precast Concrete	89 ft
#3	HP14x117	Steel	106 ft
#4	HP12x53	Steel	70 ft

Vibration Monitoring

Data collectors were placed at various locations throughout the pile installation and testing process. The data collectors utilized for this project were Minimate Plus tri-axial geophones manufactured by Instantel. Each tri-axial geophone unit contains three geophones oriented on three mutually perpendicular axes. The units come with software allowing data collection and analysis in several configurations. For this research, the units were configured to collect histogram data during two second intervals. When configured in this way the data collector measures all vibrations over the interval, but only records the PPV and frequency for each geophone.

The geophones were placed at predetermined distances from each pile during installation. Three of the data collectors were located at approximately 50, 100, and 150 feet. A fourth data collector, which had two geophone units attached to it, was located at various distances throughout testing to collect additional information. Additionally, the fourth data collector was used to collect full waveform data for additional analysis.

Table 8 contains a detailed account of the location of each data collector during testing. During the initial driving of the 36 inch precast concrete pile (PCP), geophone number three was located at the edge of the project site near Southern Fish and Oyster, an adjacent property owner. The fourth data collector had one geophone unit placed at 100 feet from the pile and the other geophone unit was attached to the brick façade of a building that was located on the project site. Throughout the remainder of the testing, with the exception of the 7-day restrike, the fourth geophone unit was used to collect full waveform data and therefore the locations are not reported here. Please note that the 30-day restrike was at 32-days for the 36 inch concrete pile and 31-days for the 24 inch concrete pile.

Table 8: Geophone location during testing

		Geophone Unit				
Initial Drive	**Pile Type**	**#1**	**#2**	**#3**	**#4a**	**#4b**
Aug. 19, 2013	36” PCP	50 ft	150 ft	69 ft	100 ft	Building
Aug. 20, 2013	24” PCP	99.5 ft	142 ft	n/a	n/a	n/a
Aug. 21, 2013	HP 12	53 ft	101 ft	144 ft	n/a	n/a
Aug. 21, 2013	HP 14	58 ft	106 ft	146 ft	n/a	n/a
24 Hour Restrike						
Aug. 22, 2013	HP 12	50 ft	150 ft	100 ft	n/a	n/a
Aug. 22, 2013	HP 14	50 ft	150 ft	100 ft	n/a	n/a
3-Day Restrike						
Aug. 22, 2013	36” PCP	50 ft	n/a	100 ft	n/a	n/a
Aug. 23, 2013	24” PCP	50 ft	150 ft	100 ft	n/a	n/a
7-Day Restrike						
Aug. 26, 2013	36” PCP	50 ft	150 ft	100 ft	75 ft	125 ft
Aug. 27, 2013	24” PCP	50 ft	150 ft	100 ft	75 ft	125 ft
30-Day Restrike						
Sept. 20, 2013	36” PCP	50 ft	150 ft	100 ft	n/a	n/a
Sept. 20, 2013	24” PCP	55 ft	155 ft	105 ft	n/a	n/a
Sept. 20, 2013	HP 12	50 ft	150 ft	100 ft	n/a	n/a
Sept. 20, 2013	HP 14	50 ft	150 ft	100 ft	n/a	n/a

RESULTS

Vibration Levels

Vibrations were monitored during installation and restrikes on the 36 inch concrete pile at three, seven, and thirty days. A communication error occurred between the ALDOT personnel, the pile driving contractor, and the research team during the installation of the 24 inch concrete pile which resulted in the start of driving prior to the installation of the vibration monitors. Due to this error, the 24 inch concrete pile only had vibrations monitored during the final stage of driving and at all restrikes. The steel piles were monitored during installation and during the one day and thirty day restrikes. The vibrations due to other construction activities including pile jetting, and pile template installation were also monitored.

Baseline vibration data was collected at the project site by monitoring vibration levels due to railroad activity from a pair of railroad tracks located adjacent to the project site, Figure 3. The approximate distance from the tracks to the data collectors was determined and vibration levels from train activity were evaluated. Due to the relatively low vibration levels recorded during train activity, baseline data was not collected for truck traffic.

The vibration data collected from the project site was analyzed and the peak particle velocity (PPV) from each pile was recorded. Table 9 contains a summary of the results. The largest recorded vibration during this study occurred while driving the 36 inch concrete pile and resulted in a PPV of 0.82 inches per second at a distance of 50 feet.

Table 9: Maximum PPV (in/sec) during pile driving operations

Vibration Source	Horizontal Distance from Pile		
	50 feet	100 feet	150 feet
36" Concrete Pile	0.82	0.28	0.15
HP14x117	0.18	0.09	0.11
HP12x53	0.23	0.07	0.08
Template Installation	0.22	0.08	0.09
Railroad Activity	0.03[1]	0.02[1]	0.02[1]

[1]The approximate distances were 60, 110, and 160 feet

Figure 4 shows the maximum PPV for the 36 inch concrete pile, the H-Piles, pile template installation, and railroad activity observed during testing. Since the maximum vibrations occurred during the beginning of the driving process, the 24 inch concrete pile was not included in this figure. The figure confirms that the largest vibrations recorded were associated with the installation of the 36 inch concrete pile.

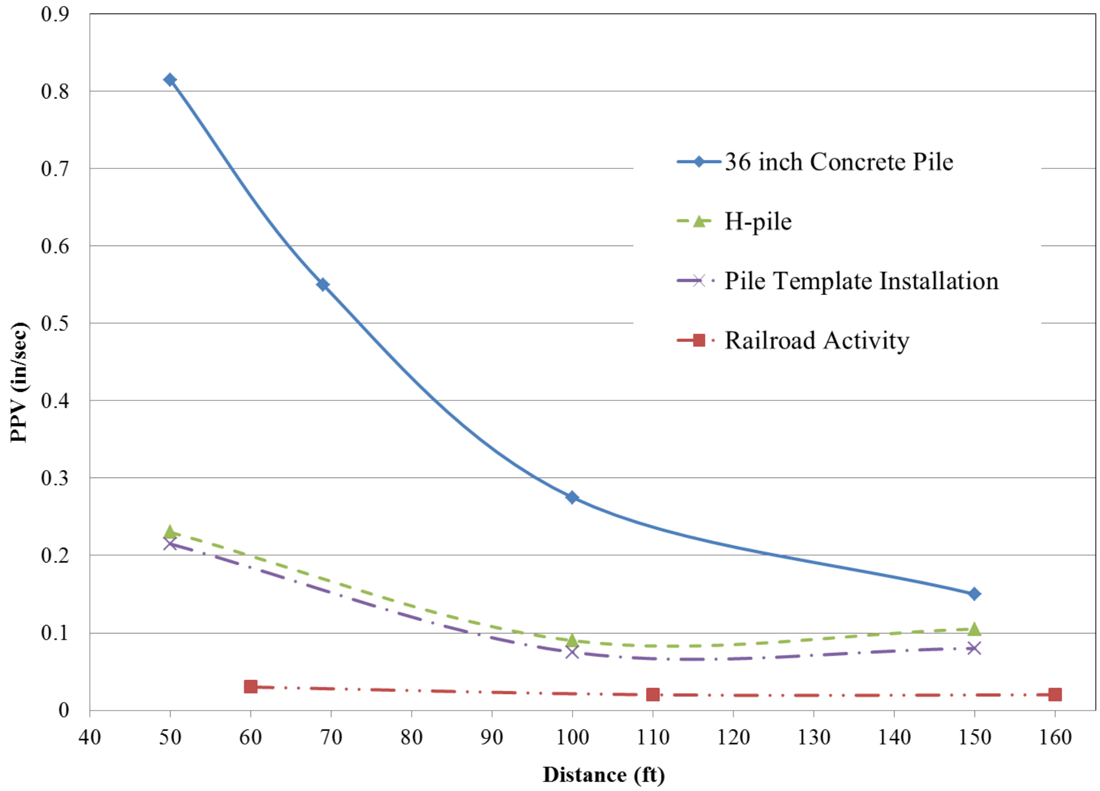

Figure 4: Maximum recorded vibration levels during pile installation

As mentioned in the vibration procedure, data was typically collected in histogram mode; however, some data was collected in full waveform mode. The full waveform data was analyzed and it was determined that the results did not add any additional information and are not included in the report. However, the results were compared to the other data collectors and all results were similar.

During the driving of the 36 inch concrete pile, one of the geophones was attached to the brick façade of a building that was located on the project site. The building was located to the south of the piles, Figure 3, and was approximately 90 feet from the 36 inch concrete pile. The brick façade was located on the west end of the building and was approximately 140 feet from the pile. The data from this geophone was analyzed and it was determined that the vibration levels were below the threshold for detection, 0.005 in/sec. This indicates that the ground vibrations did not have enough energy to cause vibrations in the building. Additionally, crack width monitors were installed on the outside wall of the building. The crack widths and lengths were monitored throughout the project and it was determined that there were no changes in any of the cracks.

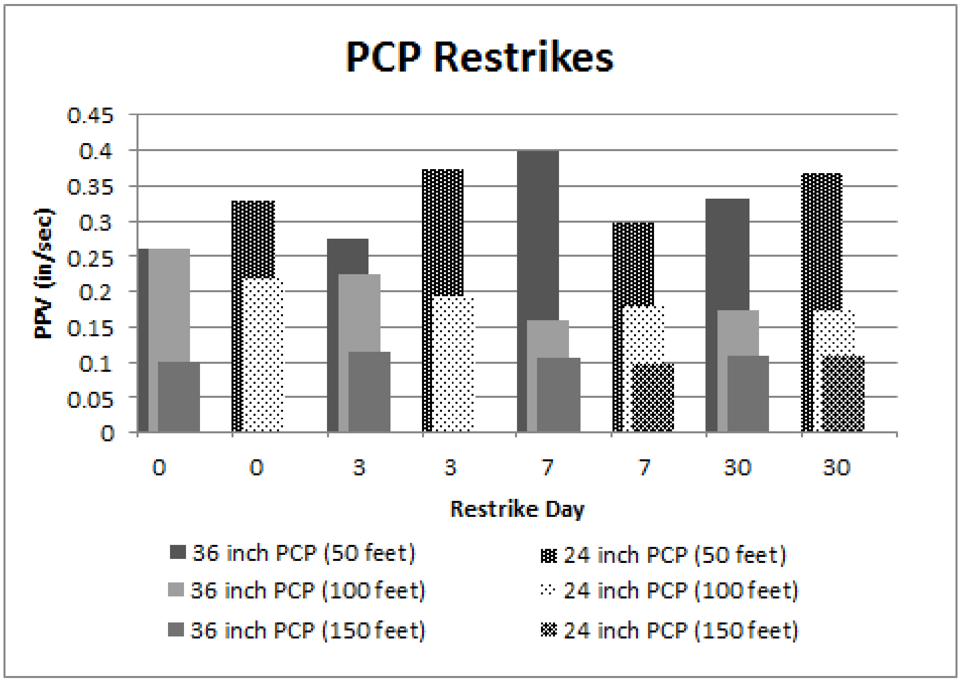

Figure 5: Bar chart of restrikes on precast concrete piles (PCP)

An analysis was performed to compare the vibrations between the 24 and 36 inch concrete piles since data was not collected throughout the driving of the 24 inch pile. Figure 5 shows a bar chart of the vibration levels for each of the concrete piles during the restrikes, note that day zero is at the end of drive. Figure 6 shows the same data in the form of a data plot. The data indicates that the vibration levels for the 24 and 36 inch concrete piles are similar and that the maximum vibrations, near the start of driving, would be expected to be approximately equal for each concrete pile.

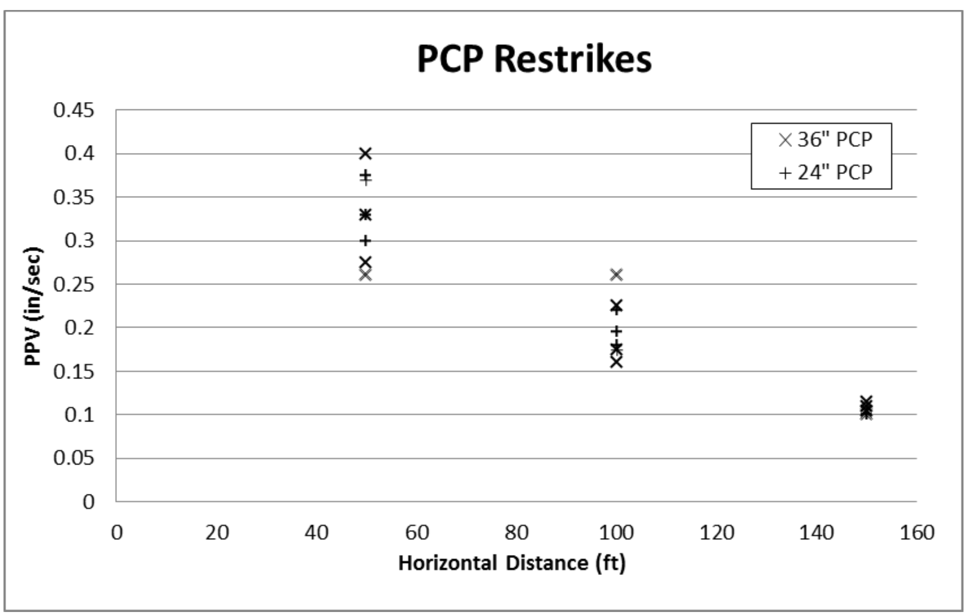

Figure 6: Data plot of restrikes on precast concrete piles (PCP)

Prediction Equation

The second major objective of this project was to develop a methodology to predict the vibration level at various distances from the pile location. Since the primary use of this research is for determining the vibration levels for concrete piles located at or near the project site, the prediction equation was developed based on the maximum peak particle velocities while driving the 36 inch concrete pile. To develop the equation Hendriks (2002) equation, Equation 3, was modified and fit to the experimental data. The only variable in the final prediction equation is the distance from the pile (d), as shown below. The peak particle velocity (V) is in inches per second. The equation is specialized for the particular conditions at the site location and should be used with caution under any other conditions.

Equation 6: $$V = 465.58d^{-1.6}$$

Figure 7 shows a plot of the experimental data and the peak particle velocities based on the prediction equation. The results indicate that the prediction equation has a close fit to the experimental data.

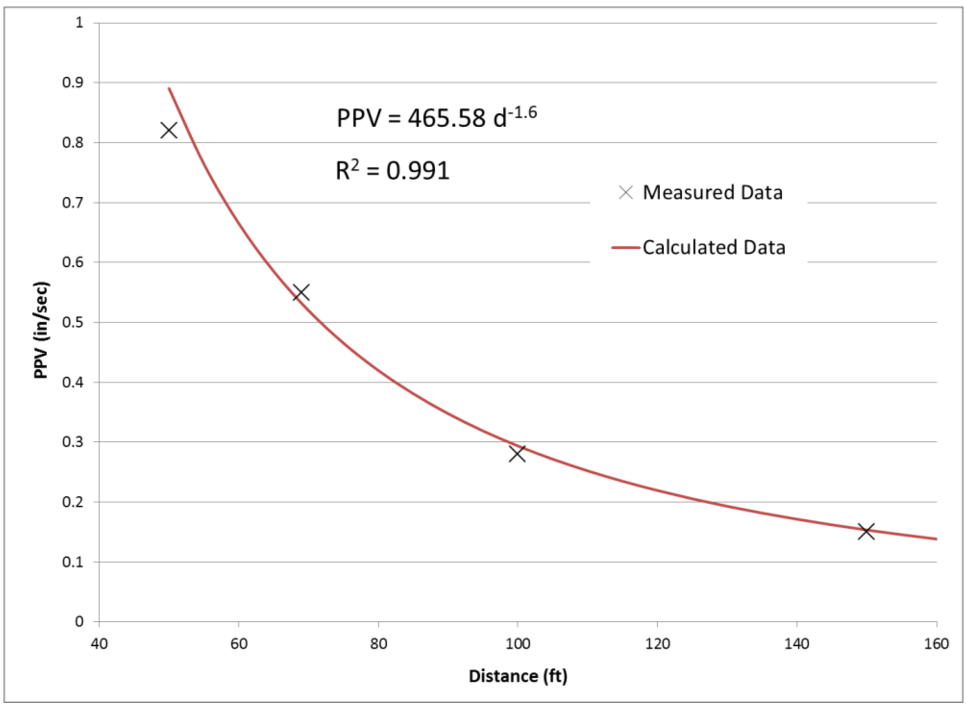

Figure 7: Measured and calculated vibrations for 36 inch concrete pile

CONCLUSIONS

The experimental data shows that the largest vibrations occurred during the installation of the 36 inch concrete pile, which was recorded as 0.82 inches per second. According to the research presented in Table 2 (Hendriks 2002), a vibration level of 0.82 inches per second has the potential to cause structural damage to an adjacent structure. However, this vibration was recorded at a distance of 50 feet from the pile; the vibration level at 100 feet from the pile was reduced to 0.275 inches per second. This vibration level could cause potential architectural damage to buildings constructed with plaster, but would not likely cause structural damage. At 150 feet the vibration levels were reduced to 0.15 inches per second, a level that would have little to no risk of damage to adjacent structures.

Based on the experimental data and a thorough review of the literature, it is recommend that a maximum vibration level of 0.5 inches per second for modern structures and 0.1 inches per second for potentially sensitive structures be allowed for construction activity at or near the location of the project site. These vibration levels are the allowable levels at the location of the structure. To determine if any structures should be surveyed and monitored for potential vibration damage, a survey distance of 150 feet for modern structures and 250 feet for potentially sensitive structures should be established. The monitoring distances should be measured from the source of the vibration. The ground vibration prediction equation that was developed would estimate a peak particle velocity of 0.15 inches per second at 150 feet and 0.07 inches per second at 250 feet. The survey distances are well beyond the distance where the prediction equation would estimate vibration levels of 0.5 and 0.1 inches per second and therefore would represent conservative survey distances to ensure adjacent structures are not damaged.

Recommendations for Future Research

The research presented in this report contains detailed analysis for a particular location in the state of Alabama; however, data has not been collected and analyzed for other regions of the state with differing soil conditions. A state wide research project should be initiated to determine vibration propagation and attenuation criteria for soil conditions located throughout the state. This data could be used to develop prediction equations that could be used in project planning. Additionally, the results of this research could be used to develop model vibration specifications for the state of Alabama.

In addition to the research mentioned above, it is recommended that a vibration monitoring program be developed for any large scale construction projects in urban environments. These programs could be used not only to ensure the construction activity is not damaging nearby structures, but to ensure the public that the DOT is proactive in preventing damage.

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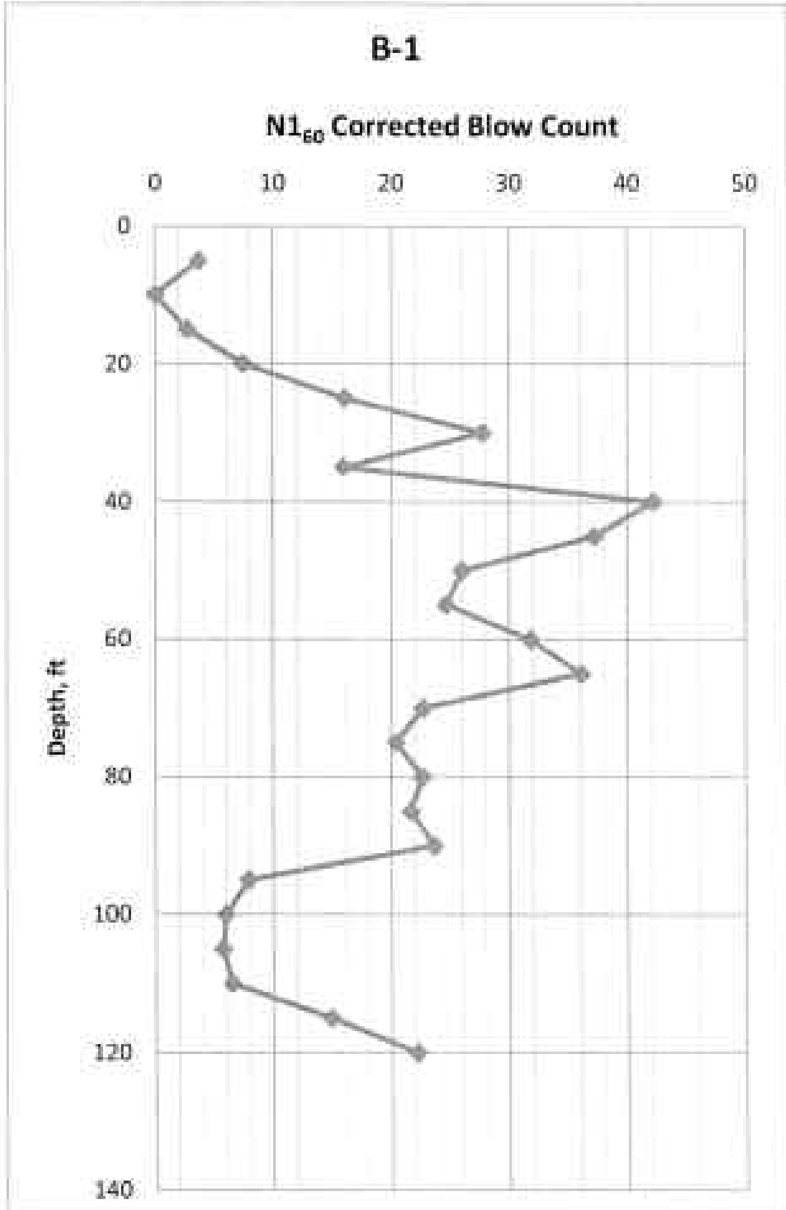
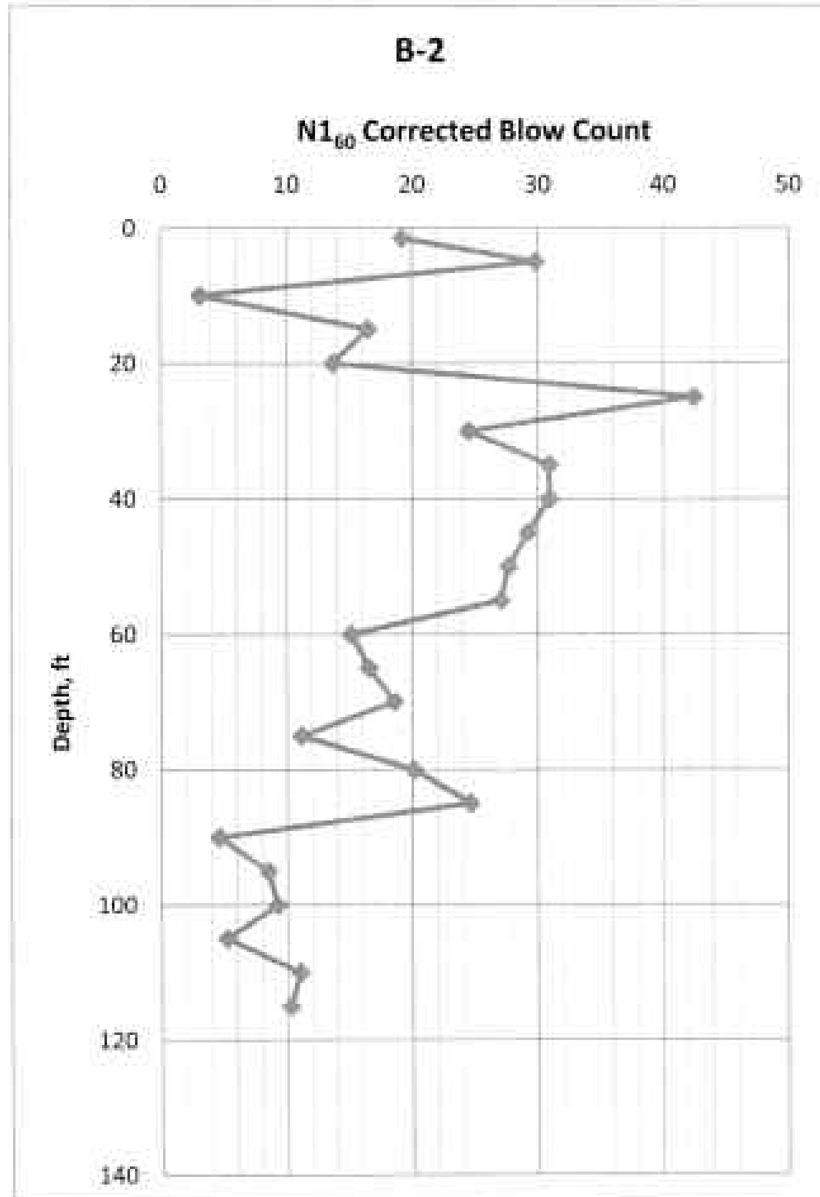
Appendix A: Soil Reports

Two soil investigations were performed at the site. The first was a Standard Penetration Test (SPT), which was performed at two locations. The first location, labeled B-1 in the documents that follow, was located at a property owned by ALDOT that is several hundred feet to the west of the project site. This location was an alternate location for testing. The second location, labeled B-2, was at the project site in the vicinity of where the test piles were installed. The SPT test was performed by an ALDOT drill crew.

The second soil investigation performed was a Seismic Cone Penetration Test (SCPT). Two locations were also investigated, both on the project site. The first test was performed at the location of the test piles and the second was located at 100 to 120 feet from the test piles. The results of both investigations are included here. The SCPT was conducted by Southern Earth Sciences.


B-1
N1$_{60}$ Corrected Blow Count
0
10
20
30
40
50
Depth, ft
0
20
40
60
80
100
120
140


B-2
N1$_{60}$ Corrected Blow Count
0
10
20
30
40
50
Depth, ft
0
20
40
60
80
100
120
140

Project# DPI-0030 (005) Division 9th

Station ______ Offset ______ Ft ______

Ground Elev. 0.0 Water Elev. in Hole ______

Depth of Strata BOR# B-1 Visual BOR Loc. ______

From	To	Consistency or Density	Approx. Moisture	Color	Basic Matl.
0.0	0.3	Asphalt			
0.3	18.5	V. Loose	Moist	Br	br. sand
18.5	23.5	Loose	Moist	Br	SAND
23.5	38.5	Med	Moist	TAN	SAND
38.5	63.5	Dense	Moist	TAN	sand
63.5	68.5	Very Dense	Moist	TAN	Sand
68.5	93.5	Dense	Moist	Tan	Sand
93.5	108.5	Stiff	Moist	Gray	Clay
108.5	118.5	HARD	Moist	Gray	Clay
118.5	120.0	DENSE	Moist	Gray	SAND

Remarks by Driller INStalled well monitor

GPS Cord. 42' 1"

LAT. water - 10' 3" 24 HRS

LONG. ______

County Mobile Date 8-8-12

______ C/L Driller Young / Evans

Type Drill Used SE 9030 Total Hole Depth 120.0

Identification CME 550X 2.25 Hollow Stem

Other Pertinent Components	Sample No.	Penetration or Sample Elev. From	To	"N" Blow .5	1.0	1.5	"N" Value
*	1-A	3.5	5.0	1	1	1	2
W/ clay *	1-B	8.5	10.0	W	O	H	WOH
*	1-C	13.5	15.0	WOH	1	1	2
	1-D	18.5	20.0	1	2	4	6
	1-E	23.5	25.0	5	5	9	14
	1-F	28.5	30.0	10	12	14	26
	1-G	33.5	35.0	9	7	9	16
W/ Sand *	1-H	38.5	40.0	26	23	22	45
W/ Sand *	1-I	43.5	45.5	23	23	19	42
+ org matl	1-J	48.5	50.0	11	14	17	31
	1-K	53.5	55.0	9	16	15	31
	1-L	58.5	60.0	18	20	22	42
*	1-M	63.5	65.0	20	23	27	50
*	1-N	68.5	70.0	14	16	17	33
	1-O	73.5	75.0	7	15	16	31

* Samples in JARS

Project# DPT-0030 (005) Division 9th

Station ______ Offset ______ Ft ______

Ground Elev. ______ Water Elev. in Hole ______

Depth of Strata BOR# B-1 Visual BOR Loc. ______

From	To	Consistency or Density	Approx. Moisture	Color	Basic Matl.

Remarks by Driller ______

GPS Cord. ______

LAT. ______

LONG. ______

County Mobile Date 8-6-12

______ C/L Driller Young/Evans

Type Drill Used SE 9050 Total Hole Depth 120.0

Identification CME 550X 2.25 Hollow stem

Other Pertinent Components	Sample No.	Penetration or Sample Elev. From	To	"N" Blow .5	1.0	1.5	"N" Value
	1-P	78.5	80.0	12	17	19	36
	1-Q	83.5	85.0	12	18	18	36
	1-R	88.5	90.0	17	22	19	41
*	1-S	93.5	95.0	3	6	8	14
	1-T	98.5	100.0	5	5	6	11
	1-U	103.5	105.0	4	5	6	11
*	1-V	108.5	110.0	3	6	7	13
*	1-W	113.5	115.0	6	15	16	31
*	1-X	118.5	120.0	13	21	27	48

1-S has 4 jar samples of clay

Project# DP1-0030 (005) Division 9th

Station ______ Offset ______ Ft ______

Ground Elev. 0.0 Water Elev. in Hole ______

Depth of Strata BOR# B-2 Visual BOR Loc. ______

From	To	Consistency or Density	Approx. Moisture	Color	Basic Mat'l.
0.0	0.2	Topsoil	—		
0.2	3.5	Loose	Moist	Br	Sand
3.5	8.5	Med	Moist	Br	Sand
8.5	13.5	V Loose	Moist	Br	Sand
13.5	23.5	Med	Moist	Gray	Sand
23.5	28.5	Dense	Moist	Tan	Sand
28.5	33.5	Med	Moist	Tan	Sand
33.5	58.5	Dense	Moist	Tan	Sand
58.5	78.5	Med	Moist	Tan	Sand
78.5	89.5	Dense	Moist	Tan	Sand
89.5	93.5	Stiff	Moist	Gray	Clay
93.5	103.5	V Stiff	Moist	Gray	Clay
103.5	108.5	Stiff	Moist	Gray	Clay
108.5	115.0	Med	Moist	Gray	Sand

Remarks by Driller ______

GPS Cord. ______

LAT. ______

LONG. ______

County Mobile Date 8-9-12

______ C/L Driller Turner / Evans

Type Drill Used SE 9050 Total Hole Depth 115.0

Identification CME 550X 2.25 Hollow Stems

Other Pertinent Components		Sample No.	Penetration or Sample Elev. From	To	"N" Blow .5	1.0	1.5	"N" Value
	*	2-A	0.0	1.5	4	4	4	8
w/Gravel	*	2-B	3.5	5.0	5	7	9	16
w/org. mat'l	*	2-C	8.5	10.0	1	1	1	2
	*	2-D	13.5	15.0	2	5	7	12
		2-E	18.5	20.0	5	4	7	11
	*	2-F	23.5	25.0	16	18	19	37
		2-G	28.5	30.0	10	11	12	23
	*	2-H	33.5	35.0	7	15	16	31
		2-I	38.5	40.0	7	13	20	33
		2-J	43.5	45.0	9	14	19	33
w/Sand &		2-K	48.5	50.0	7	15	18	33
org. mat'l		2-L	53.5	55.0	10	16	18	34
	*	2-M	58.5	60.0	10	10	10	20
		2-N	63.5	65.0	6	12	11	23
		2-O	68.5	70.0	12	17	10	27

* Jar Sample

Project# ______ Division ______

Station ______ Offset ______ Ft ______

Ground Elev. ______ Water Elev. in Hole ______

Depth of Strata BOR# B-2 Visual BOR Loc. ______

From	To	Consistency or Density	Approx. Moisture	Color	Basic Matl.

Remarks by Driller ______

GPS Cord. ______

LAT. ______

LONG. ______

County ______ Date 8-9-12

______ C/L Driller ______

Type Drill Used ______ Total Hole Depth 115.0

Identification

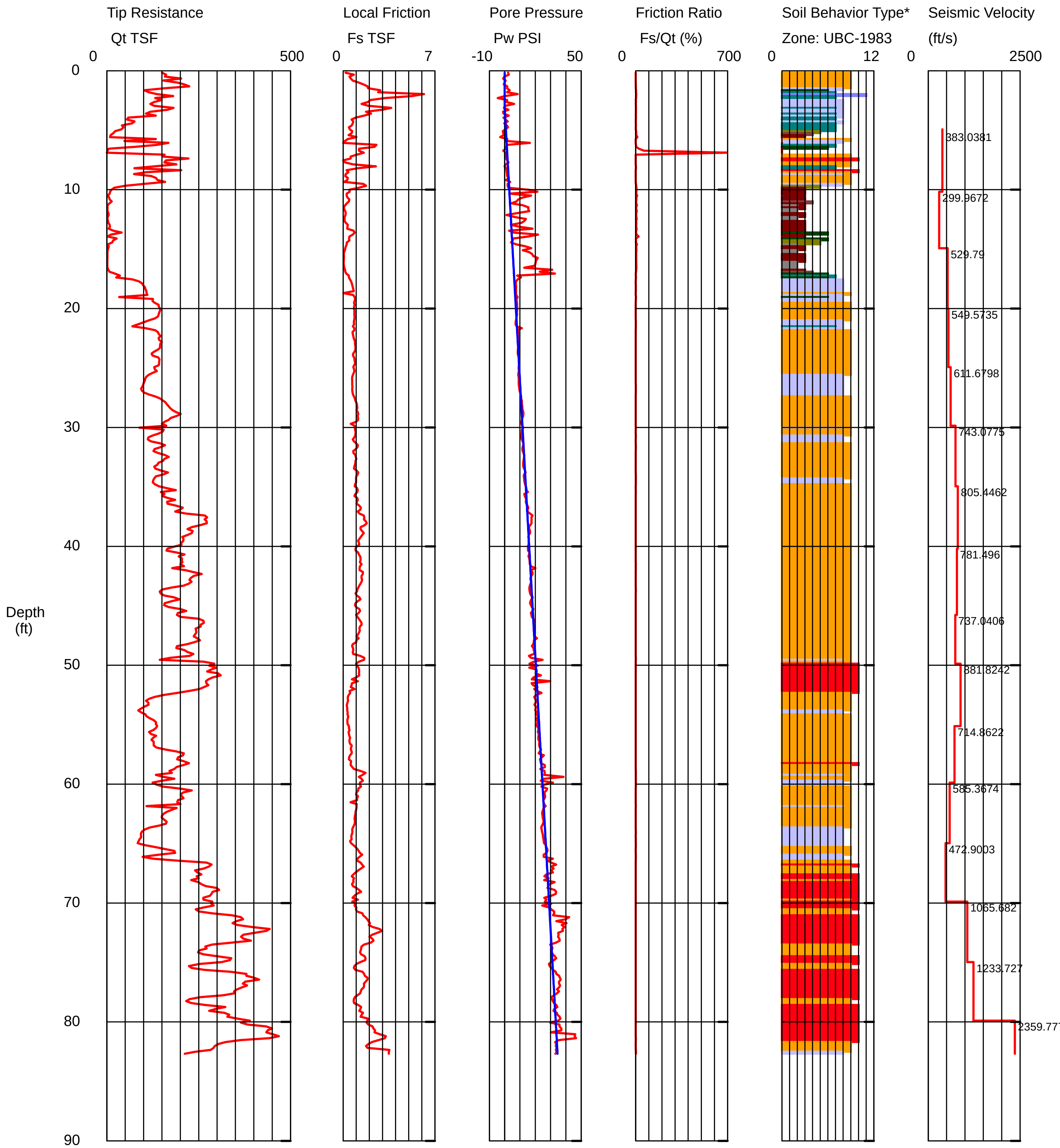
Other Pertinent Components	Sample No.	Penetration or Sample Elev. From	To	"N" Blow .5	1.0	1.5	"N" Value
	2-P	73.5	75	6	7	10	17
*	2-Q	78.5	80.0	6	11	21	32
	2-R	83.5	8.50	12	18	23	A1
*	2-S	88.5	90.0	4	4	4	8
*	2-T	93.5	95.0	6	7	8	15
*	2-U	98.5	100.0	1	9	8	17
*	2-V	103.5	105.0	2	4	6	10
*	2-W	108.5	110.0	5	9	13	22
	2-X	113.5	115.0	6	9	13	22

2-T has 3 Jars
2-U has 2 Jars
2-V has 3 Jars

Southern Earth Sciences

Operator: Mike Wright
Sounding: SCPT-1
Cone Used: DDG0892

CPT Date/Time: 8/14/2013 9:08:56 AM
Location: Test Pile Evaluation
Job Number: 13-000



Maximum Depth = 82.68 feet

Depth Increment = 0.164 feet

1 sensitive fine grained	4 silty clay to clay	7 silty sand to sandy silt	10 gravelly sand to sand
2 organic material	5 clayey silt to silty clay	8 sand to silty sand	11 very stiff fine grained (*)
3 clay	6 sandy silt to clayey silt	9 sand	12 sand to clayey sand (*)

Groundwater measured at 3.1'

N30.68546 W88.03791

*Soil behavior type and SPT based on data from UBC-1983

CONE PENETRATION TEST LOG

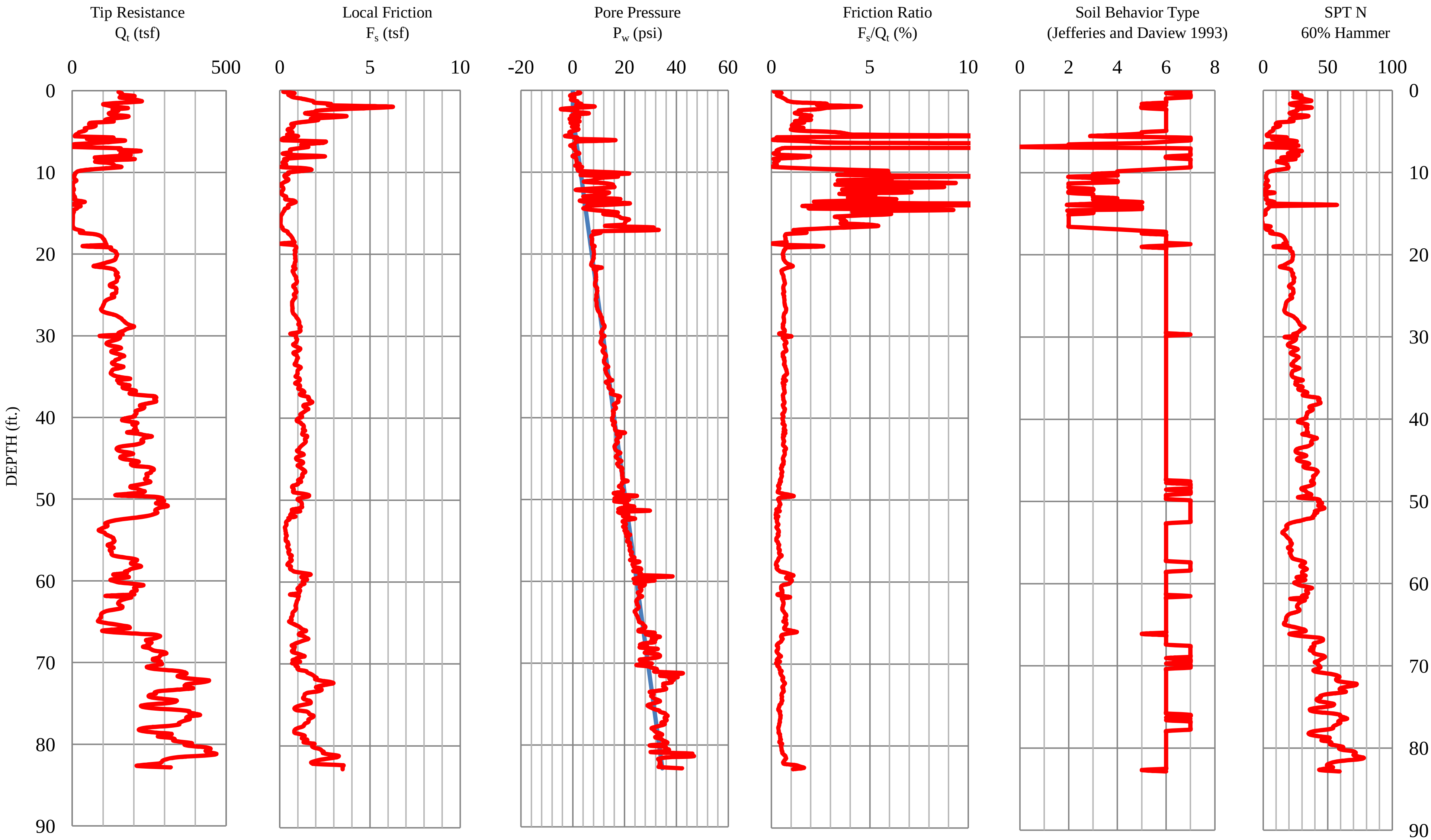
SOUTHERN EARTH SCIENCES, INC.

Geotechnical, Environmental & Construction Materials Testing

Project Name: Test Pile Evaluation
Project No.: 13-000
Sounding: SCPT-1

Cone Used: DDG0892
Operator: Mike Wright
CPT Date: 8/14/2013

Groundwater Level: 3.1 feet
Elevation: Unknown
Lat/Long: N30.68546 W88.03791



Baseline Data:

	Q_t (tsf)	F_s (tsf)	P_w (psi)
Initial Baseline:	0	0	0
Final Baseline:	-0.602	0.002	-0.172

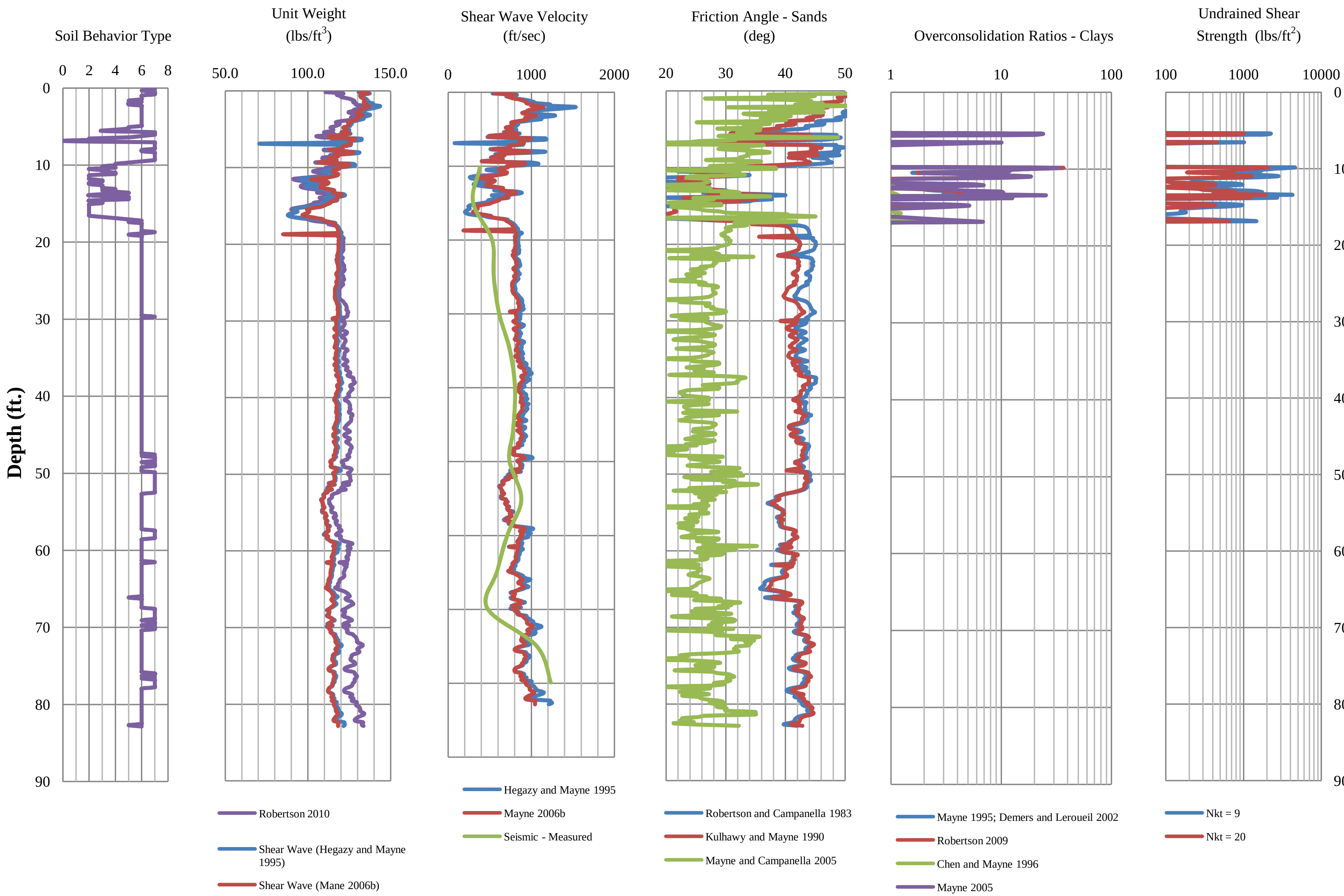
SPT N, SOIL BEHAVIOR TYPE, OR ZONE NUMBER FROM CPT CLASSIFICATION INDEX, Ic

Organic Clay Soils = 2, Clays = 3, Silt Mixtures = 4, Sand Mixtures = 5, Sands = 6, Gravelly Sands = 7

CONE PENETRATION TEST LOG

SOUTHERN EARTH SCIENCES, INC.
Geotechnical, Environmental & Construction Materials Testing

Project Name:	Test Pile Evaluation	**Cone Used:**	DDG0892	**Groundwater Level:**	3.1 feet
Project No.:	13-000	**Operator:**	Mike Wright	**Elevation:**	Unknown
Sounding:	SCPT-1	**CPT Date:**	8/14/2013	**Lat/Long:**	N30.68546 W88.03791

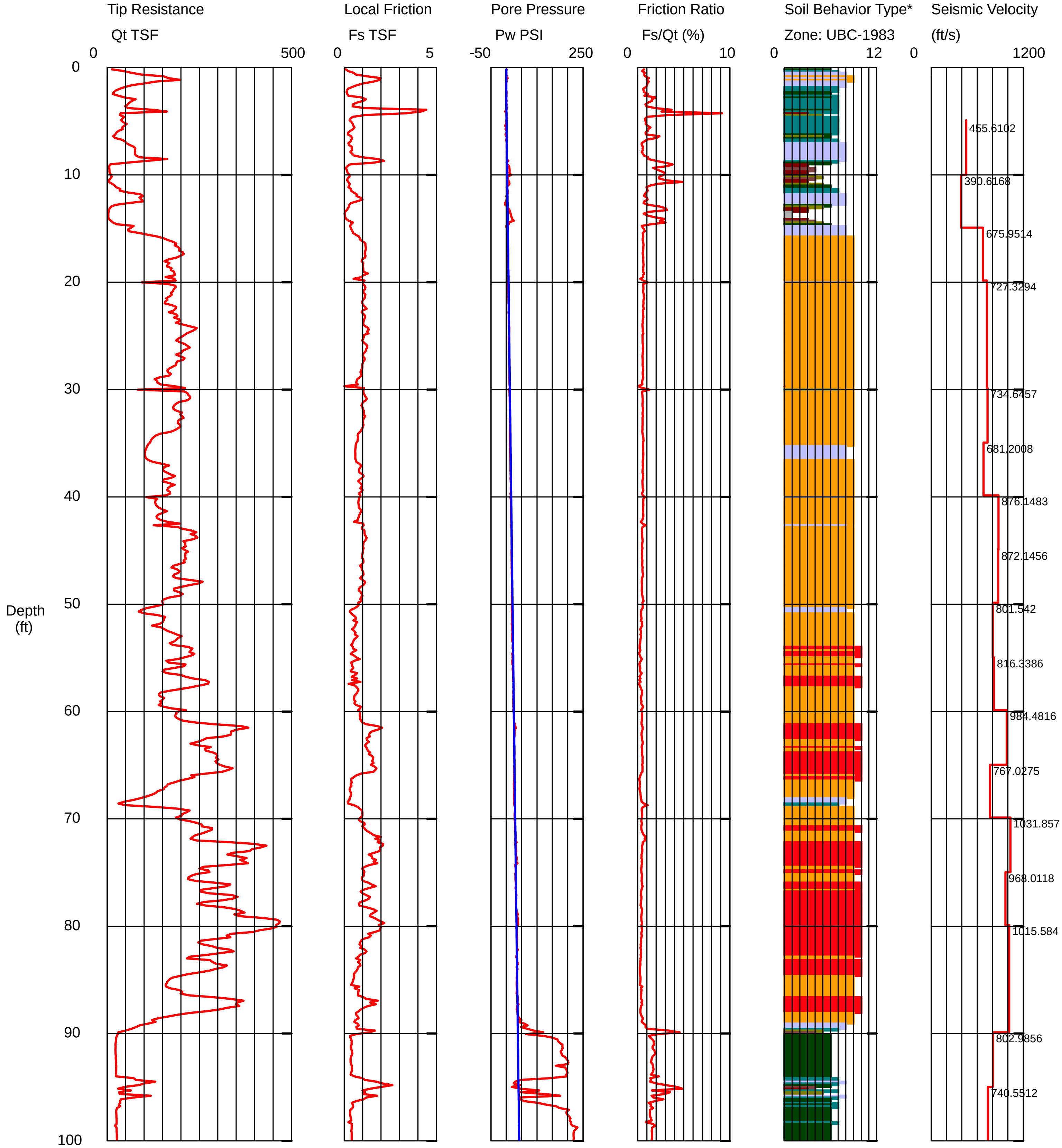


PARAMETERS ABOVE ARE BASED UPON EMPIRICAL CORRELATIONS AND SHOULD BE CONSIDERED APPROXIMATE. IT IS RECOMMENDED THAT CALCULATED PARAMETERS BE CORRELATED BY SPECIFIC LABORATORY DATA AND/OR LOCAL EXERIENCE.

Southern Earth Sciences

Operator: Mike Wright
Sounding: SCPT-2
Cone Used: DDG0892

CPT Date/Time: 8/14/2013 10:35:15 AM
Location: Test Pile Evaluation
Job Number: 13-000



Maximum Depth = 99.90 feet

Depth Increment = 0.164 feet

1 sensitive fine grained	4 silty clay to clay	7 silty sand to sandy silt	10 gravelly sand to sand
2 organic material	5 clayey silt to silty clay	8 sand to silty sand	11 very stiff fine grained (*)
3 clay	6 sandy silt to clayey silt	9 sand	12 sand to clayey sand (*)

Groundwater measured at 3.2'

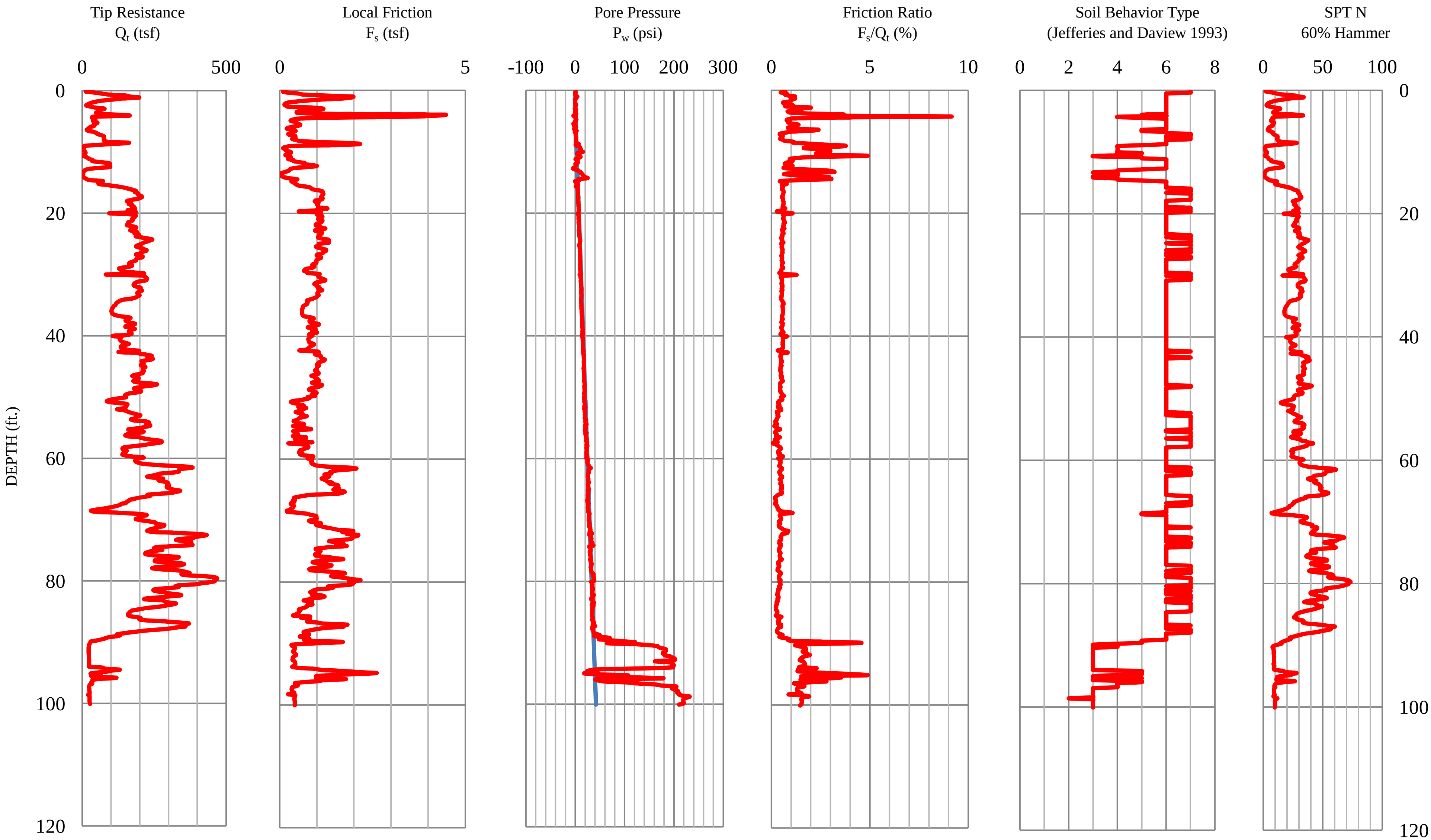
N30.68541 W88.03821

*Soil behavior type and SPT based on data from UBC-1983

CONE PENETRATION TEST LOG

SOUTHERN EARTH SCIENCES, INC.
Geotechnical, Environmental & Construction Materials Testing

Project Name:	Test Pile Evaluation	**Cone Used:**	DDG0892	**Groundwater Level:**	3.2 feet
Project No.:	13-000	**Operator:**	Mike Wright	**Elevation:**	Unknown
Sounding:	SCPT-2	**CPT Date:**	8/14/2013	**Lat/Long:**	N30.68541 W88.03821



Baseline Data:

	Q_t (tsf)	F_s (tsf)	P_w (psi)
Initial Baseline:	0	0	0
Final Baseline:	0.357	0.012	0.210

SPT N, SOIL BEHAVIOR TYPE, OR ZONE NUMBER FROM CPT CLASSIFICATION INDEX, Ic

Organic Clay Soils = 2, Clays = 3, Silt Mixtures = 4, Sand Mixtures = 5, Sands = 6, Gravelly Sands = 7

SOUTHERN EARTH SCIENCES, INC.

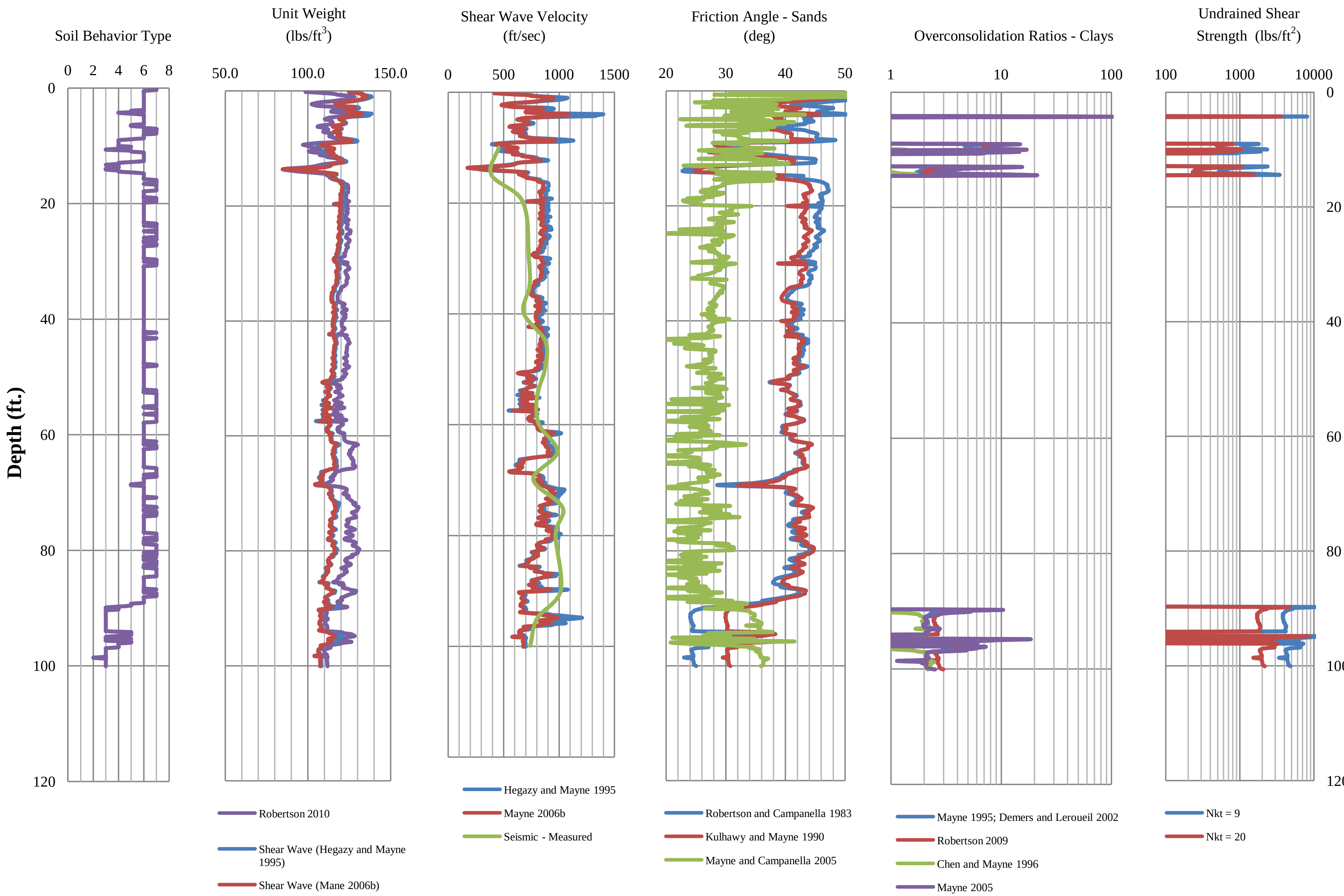
Geotechnical, Environmental & Construction Materials Testing

CONE PENETRATION TEST LOG

Project Name: Test Pile Evaluation
Project No.: 13-000
Sounding: SCPT-2

Cone Used: DDG0892
Operator: Mike Wright
CPT Date: 8/14/2013

Groundwater Level: 3.2 feet
Elevation: Unknown
Lat/Long: N30.68541 W88.03821



PARAMETERS ABOVE ARE BASED UPON EMPIRICAL CORRELATIONS AND SHOULD BE CONSIDERED APPROXIMATE. IT IS RECOMMENDED THAT CALCULATED PARAMETERS BE CORRELATED BY SPECIFIC LABORATORY DATA AND/OR LOCAL EXERIENCE.

Appendix B: Pile Driving Hammer Information

	Fuel Setting #1	Fuel Setting #2	Fuel Setting #3	Fuel Setting #4
Concrete Piles used Delmag Model D-62-22 Single Acting Diesel Hammer				
36 in PCP				
Setting Usage	Down to 43 feet	43 to 45 feet	45 to 48 feet	48 feet to end Restrikes
Rated Energy	78,960 ft. lbs.	109,725 ft. lbs.	138,960 ft. lbs.	165,000 ft. lbs
24 in PCP				
Setting Usage	Down to 61 feet	61 feet to end Restrikes	N/A	N/A
Rated Energy	78,960 ft. lbs.	109,725 ft. lbs.		
Steel Piles used APE Model D30-42 Single Acting Diesel Hammer				
HP 14				
Setting Usage	N/A	N/A	Entire depth Restrikes	N/A
Rated Energy			66,977 ft. lbs.	
HP 12				
Setting Usage	N/A	Entire depth Restrikes	N/A	N/A
Rated Energy		55,070 ft. lbs		

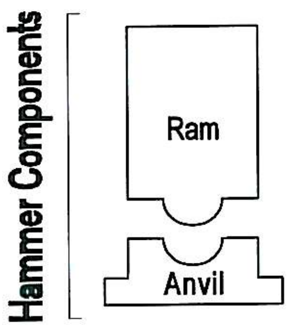
FORM C-14 **ALABAMA DEPARTMENT OF TRANSPORTATION**

Revised 08-07-95 **PILE AND DRIVING EQUIPMENT DATA FORM**

Project Number	County	Division
USA Test Pile & Vibration	Mobile	9th

Pile Driving Contractor or Subcontractor	Bridge Identification Number
Jordan Pile Driving Inc.	N/A

Details of access method to pile top for dynamic testing are: ☐ Attached ☒ Not Applicable



Hammer

Manufacturer: Delmag Model: D-62-22

Type: S.A. Diesel Serial No.: 238

Rated Energy: 165,000 (ft.-lbs.) at 11.3 (ft.) Length of Stroke

Modifications: Adjustable Fuel Pump

Pump Setting 1	78,960 ft. lbs.
Pump Setting 2	109,725 ft. lbs.
Pump Setting 3	136,950 ft. lbs.
Pump Setting 4	165,000 ft. lbs.

Capblock (Hammer Cushion)

Material: Aluminum & Micarta Alternating

Thickness: 6 (in.) Area: 381 (in.^{2})

Modulus of Elasticity - E : 450 KSI (P.S.I.)

Coefficient of Restitution - e : 0.8

Pile Cap

Helmet ✓
Bonnet
Anvil Block
Drivehead

Weight : 10,000 (lbs.)

Note: Should include weight of striker plate.

Pile Cushion

Cushion Material: Plywood

Thickness: 10 (in.) Area: 576 (in.^{2})

Modulus of Elasticity - E : 45 KSI (P.S.I.)

Coefficient of Restitution - e : 0.5

Pile

Pile Type: 36" x 36" & 24" x 24" Prestressed Concrete Test Pile

Length (in Leads): 89' & 81' (ft.)

Weight / Ft: 936 & 510 (lbs./ft.)

Wall Thickness: NA (in.) Taper: NA

Cross Sectional Area: 489 & 898 (in^2)

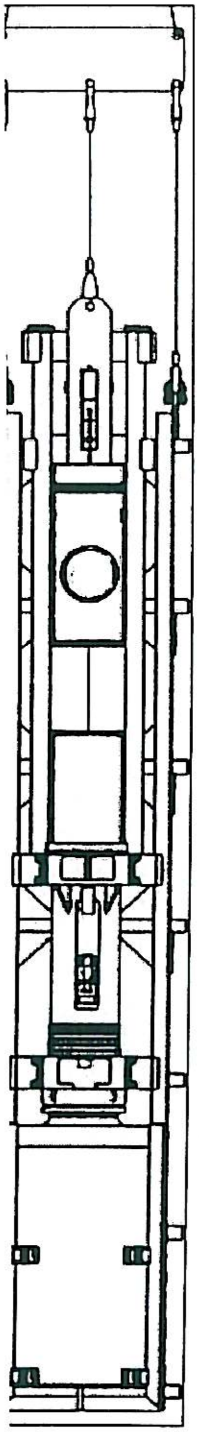
Design Pile Capacity: ______ (Tons)

Description of Splice: N/A

Tip Treatment Description: N/A

Note: If mandrel is used to drive this pile, attach separate manufacturer's detail sheet(s) including weight and dimensions.

Submitted By: Davis Daniel Date: ______



Model D62-22 Diesel Hammer

Maximum obtainable energy	203,216 ft-lbs
Maximum obtainable stroke	178 inches
Pump setting 1: (minimum)	78,956 ft-lbs
Pump setting 2:	109,749 ft-lbs
Pump setting 3:	137,186 ft-lbs
Pump setting 4: (maximum)	164,250 ft-lbs
Stroke at rated energy	135 inches
Energy at rated stroke	165,000 ft-lbs
Speed (blows per minute)	36-50
Ram	13,700 lbs
Anvil	2,833 lbs
Hammer weight (includes trip device)	29,491 lbs
Typical operating (weight with drive cap)	32,963 lbs
Fuel tank (runs on diesel or bio-diesel)	25.86 gal
Oil tank	8.32 gal
Weight	1100 lbs
Diameter	25 inches
Thickness	8 inches
Type	Monocast MC 901
Diameter	25 inches
Thickness	2 inches
Elastic-modulus	285 kips per square inch
Coeff. of restrituion	0.8
Weight (fits 8 by 26 inch leads)	1,350 lbs
Diesel or Bio-diesel fuel	5.28 gal/hr
Lubrication oil	0.84 gal/hr
**Grease twice per day	
Length overall	232.6 inches
Length over cylinder extension	272.0 inches
Impact block diameter	27.9 inches
Width over bolts	32.6 inches
Hammer width overall	31.5 inches
Width for guiding- face to face	22.0 inches
Hammer center to pump guard	19.3 inches
Hammer center to bolt center	15.0 inches
Hammer depth overall	38.2 inches
Minimum clearance for leads	19.7 inches

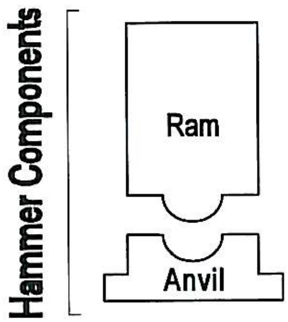
FORM C-14 **ALABAMA DEPARTMENT OF TRANSPORTATION**

Revised 08-07-95 **PILE AND DRIVING EQUIPMENT DATA FORM**

Project Number	County	Division
USA Test Pile & Vibration	Mobile	9th

Pile Driving Contractor or Subcontractor	Bridge Identification Number
Jordan Pile Driving Inc.	N/A

Details of access method to pile top for dynamic testing are: ☐ Attached ☒ Not Applicable



Hammer

Manufacturer: APE Model: D30-42

Type: S.A. Diesel Serial No.: ____

Rated Energy: 74,419 (ft.-lbs.) at 11.25 (ft.) Length of Stroke

Modifications: Adjustable Fuel Pump

Pump Setting 1	37,209 ft. lbs.
Pump Setting 2	55,070 ft. lbs.
Pump Setting 3	66,977 ft. lbs.
Pump Setting 4	74,419 ft. lbs.

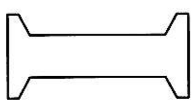
Capblock (Hammer Cushion)

Material: Aluminum & Micarta Alternating

Thickness: 4 (in.) Area: 398 (in.^{2})

Modulus of Elasticity - E : 285 (P.S.I.)

Coefficient of Restitution - e : 0.8



Pile Cap

Helmet ✓
Bonnet
Anvil Block
Drivehead

Weight : 1,704 (lbs.)

Note: Should include weight of striker plate.

Pile Cushion

Cushion Material: N/A

Thickness: N/A (in.) Area: N/A (in.^{2})

Modulus of Elasticity - E : N/A (P.S.I.)

Coefficient of Restitution - e : N/A

Pile

Pile Type: HP 12 x 53 & HP 14 x117

Length (in Leads): 70' & 106' (ft.)

Weight / Ft: 53 & 117 (lbs./ft.)

Wall Thickness: N/A (in.) Taper: NA

Cross Sectional Area: ____ (in^2)

Design Pile Capacity: ____ (Tons)

Description of Splice: Mechanical

Tip Treatment Description: ____

Note: If mandrel is used to drive this pile, attach separate manufacturer's detail sheet(s) including weight and dimensions.

Submitted By: ____ Date: ____

Davis Daniel

APE Model D30-42 Single Acting Diesel Impact Hammer

D30-42 Finishing Dolphin Piles.

Optional Variable Throttle Control.

Drive Base Assembly.

MODEL D30-42 (3.0 metric ton ram)

SPECIFICATIONS

Stroke at maximum rated energy	135 in (343 cm)
Maximum rated energy (Setting 4)	74,419 ft-lbs (100.47 kNm)
Setting 3	66,977 ft-lbs (90.42 kNm)
Setting 2	55,070 ft-lbs (74.34 kNm)
Minimum rated energy (Setting 1)	37,209 ft-lbs (50.23 kNm)
(Variable throttle allows for infinite fuel settings)	
Maximum obtainable stroke	157 in (381 cm)
Maximum obtainable energy	86,546 ft-lbs (117 kNm)
Speed (blows per minute)	34-53

WEIGHTS

Ram	6,615 lbs (3,000 kg)
Anvil	1,358 lbs (616 kg)
Anvil cross sectional area	367.94 in² (2373.80 cm²)
Hammer weight (includes trip device)	13,571 lbs (6,154 kg)
Typical operating (weight with DB26 and H-beam insert)	16,223 lbs (7,357 kg)

CAPACITIES

Fuel tank (runs on diesel or bio-diesel)	17.4 gal (65 liters)
Oil tank	5 gal (19 liters)

CONSUMPTION

Diesel or Bio-diesel fuel	2.6 gal/hr (9.84 liters/hr)
Lubrication	0.26 gal/hr (1 liters/hr)
Grease	8 to 10 pumps every 45 minutes of operation time.

STRIKER PLATE FOR DB 26

Weight	628 lbs (284 kg)
Diameter	22.5 in (57.15 cm)
Area	398 in² (2567.74 cm²)
Thickness	6 in (15.24 cm)

CUSHION MATERIAL

Type/Qty	Micarta / 2 each
Diameter-DB26	22.5 in (57.15 cm)
Thickness	1 in (25.4 mm)
Type/Qty	Aluminum / 3 each
Thickness	1/2 in (12.7 mm)
Diameter	22.5 in (57.15 cm)
Total Combined Thickness	3.5 in (8.89 cm)
Area	398 in² (2567.74 cm²)
Elastic-modulus	285 ksi (1,965 mpa)
Coeff. of restitution	0.8

DRIVE CAP

DB 26:	1,076 lbs (488 kg)

INSERT WEIGHT

H-Beam insert for 12" (305 mm) and 14" (355 mm):	948 lbs (430 kg)
Large pipe insert for sizes 12" to 24" diameter:	1,830 lbs (830 kg)

MINIMUM BOX LEAD SIZE/OPERATING LENGTH

Minimum box leader size	8 in x 26 in (20.32 cm x 66 cm)
Operating length as described above	354 in (900 cm)

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