Hydroacoustic Parametric Study of Pile Driving-Induced Anthropogenic Sound

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Abstract

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Anthropogenic sound in Florida's waters and coastal waterways is most commonly caused by overwater development, marine traffic, and military activity. Overwater construction has increased over the years as a result of aging infrastructure and rising expansions around the United States, including more than forty US Naval facilities containing tens of thousands of feet of pier. Construction methodology, such as pile driving, has risen in shallow waters to build structures such as bridges, piers, and wind farms, with significant consequences for marine life and the environment. More precisely, pile driving activities generate significant decibel levels in the surrounding marine environment. Measurements taken from hydrophones placed in the water near the construction site indicate that the high sound pressure levels produced may be harmful to marine life and the environment. As a result, standards have been established to help alleviate and decrease the possible harm that high decibel sound levels may produce. However, these additional steps increase the overall cost of the construction project. This thesis focuses on replicating the pile driving process using finite element modeling to hydroacoustic parametric study of pile driving-induced anthropogenic sound in neighboring Florida seas, as well as the possible environmental impact of the state's numerous naval base piers. The modeling predictions can then be used to identify the distance from the pile at which marine life and the environment are no longer adversely affected. In addition, computer modeling can reduce construction costs when compared to on-site sensors and monitoring.

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General Audience Abstract

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Abstract

Over recent years there has been an increase in the amount of manmade noise in Florida and its coastal waterways due to overwater construction, marine traffic, and military activities. Pile driving construction has increased in shallow waters to build infrastructure, which includes bridges, piers, and wind farms, resulting in a negative impact for marine life and the environment. Federal agencies have established guidelines to ease the harmful effects construction has on marine life and the environment. However, there is concern that these recent guidelines may not properly consider all the geometric and hydrographic variables of manmade noise that affect the high sound exposure levels during pile driving. With a more accurate understanding of the sound generation produced from pile driving, predictions can assist with sound mitigation to ensure less harm to the marine life and environment. In turn, construction companies and government agencies informed with this enhanced understanding can make better decisions that lead to fewer (or possibly eliminate) transmission loss discrepancies and costly noise mitigation measures. Consideration of the marine environment is one of the United States Navy's top priorities with naval stations located throughout the State of Florida that possess thousands of feet of waterfront structures, including piers, requiring routine maintenance and construction. This thesis models the pile driving process through finite element modeling in COMSOL Multiphysics computer software, testing the various parameters that Florida waters may encounter with pile driving on the surrounding coast as well as naval bases.

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1. Introduction

Construction efforts have significantly increased over the years to update aging infrastructure throughout the United States (U.S.), including the U.S. Navy's various waterfront infrastructure across forty U.S. naval installations to include piers, pylons, and other overwater structures [1-2]. The construction process to replace and repair waterfront infrastructure often requires marine pile driving, which raises concern due to the anthropogenic noise. The sound pressure waves created from pile driving pose potential threats to underwater marine life that can result in harm or even death. Over the last 14 years, studies have investigated how pile driving sound levels correlate to resulting harm for marine life [2-13]. Additionally, previously completed pile driving projects report construction cost increases due to the popularity of environmental monitoring initiatives. [14-16].

Federal agencies have implemented guidelines and environmental monitoring procedures that have become more regulated during construction activities to mitigate the effects of the sound levels produced. The current guidelines are based on a simplified transmission loss formula [1-5,12,13]. The State of Florida is one of the many locations where increased construction is taking place due to its popular coastal attractions and constant need for increased infrastructure. Florida also follows the simplified transmission loss formula for pile driving along its coasts [4-5,12,13].

Recent reviews examined the most relevant federal policies and guidelines in place to protect marine life and their environment from underwater pile driving noise [4-5,12,13]. This work presents simulated results of underwater anthropogenic noise due to waterfront pile driving using finite element modeling (FEM) through COMSOL Multiphysics computer software. The simulated results are compared with recent measurements collected from various construction sites within Florida waters to determine if discrepancies exist from anthropogenic noise in the field compared to the federal guidelines and policies in place, which will be covered in later sections [5,12,13]. The ability to predict sound propagation due to pile driving can not only protect the marine life and environment but assist the U.S. Navy to meet its operational mission requirements while maintaining compliance with federal guidelines.

2. Background

2.1. Policies and Procedures

Over the past 15 years, various policies have been put in place to mitigate the effects of marine pile driving construction. This section of the literature review examines the most relevant policies. In 2009, ten federal agencies, as part of the Joint Subcommittee of Ocean Science and Technology (JSOST), formed an interagency task force on anthropogenic sound and the marine environment [17]. As a result of this task force, the agencies agreed on high priority research recommendations to:

(1) "Develop and validate mitigation measures to minimize demonstrated adverse effects from anthropogenic noise" [17].

(2) "Test/validate mitigation measures to minimize sound output and/or explore alternatives to sound sources with adverse effects" [17].

(3) "Explore need for and effectiveness of time/area closures versus operational mitigation measures" [17].

The National Marine Fisheries Service (NMFS) Policy was initially issued in November 2016. This policy was created with offices throughout the National Oceanic and Atmospheric Administration (NOAA) to develop the Ocean Noise Strategy Roadmap (Strategy Roadmap). The goal of the Strategy Roadmap is to minimize the effects of anthropogenic noise over the next 10 years [18].

In December 2016, shortly after the release of the new 2016 NMFS policy, the Florida Department of Transportation (FDOT) accepted all assigned National Environmental Policy Act (NEPA) responsibilities from the Federal Highway Administration (FHA), which resulted in a memorandum of understanding that was renewed in May 2022 [19]. The memorandum stated that the FDOT Office of Environmental Management would continue to verify NEPA compliance on all federal roadway projects statewide [19]. Additionally, the NMFS and the United States Fish and Wildlife Service (USFWS) voiced concerns about anthropogenic noise generated from pile driving and the lasting effects on marine life [19]. An increase in policies and monitoring procedures for waterfront construction is expected as concerns grow from these agencies, and infrastructure ages and sea levels rise. If policies and monitoring procedures become more regulated, construction costs may increase with the required additional measures in place [14-16]. Additionally, construction completion times would slow down and could be delayed in order to comply with the extra monitoring procedures. As a result, it is essential that all parties involved in the process understand the sound levels produced during construction activities to ensure the correct measures are in place to protect marine life and their environment. If construction companies fail to comply with policies and regulations in place, it can result in not only harm to the animals and the environment, but legal consequences.

The anthropogenic noise level transmitted during pile driving leads to dangerous sound-exposure levels and poses a threat to the marine environment. To determine the threshold for safe versus dangerous sound, studies typically focus on transmission loss values [4-5,12,13]. Key stakeholders from Federal Highway Administration (FHWA), NOAA, NMFS, USFWS, Departments of Transportation from California, Oregon, and Washington, and national experts gathered to develop a common interim criterion for injury to fish to assess the potential impacts of pile driving to protect specified fish and their habitat [4,20]. Table 1 summarizes the results produced from the stakeholder meeting which the Florida Department of Transportation also follows [4,13].

Table 1: Guidelines for underwater sound produced by impact pile driving [4]

Effect	Metric	Fish Mass	Threshold (dB re 1 μPa)
Onset of Physical Injury	Peak Pressure (L_{peak})	N/A	206 dB
	Accumulated Sound Exposure Level ($SEL_{cumulative}$)	$\geq 2g$	187 dB
		$< 2g$	183 dB
Adverse Behavioral Effects	Root Mean Square Pressure (RMS)	N/A	150 dB

Each fish species is unique and is therefore affected by sound differently. It is important to recognize the metrics for the subsequent studies and what the thresholds are for various fish, which will be expanded on in the following sections. The values in Table 1 provide a baseline overview of underwater sound thresholds to provide readers with increased awareness of the severity of damage that pile driving creates.

2.2 Sound and Transmission Loss

In order to understand the effects of sound, one must first understand what sound is and how it is measured. Sound is defined as "small disturbances in a fluid from ambient conditions through which energy is transferred away from a source by progressive fluctuations of pressure (or sound waves)" [4]. For the purposes of this review, the pile is the source that vibrates due to the impact of the hydraulic hammer. The vibration then causes a pressure difference as the vibrations travel longitudinally (through fluids and gases) [4]. The magnitude of the sound waves measured is the sound level, usually measured in decibel (dB), which includes the sound pressure level (SPL). SPL is referred to as Peak Pressure in Table 1 and annotated as Peak in Figure 1.

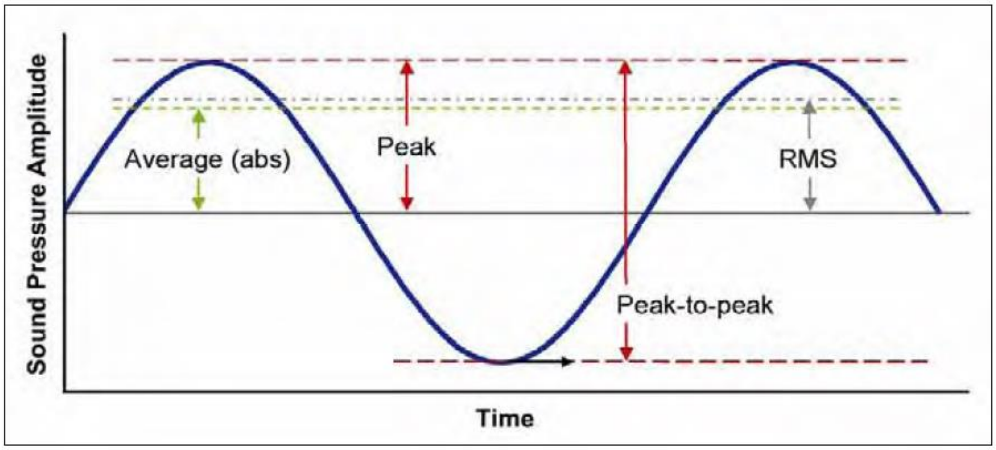


Figure 1: Sound level metrics [4]

The root-mean-squared (RMS) sound pressure is the square root of the squared pressure average over a period of time. RMS pressure is usually utilized with impulsive sounds and is measured in pascal (Pa) and can be calculated by:

$$p_{rms} = \sqrt{\frac{1}{\tau}\int_{\tau} p^2(t)dt} \qquad (1)$$

where τ is the pulse duration in seconds and p is the sound pressure level in pascals (Pa) [4,13,21].

The sound pressure level (SPL) is the decibel representation of the RMS acoustic pressure as defined in equation (2):

$$SPL_{rms} = 20\, log\, (\frac{p_{rms}}{p_{ref}}) \qquad (2)$$

where p_{rms} is the pressure exerted by the sound and p_{ref} is the reference pressure (i.e. $1\mu Pa$ for water) [4,21].

Lastly, the sound exposure level (SEL) is the decibel representation of sound energy levels over time as defined in equation (3) below [5]:

$$SEL = 10\, log \int_0^T p^2(t)dt \qquad (3)$$

where T is the time of the sound event in seconds.

Transmission loss (TL) is defined as a quantitative value to describe the sound attenuation or loss, at a specific range using the distances from the source and the receiver. As the range increases from the source, the sound level attenuation increases. Transmission loss calculations can vary depending on distances from a source point. For distances closer to the pile, spherical spreading is more dominate and equation (4) may be used to calculate transmission loss in decibels (dB) [5].

$$TL = -10\ log_{10}\left(\frac{I}{I_o}\right) = \ 10\ log_{10}(R^2) = \ 20\ log_{10}\left(\frac{R}{R_o}\right) \tag{4}$$

The value *I* is the transmitted sound intensity and I_o is the inbound sound intensity. The value *R* is the range from the source and R_o is the reference range. However, for distances further away from the pile, cylindrical spreading is more dominate and transmission loss, in dB, can be calculated using equation (5) [5]:

$$TL = -10\ log_{10}\left(\frac{I}{I_o}\right) = \ 10\ log_{10}\left(\frac{R}{R_o}\right) \tag{5}$$

The studies in this review and current guidelines use the practical spreading loss model (PSLM) which was recommended by Buehler et al. (2015) to split the difference between equations (4) and (5), spherical and cylindrical spreading respectively, resulting in equation (6) [4,5]:

$$TL = F\ log_{10}(R) \tag{6}$$

Where TL is a function of a constant *F* (transmission loss coefficient) multiplied by the base 10 logarithm of the range (*R*) from the source point [12,13].

The National Marine Fisheries Service (NMFS) guidelines and the Navy use *F = 15* to be assumed [4-5,12,13]. This assumption uses the practical spreading loss model, and simplifies the transmission loss for fish which is given by:

$$TL = 15\ log_{10}(R) \tag{7}$$

Equation (7) assumes that sound is projected as a monopole point source and most of the transmission loss is due to mode stripping [12,13]. Equation (7) is straightforward to implement; however, a disadvantage is that the transmission loss data is often underestimated. When equation (7) is simplified, 24 input parameters including water depth, bottom loss, and the concept that different sound frequencies are attenuated differently are not considered [4,5,12,13,17, 22]. As a result, data may be over conservative, but this is the simplest model to use during construction.

In conjunction with anthropogenic noise prediction models, studies of anthropogenic noise mitigation strategies have been conducted [23-29]. The three most common sources of physical noise mitigation strategies are air bubble curtains, screens, and pile casings. When they are used, the three mitigation strategies mentioned can individually be placed around the exterior of a pile to produce a buffer in the water between the sound source (the pile) and the receiver (possible marine life). For example, an air bubble curtain produces a constant stream of air bubbles that surround the pile absorbing the noise that pile driving produces. The use of air bubble curtains can reduce anthropogenic noise caused by pile driving up to 30 dB [30]. Applying one of the three aforementioned damping measures to pile driving construction is a method to reduce noise, but project managers should be aware that noise mitigation strategies typically increase the cost of the overall project [14-16]. This is due to costs associated with additional competent personnel who are trained to collect and interpret sound data as well as additional equipment needed for damping or monitoring [14-16].

2.3 Pile Driving Classification

The two main components of pile driving include the pile driver (or hammer) and the pile. There are three types of hammers that differ in their mechanical principles: 1. impact, 2. vibratory, and 3. push-in [30]. This paper focuses on impact and vibratory hammers. The general process of waterfront pile driving utilizes a pile of material and geometry, shown below in Figure 2, that is driven into the seabed with the use of a hydraulic hammer (hydraulic impact or vibratory). This technique is used to position the piles into relatively shallow water for construction of offshore windfarms, bridge supports, wharfs, piers, and various other structures [3,5,31]. The type of pile and hammer used for construction depends on the structure to be built and its surrounding geological conditions. However, the choice in pile material and size factors into the resulting sound levels produced while pile driving as discussed later in this paper.

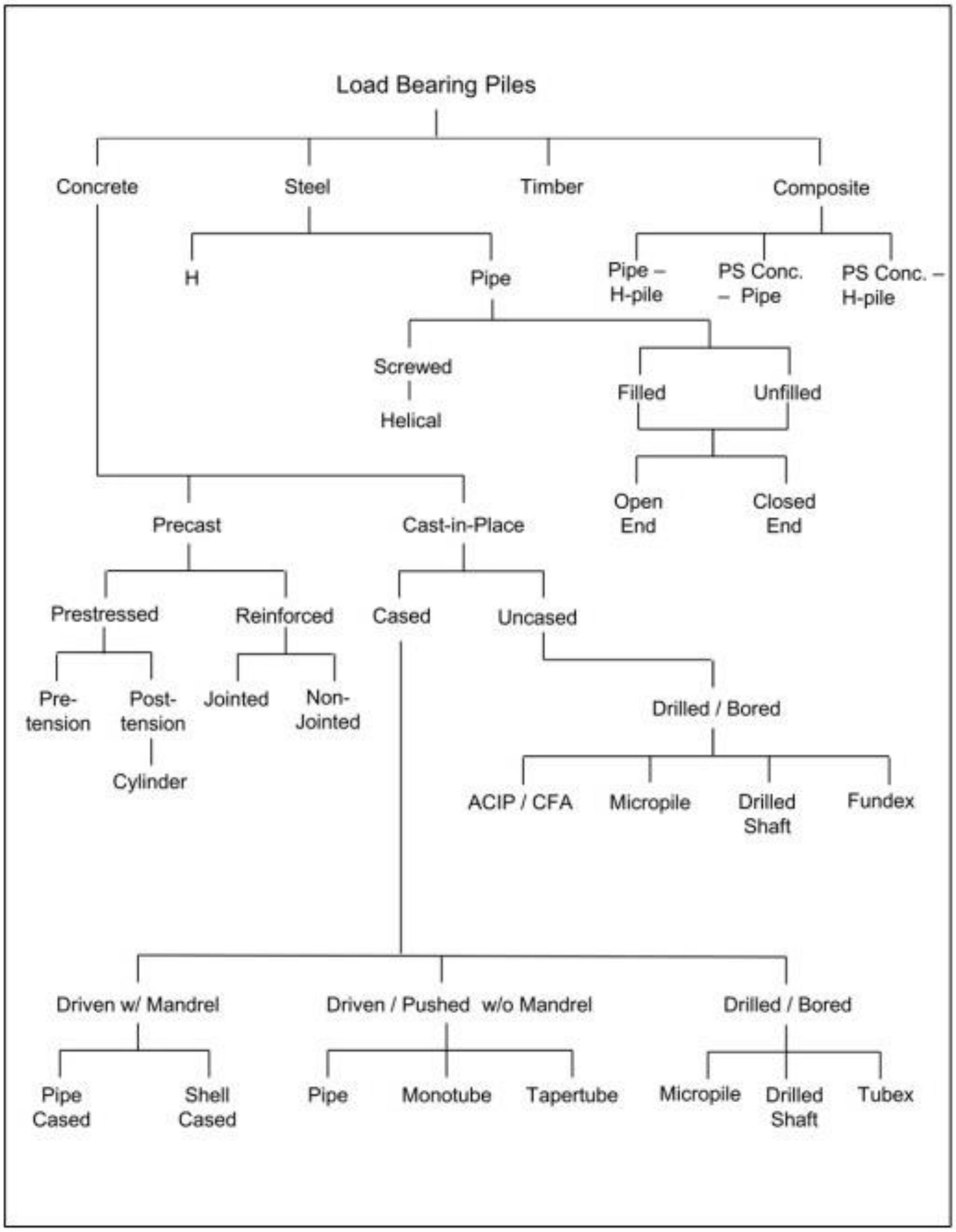


Figure 2: Pile classification chart [32]

The top row of Figure 2 displays what the primary material piles are composed of, and the columns in Figure 2 further breaks down the material into more specific geometries that result in the final product. A majority of the waterfront construction projects utilize concrete and/or steel piles due to their material properties and the environment the piles will be placed in, which will be discussed in the later sections.

Prestressed concrete piles are the most common in Florida waters [33]. Their applications are typically used where limestone stratum or dense stratum exists no deeper than 125 feet below ground [33]. Concrete piles are also commonly used in corrosive environments, such as pile driving in seawater [33]. Piles made of concrete typically have a hollow core to reduce weight for handling, however, the ends are usually capped to protect the pile from the hammer blows during driving.

Steel piles are not as common as concrete piles in Florida waters; however, they are typically used when a pile over 125 feet is required and/or geotechnical data displays variable subsurface conditions [33]. One advantage of utilizing steel piles is their ease of splicing to extend lengths by welding [33].

3. Objectives

This work utilized finite element modeling (FEM) through COMSOL Multiphysics computer software to simulate pile driving and compare the results to sound data collected at various pile driving sites within Florida waters. First, the case utilized parameters and software components of Reinhall and Dalh's study from Washington State to verify working FEM simulations [3]. Once verified, a parametric study similar to the University of North Florida (UNF) historical studies was investigated. The parametric study included analyzing different pile materials, pile diameters, and damping effects at various distances. Analysis of the resulting data will aid in a better understanding of the correlation between sound attenuation and the effects of pile driving parameters. The raw sound data collected was from a series of buoy systems in place at the multiple pile driving sites in the UNF studies and aided in the parametric setup of the FEM simulation. As a result, the simulated sound generated from pile driving could be predicted prior to construction based on known construction and environmental parameters. Additionally, if needed, the use of multiple sound mitigation measures such as a pile cushion can be input to bring sound levels within policy tolerance. These results can then be compared against the National Marine Fisheries Service guidelines in Table 1 for impact pile driving to predict if fish will be harmed or not. In addition, utilizing this data to predict the sound generation could reduce construction costs and satisfy marine environment policy [14-16].

4. Historical Data Collection

The section below covers past studies conducted by the University of North Florida (UNF) with the goal to collect sound data to calibrate transmission loss coefficients and measure sound exposure level from five pile driving sites in Northern Florida waters [5]. The UNF studies utilized a series of five buoys known as Pile Driving Analyzers (PDA) to collect data at each pile driving site [5]. The five PDAs collectively made up a data collection system that was employed at varying distances. Measurements were taken at five bridge sites in Florida waters that will be referred to as: Dunn’s Creek Bridge, Ribault River Bridge, Suwannee River Bridge, Bayway E Bridge, and John Sims Parkway Bridge [5].

4.1 Historical Data Collection System

The PDAs from the UNF experiment were designed by Jonathan Berube, a graduate student, to collect data of anthropogenic noise from waterfront pile driving [5]. Each PDA is made up of an aluminum frame, pontoons, electronics housing, a hydrophone with associated electronics, Wi-Fi mast, and an anchoring system, which is shown in Figure 3a and 3b. Five of these PDA’s made up the data collection system; each PDA was deployed at varying distances to collect data as described below.

Figure 3a (left) and 3b (right): pile driving analyzer [12]

Figure 3a shows the complete PDA system prior to being launched. This includes an anchoring system (buoy and anchor) used during data collection to secure the PDA in place on the river bottom. The 2-inch by 1-inch welded, rectangular tubing, aluminum frame was connected to two small pontoons for buoyancy. Each frame housed a Pelican 1450 box to hold the electronics.

Figure 3b illustrates the interior of the watertight Pelican 1450 box that houses the electronics. The inside of the electronic housing consists of “Bruel and Kjaer 2250 handheld analyzers; Bruel and Kjaer 2647 charge converters; L-Com BT-CAT5-P1 power-over-Ethernet converter; two 12-volt direct current motorcycle batteries connected in series; and Pace Scientific XR-440M pocket loggers for the thermocouples” [5]. The Wi-Fi capability allowed the researchers to project live sound data as the pile driving was in progress [5].

Prior to the deployment of the data collection system, electronics were charged and verified to be operational. The PDAs were deployed one at a time starting at approximately 25-meters from the pile driving location (but as close as safely possible), starting with Buoy 1, then doubling in distance, ultimately ending at a distance of 400 meters with Buoy 5 [5]. The buoys were then adjusted and relocated as needed to ensure they were within line of sight of the pile driving source [5]. While in the water, each PDA was attached to a river anchor to hold its position throughout data collection [5].

4.2 Suwannee River Bridge Site

The Suwannee River Bridge is located within the vicinity of Dowling Park, Florida [5]. As shown below, Figure 4 provides an aerial view of the Suwannee River Bridge location in Florida, depicted by the yellow pin, where the data was collected. The Suwannee River Bridge pile driving utilized a Del-Mag Model D-46 Impact Driver located at Jacksonville, Florida to set three steel trestle piles into the river [5].

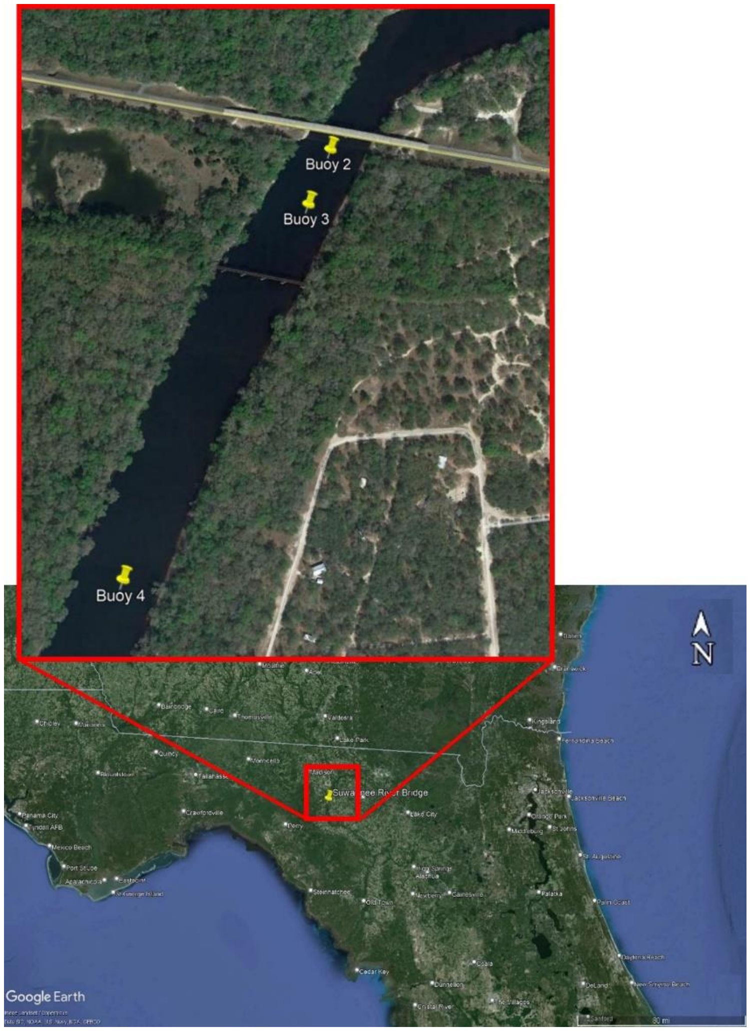


Figure 4: Suwannee River Bridge pile driving site location [5]

The piles consisted of three 24-inch diameter by 60-foot-long open-ended steel piles, driven 28 feet into the sediment [5]. The surface sediment was classified as fine to medium sand (SP). Additional details for the Suwannee River site are provided in Appendix A, including geotechnical boring logs and pile driver specifications.

Below, Table 2 summarizes the five pile driving sites from the past UNF study, which includes information about the pile, hammer, and number of piles. The COMSOL Multiphysics simulation will utilize similar parameters applied to the Suwannee River Bridge pile driving site.

Table 2: Pile and hammer summary [5]

Site Name	Pile Type	Hammer Type	Number of Piles
Dunn’s Creek Bridge	PZ-27 sheet pile steel	Model 200T Vibratory Hammer	2
Ribault River Bridge	24” square PCP	APE Model D36-42	4
Suwannee River Bridge	24” open ended steel pile	Del-Mag Model D46 Impact Driver	3
Bayway E Bridge	36” open ended steel pile	Model 200T Vibratory Hammer	1
John Sims Parkway Bridge	18” square PCP	BSP CX-85u Impact Driver	1

As previously discussed in the pile driving classification section, a mixture of steel and prestressed concrete piles (PCP) were used at the five pile driving sites, which aligns with Florida’s most popular pile material types. Referencing Florida’s most commonly selected pile materials helped guide the pile driving parameter selection for the COMSOL Multiphysics simulations, which will be discussed in the methodology section.

4.3 Historical Data Collection Analysis

At each of the five pile driving sites, relevant geotechnical boring logs and pile driver specifications were provided to the UNF research team which aided overall data collection [5]. As seen in Figure 5, an example of the sound signals collected at the Suwannee River Bridge pile driving site, where LZ_{peak} (the greatest value of the sound signal) is measured in decibels (dB). It was noted at this site that two of the five hydrophones and global position systems (GPS) unfortunately malfunctioned [5]. Due to the malfunctions, the distances of the PDA's were approximated utilizing a laser range finder onboard a nearby boat [5]. Data was collected from Buoy 2, 3, and 4 at an approximate buoy distance of 15 m, 65 m, and 502 m from the pile respectively [5]. The three spikes in the data represent the three pile driving tests at the Suwannee River Bridge site. It is evident as seen in Figure 5 that three pile driving events occurred, starting at approximately 08:40 and producing sound levels over 200 dB at Buoy 2.

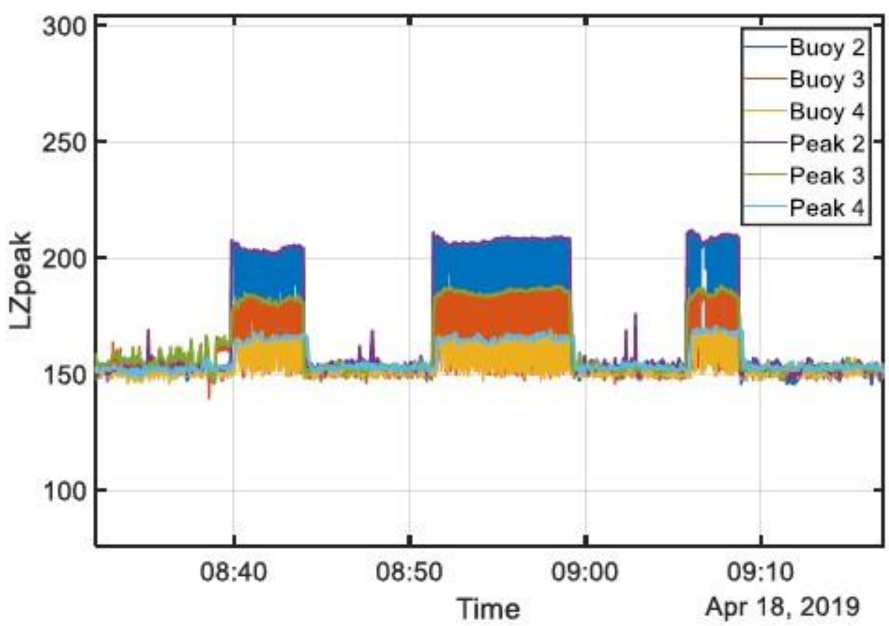


Figure 5: Raw data from Suwannee River Bridge [5]

After data collection was complete, best-fit regression curves were created to show peak pressure, SEL, and RMS values for each of the piles driven which are summarized in Appendix B [5]. Rearranging equation (5), the dissipating sound pressure or transmission loss coefficient (F) values were consistently greater than the NMFS guideline value of F = 15 from equation (7) [5]. For the

Suwannee River Bridge site, *F* values averaged to 26 [5]. The larger *F* values are most likely linked to the simplified transmission loss model and lack of input parameters that play a role in transmission loss [22].

5. Historical Data Collection Study Two

Similarly, a second graduate student from the University of North Florida conducted a study in the vicinity of Jacksonville, Florida in 2021. The pile driving activities from their study were for roadway projects. The student's goal was to implement the sound data collected with the Pile Driving Analyzer (PDA) developed by Jonathan Berube and make a correlation between the sound-level data and the PDA output [12].

5.1 Historical Data Collection System

The second iteration of this study also utilized the PDAs that Berube developed with some slight modifications, including only using Buoy 1 for data collection. Similar to the first study, there were time synchronization issues between the PDAs and the global position system (GPS) data throughout data collection [12]. The recorded timestamps did not match up. As a result, the GPS was only used for official times, not a synchronized validated time between both the PDAs and GPS [12]. Additionally, during data collection, the blow counts recorded from the PDA system did not always match the blow counts from the sound signals. When this happened, it was resolved by normalizing the PDAs blow count data relative to the sound level blow count data [12].

Prior to any data collection, this study was coordinated with the FDOT and contractors that conducted the actual pile driving at each site location [12]. To allow for more accurate comparisons between construction sites and data results, the sites chosen were similar in intercoastal characteristics such as pile dimensions and pile material [12]. Table 3 summarizes the pile and hammer information at each of the three pile driving site locations.

Table 3: Pile and hammer summary [12]

Site Name	Pile Type	Hammer Type	Number of Piles
Ribault River Bridge	24” square PCP	APE D50	1
County Road (CR) 218 over South Fork Black Creek	24” square PCP	APE 62-55 & APE 66-55	2
State Road (SR) 23 over Black Creek	24” square PCP	APE D62/70	11

Unlike the first UNF study, all three pile driving site locations listed in Table 3 used 24-inch square prestressed concrete piles (PCP). Since all three pile types were comprised of the same material, it helped to reduce the independent variables in the data collection and make stronger correlations between the PDAs and pile driving sound produced.

6. Methodology

6.1 Simulation Verification

Sound generation of the pile driving process can be predicted through finite element modeling (FEM) by computer simulation using COMSOL Multiphysics software to test the various parameters that construction sites may encounter during pile driving on the coastal waters. Initially, to test and verify the model results, a finite element simulation resembling Reinhall and Dahl's concept was set up and comparable results were obtained as depicted in Figures 6 and 7 [3,6-11]. Both Reinhall and Dahl and the current FEM simulation utilized a hollow steel pile approximately 32 m (105 ft) long, with a diameter 76.2 cm (30 in) and a wall thickness of 2.54 cm (1 in). The pile was driven into the sediment approximately 14 m.

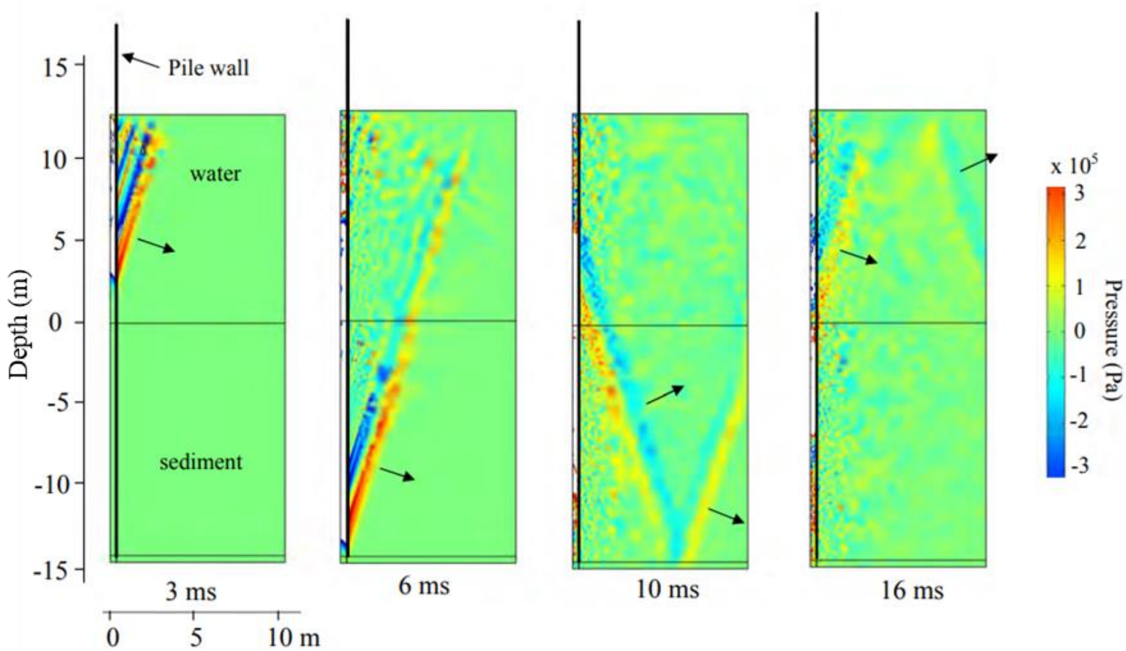


Figure 6: Acoustic pressure plot at 3, 6, 10, and 16 milliseconds by Reinhall and Dahl [3]

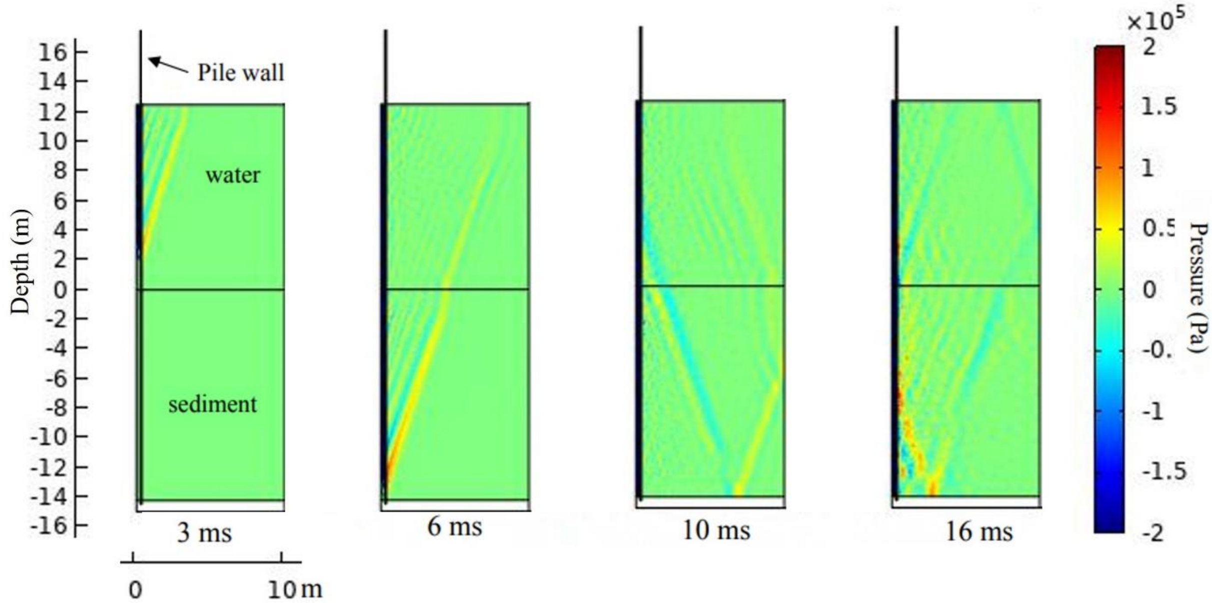


Figure 7: Acoustic pressure plot verification results at 3, 6, 10, and 16 milliseconds

The total acoustic pressure plots in Figures 6 and 7 are snapshots taken during the simulation at 3 ms, 6 ms, 10 ms, and 16 ms after the hammer impact. Figure 7 displays a normalized total acoustic pressure scale in pascals for comparison to Figure 6. During comparison of both figures, the radial displacement waves traveling along the length of the pile produce similar trends. The perfectly matched layers (PML) along the water and sediment domains prevented wave reflections at the simulated boundaries to replicate an infinite free space such as the ocean or a long river.

The simulation was also verified and validated by comparing Figure 8 to Figure 9. After a hammer blow, a compression wave traveled down the pile causing a radial deformation due to Poisson's ratio effect [3]. This phenomenon is where the pile changes shape due to the propagating axial stress perpendicular to the applied force. As a result, the stress created a spike that oscillated down the pile after the initial blow. A similar spike in the acoustic pressure propagated down the pile wall as illustrated in Figures 8 and 9 snapshots below.

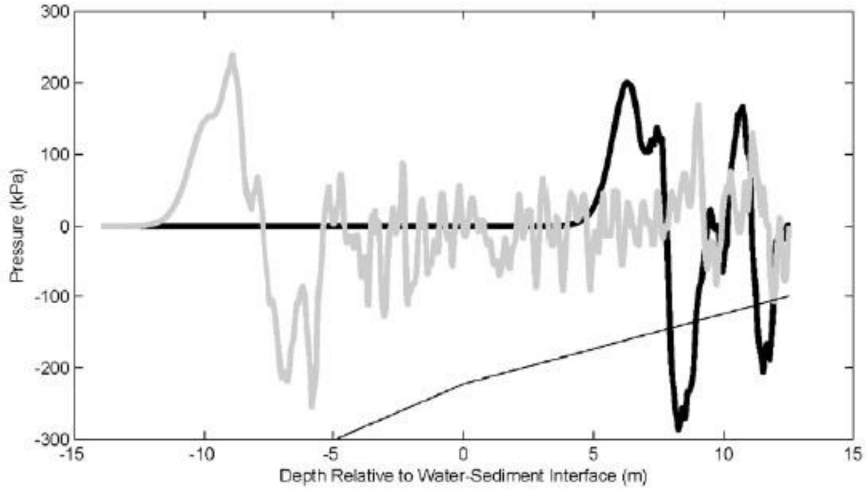


Figure 8: Acoustic pressure along the pile at a range of 1 m from the pile wall at 3 ms (black line) and 6 ms (grey line) by Reinhall and Dahl [3]

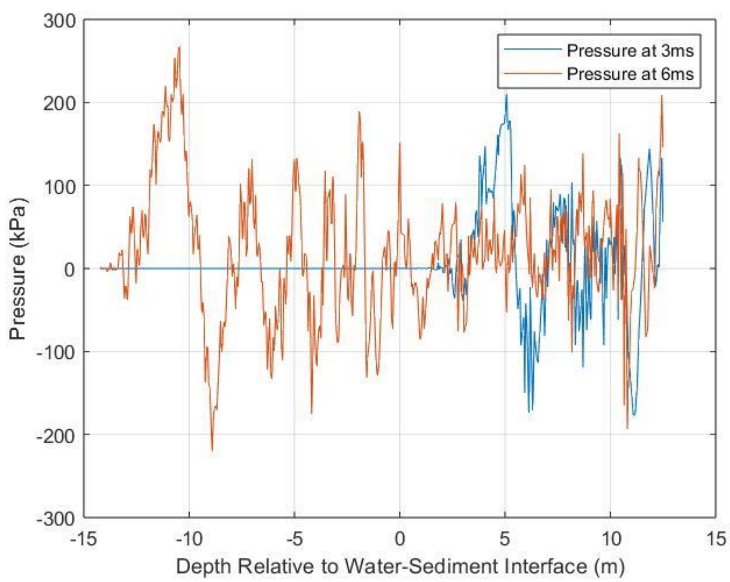
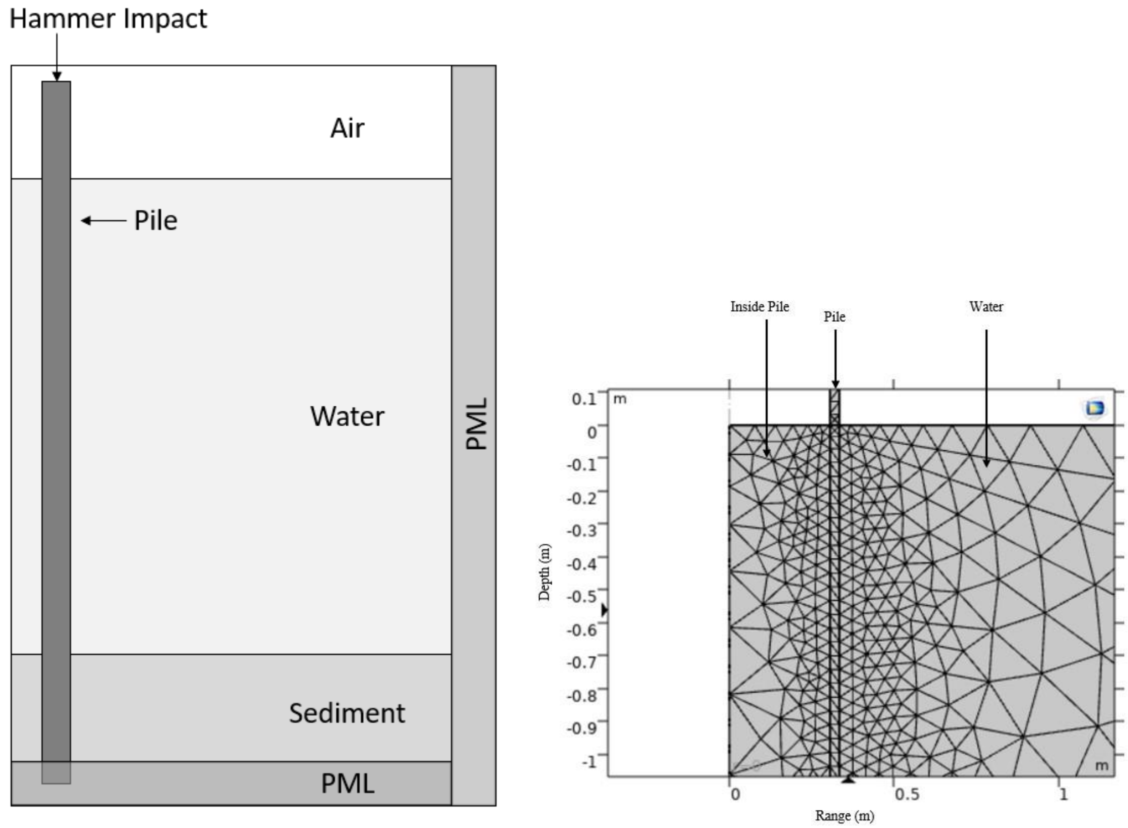


Figure 9: Acoustic pressure along the pile at a range of 1 m from the pile wall at 3 ms (blue line) and 6 ms (red line) verification results

The acoustic pressure spike was captured at 1 m from the pile wall at 3 ms and 6 ms after the hammer blow. The water surface is at 12.5 m along the x-axis in Figures 8 and 9. Figure 9 captures the normalized acoustic pressure values similar to those calculated by Reinhall and Dahl [3]. For comparison, visual observation at approximately -11 m both figures 8 and 9 had a large pressure spike at about 275 kPa with a 7% deviation.

6.2 COMSOL Multiphysics Simulation

For the work performed per this thesis subject, the following setup for the simulated pile driving model used a 2D axisymmetric finite element framework of a hollow steel pile being driven into sediment in shallow water as shown in Figure 10a. Due to the multiple properties that encompass the sea bottom (sediment), it was modeled as a fluid which accounted for the compression waves produced by the pile driving [31]. Perfectly matched layers (PML) were created along the domains truncated boundaries which prevented additional reflecting waves. Figure 10b displays the corresponding mesh configuration and is described below.



(a) **(b)**

Figure 10a and 10b: Schematic representation of 2D axisymmetric finite element model and mesh

Once the simulation was set up and verified working, it was then aligned with similar pile parameters to those observed at the Suwanee Rive Bridge pile driving site in Florida as outlined in Section 4. The simulation was arranged as a dynamic 2D axisymmetric finite element framework with the pile driven into sediment in shallow water similar to Figure 10a. The model used a hollow steel pile, approximately 18.4 m (60 ft) long with a 60.9 cm (24 in) diameter. The pile was driven approximately 6.7 m (22 ft) into the sediment in water 8.5 m (28 ft) deep. Additionally, cylindrical domains of water and sediment with a radius of 10 m (32.8 ft) with perfectly matched layers were created in the finite element model. The pile was discretized by using normal, quadratic quadrilateral Lagrange elements with an element size of 9.8 mm [3] as displayed in Figure 10b. The water and sediment were discretized using extra fine, quadratic triangular elements [3]. As the finite element mesh became finer, the overall simulation computation significantly increased by a few hours. However, utilizing fine mesh parameters increased the accuracy of the simulation results. The simulation was modeled for 40 ms using a time step of 0.02 µs. Additional parameters used for the COMSOL Multiphysics simulation are summarized in Table 4.

Table 4: Overview of COMSOL simulation parameters

Parameters	Property	Value	Unit
Pile (AISI 4340 Steel)	Young's modulus	$20.5e^{10}$	Pa
	Poisson's ratio	0.28	-
	Density	7850	kg/m^3
	Length	18.44	m
	Wall thickness	0.03- 0.05	m
	Diameter	0.3048- 0.6096	m
Pile (Concrete)	Young's modulus	$25e^{9}$	Pa
	Poisson's ratio	0.20	-
	Density	2300	kg/m^3
	Length	18.44	m
	Wall thickness	0.03- 0.05	m
	Diameter	0.3048-0.6096	m
Sediment (Limestone)	Speed of sound	1625	m/s
	Density	1600	kg/m^3
	Porosity	5	-
Damping (Nylon)	Density	1150	kg/m^3

From the COMSOL Multiphysics simulation, data was collected from a water depth of 2.44 meters. The depth parameter came from the measured Suwannee River Bridge hydrophone buoy depths [5]. The historical data collection at the Suwanee River Bridge placed the hydrophone buoys as close to the pile as possible without interference. However, due to issues with data collection at the Suwannee River Bridge site, only three buoys were able to collect data [5]. The closest usable hydrophone buoy was located 15 meters from the pile. The COMSOL simulation however was set up to record data as close as 1 meter away from the pile to compare with the UNF best-fit curve as displayed in Appendix B.

7. Simulation Results

The following Figures 11 through 18 display the results of the simulated data collection from the finite element modeling in COMSOL Multiphysics computer software and were then exported into MATLAB. The odd numbered Figures: 11, 13, 15, and 17 display the total acoustic pressure in Pascals (Pa) versus time in milliseconds (ms). The even numbered Figures 12, 14, 16, and 18 display the sound exposure level in decibels versus time (ms) which was calculated using equation (3). These figures display the simulated results at a distance of 1 and 10 meters from the pile after the first hammer blow for each of the pile variations. Additional data summary plots can be found in Appendix C.

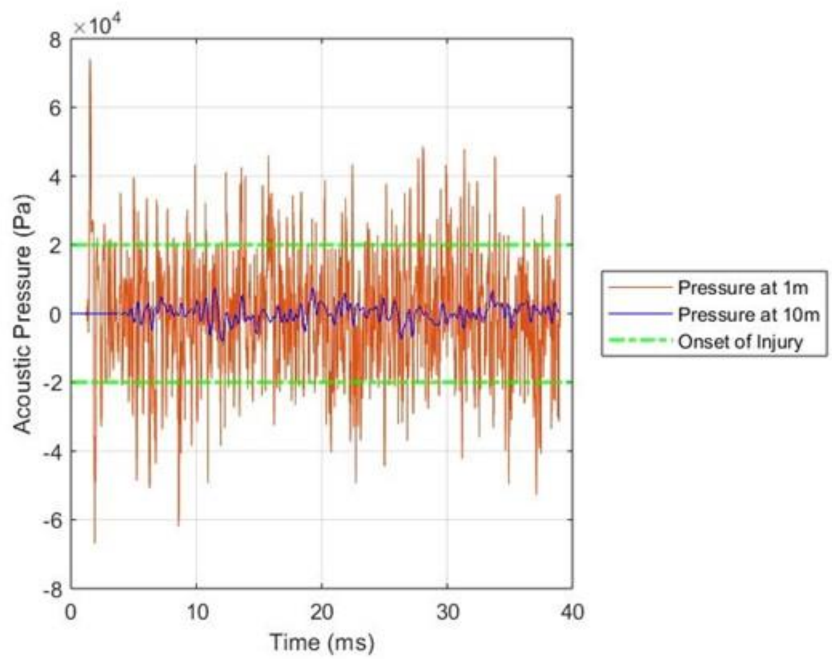


Figure 11: Steel pile with small diameter acoustic pressure (Pa)

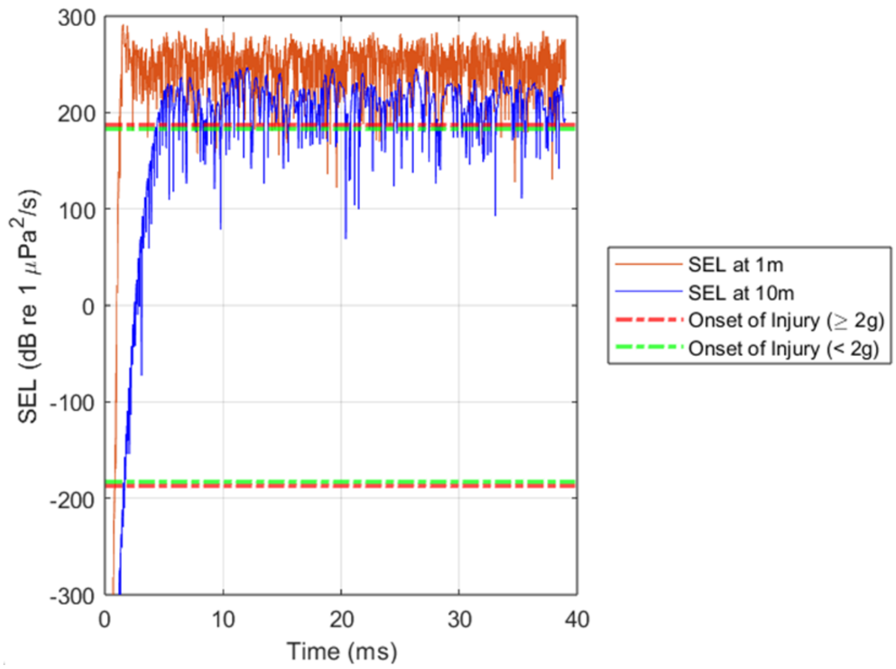


Figure 12: Steel pile with small diameter sound exposure level (dB)

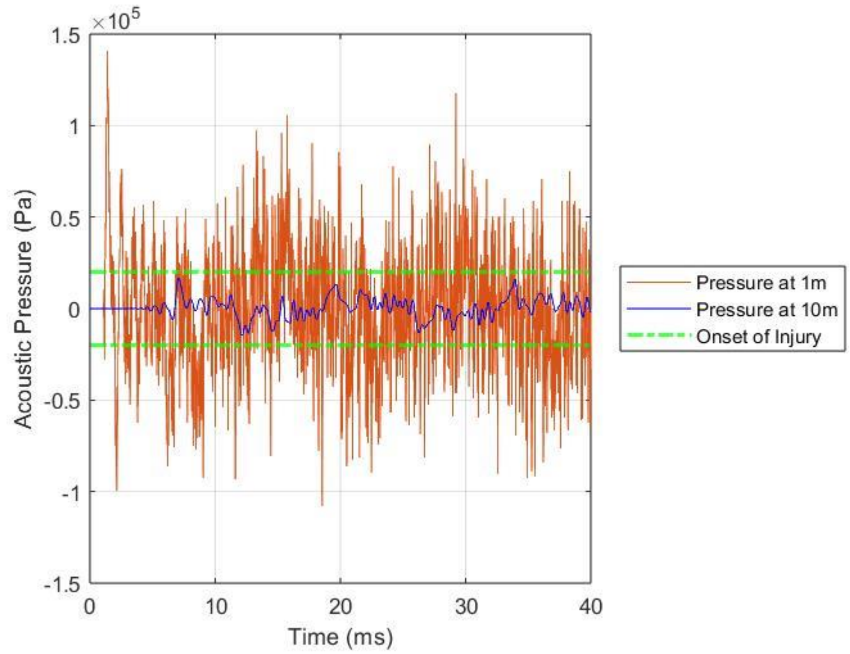


Figure 13: Steel pile with large diameter acoustic pressure (Pa)

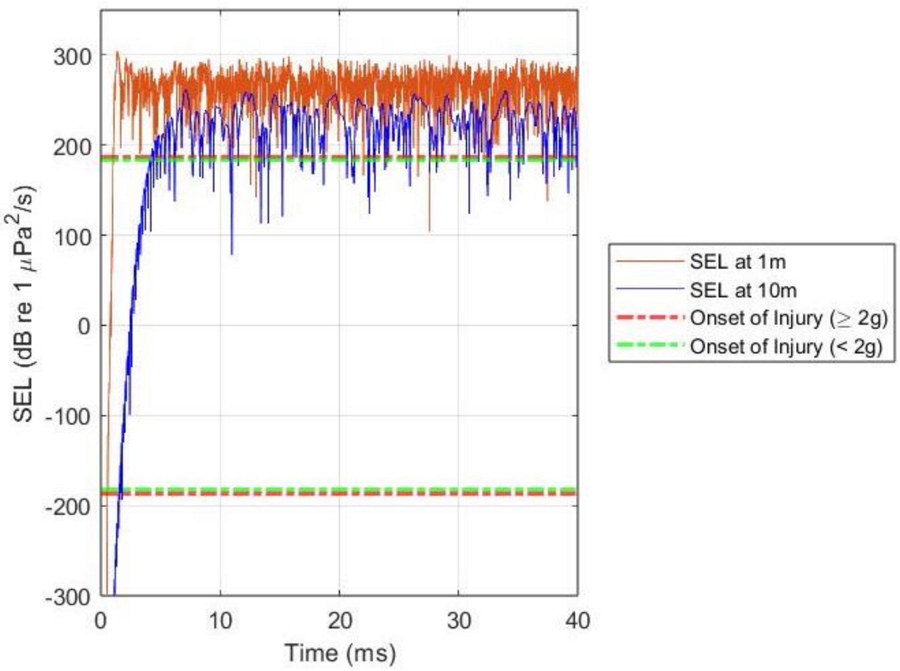


Figure 14: Steel pile large diameter sound exposure level (dB)

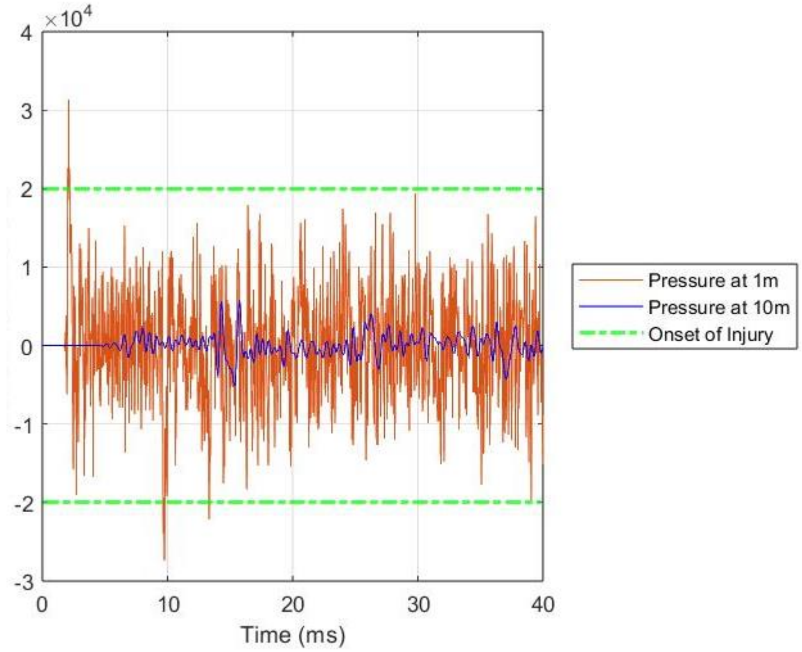


Figure 15: Concrete pile with small diameter acoustic pressure (Pa)

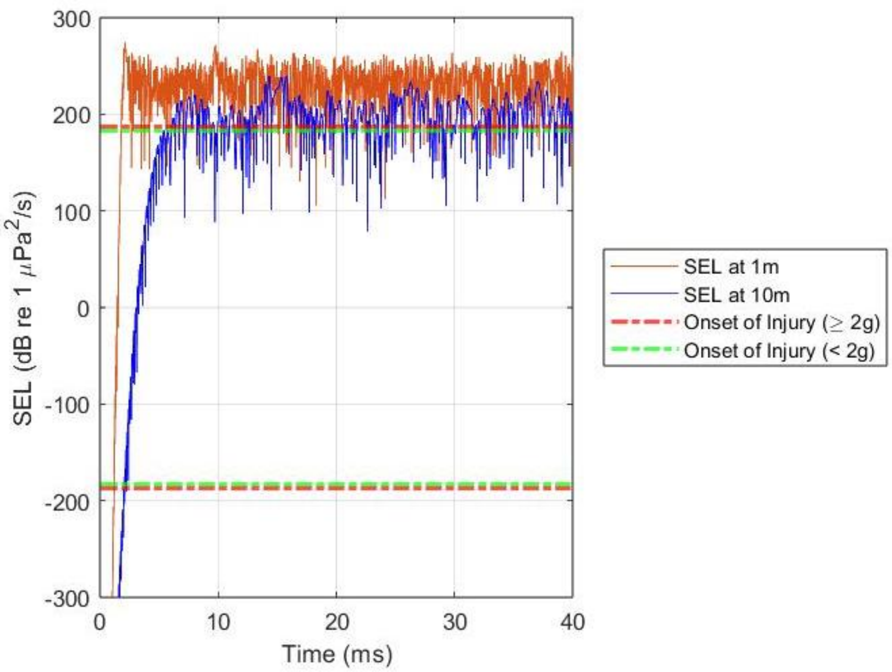


Figure 16: Concrete pile with small diameter sound exposure level (dB)

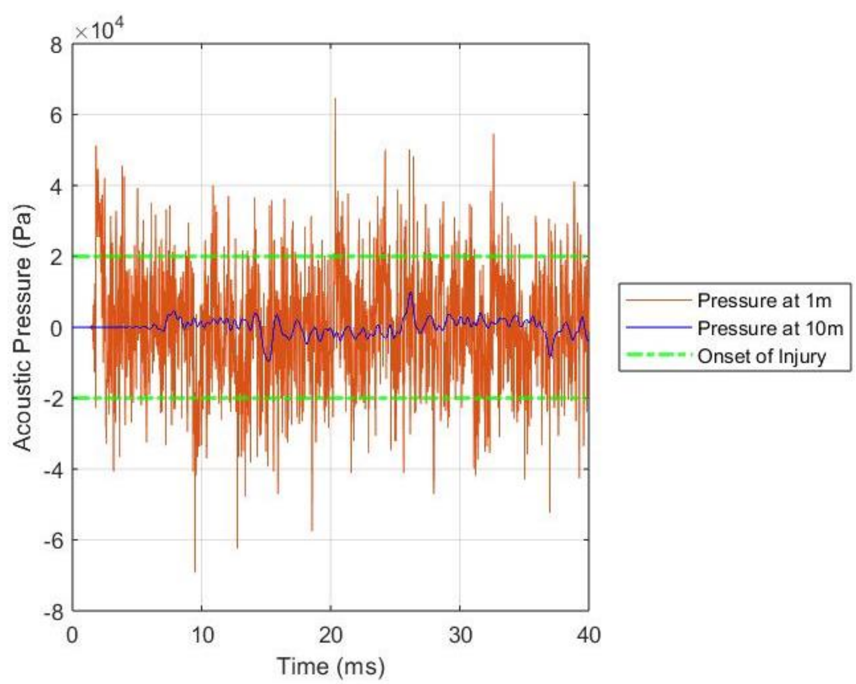


Figure 17: Concrete pile with large diameter acoustic pressure (Pa)

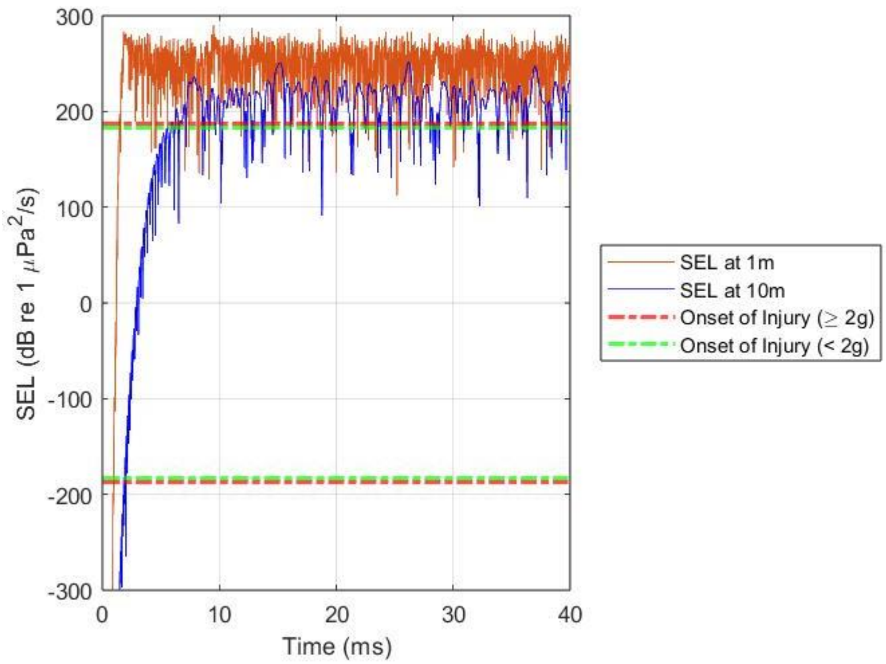


Figure 18: Concrete pile large diameter sound exposure level (dB)

In order to determine the effects of varying diameter size for steel and concrete piles, the small diameter piles were set to 0.3048 m (12 in) and the large diameter piles (corresponding to the Suwanee River Bridge) were applied at 0.6096 m (24 in). As expected, the simulations show that the large diameter piles for both steel and concrete produced a greater acoustic pressure at all measured distances due to its material properties and size. To put the results of figures 11-18 into perspective according to the Fisheries Habitat Working Group guidelines for fish, dashed lines were added to the plots corresponding to the NMFS guidelines for onset of fish injury. In Figures 11, 13, 15, and 17 the horizontal green line denotes the onset of physical injury where the peak positive and negative pressures exceed the 206 dB threshold. In Figures 12, 14, 16, and 18 the horizontal dashed green and red lines outline the positive and negative sound exposure levels 187 dB and 183 dB, respectively. The acoustic pressure decreased about 12 – 16 dB (5-7%) from the

1 m distance to the 5 m distance. At 5 m distance and greater from the pile wall, the acoustic pressures were within the 206 dB threshold for all fish sizes.

To simulate the effects of utilizing sound mitigation measures while pile driving, such as a pile cushion, Figures 19 through 22 were generated using both steel and concrete as the pile material. The pile cushion was comprised of a nylon material with a diameter of 60.9 cm (24 in) and a thickness of 0.025 m (0.08 ft).

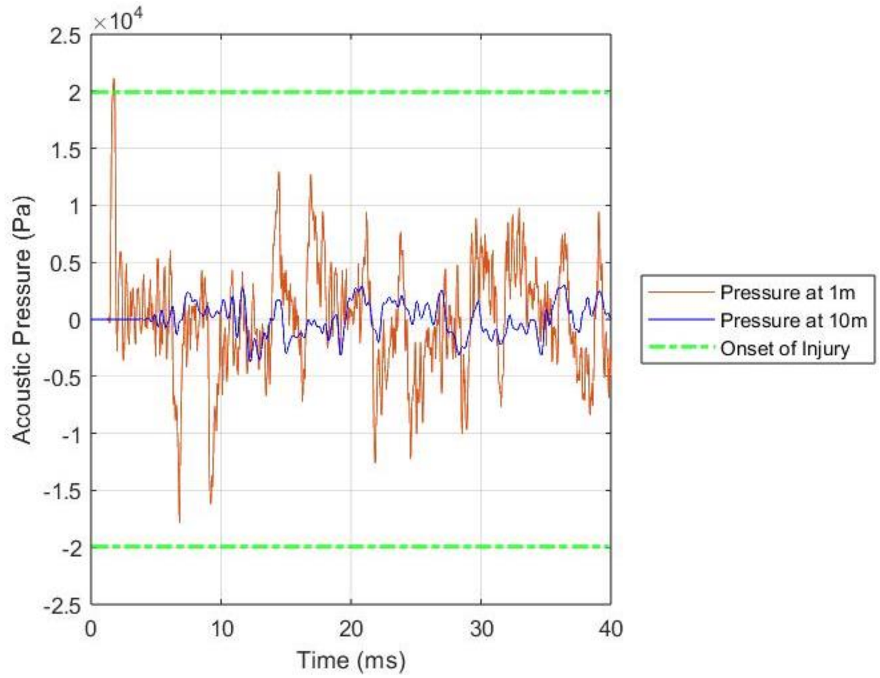


Figure 19: Steel pile with small diameter and nylon cushion acoustic pressure (Pa)

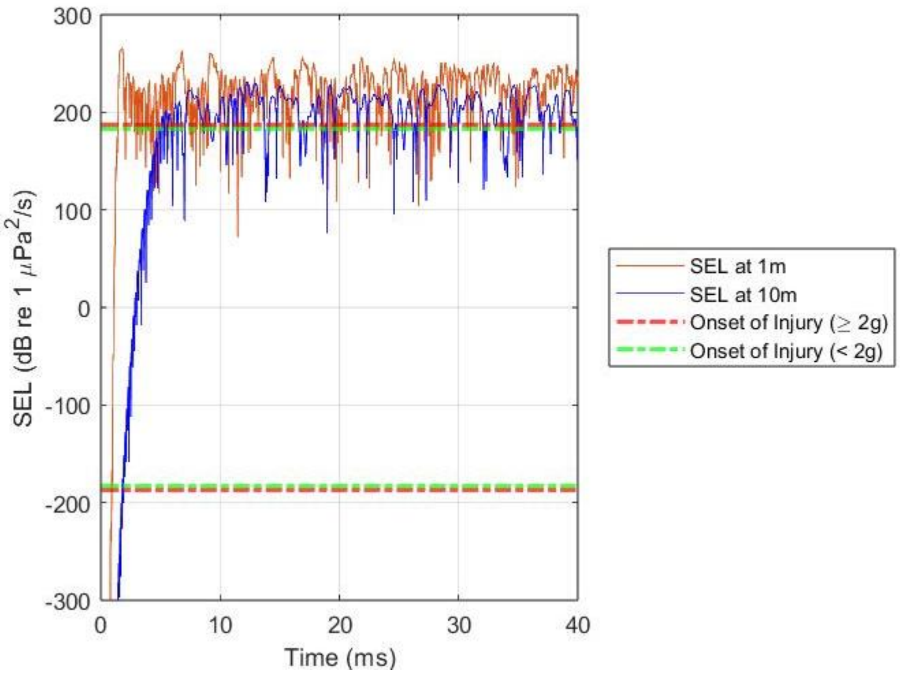


Figure 20: Steel pile with small diameter and nylon cushion sound exposure level (dB)

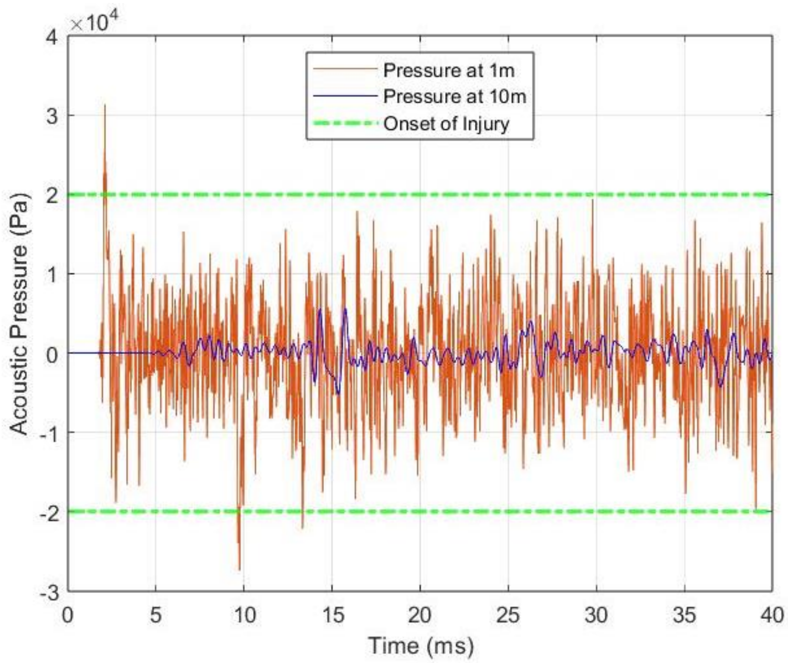


Figure 21: Concrete pile with small diameter and nylon cushion acoustic pressure (Pa)

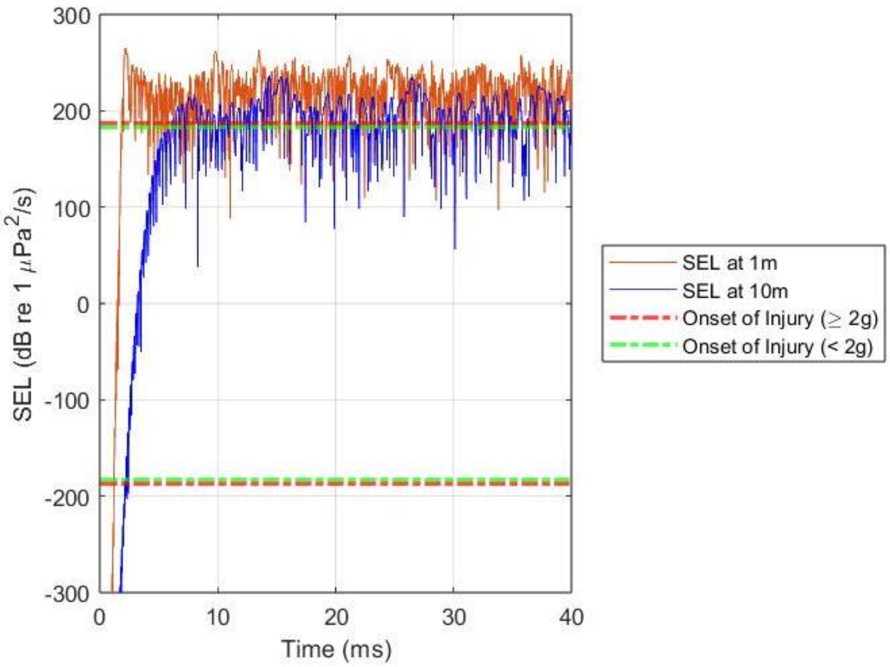


Figure 22: Concrete pile with small diameter and nylon cushion sound exposure level (dB)

A comparison of steel and concrete piles with and without the nylon cushion block were compared against each other at a distance of 10 m (32.8 ft) away from the pile wall in Figures 23 and 24 respectively. The purpose of the nylon cushion block is to act as a sound mitigation measure to reduce the overall acoustic pressure waves produced during pile driving impacts. Studies conducted by the Washington State Department of Transportation noted that nylon produced a reduction in sound pressure levels of about 4-5 dB [4]. As expected, the nylon pile cushion did dampen the acoustic pressure produced.

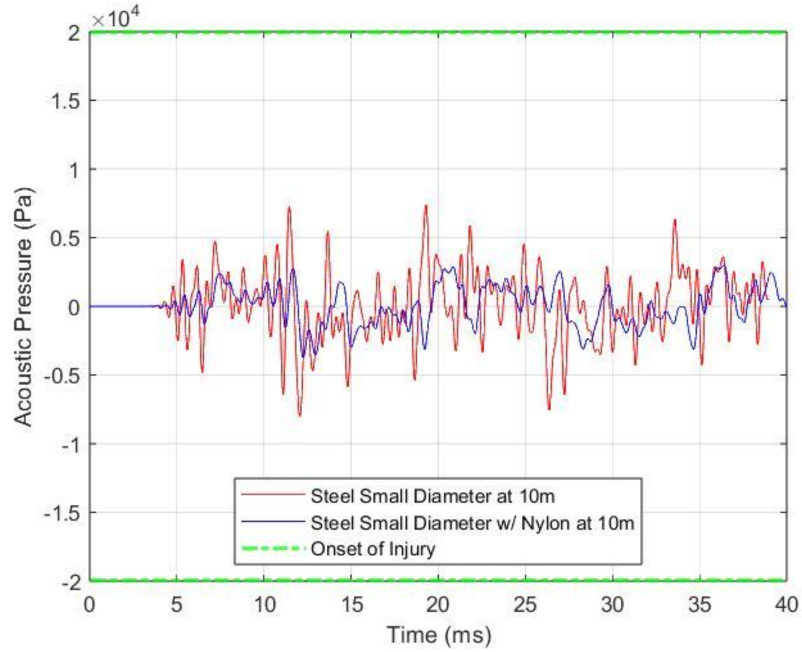


Figure 23: Steel pile small diameter with and without nylon cushion at 10 meters

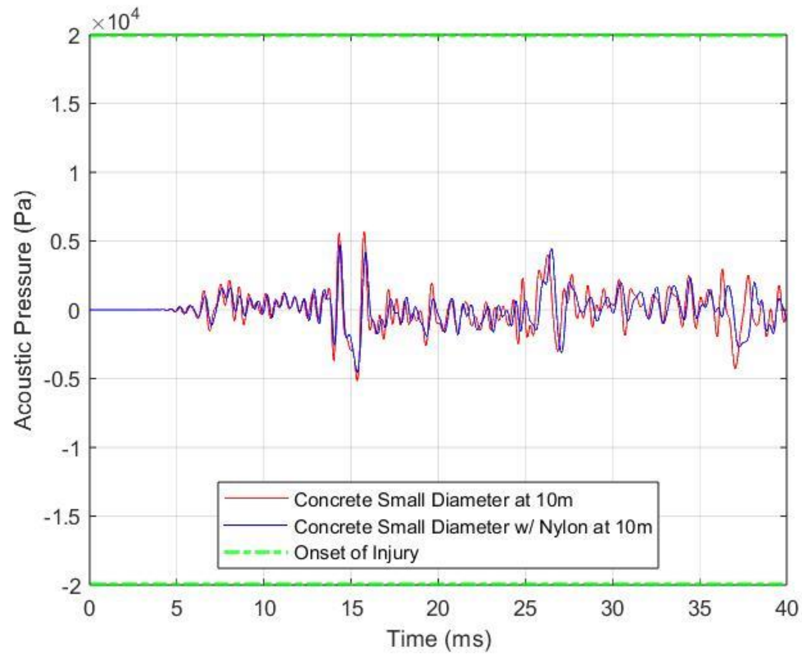


Figure 24: Concrete pile small diameter with and without nylon cushion at 10 m

The effects of a pile with nylon cushion for both steel and concrete produced similar trends. The nylon cushion had a greater damping effect for the steel pile with a 4% (8 dB) reduction in peak pressure whereas the concrete had a 1% (2 dB) reduction in acoustic pressure. The difference in acoustic pressure values can be associated with the different material properties of the piles [4].

A summary of the peak pressures (dB) and sound exposure levels (SEL) (dB) for each parameter simulated in the finite element modeling through COMSOL Multiphysics is presented below in Tables 5 and 6. The peak pressure and SEL values were calculated by exporting the COMSOL Multiphysics data to a standard text document (.txt) and writing several scripts in MATLAB to generate the outputs. The built in MATLAB command "findpeaks" was used to determine the peak pressure (dB) and equation (3) was used to calculate the SEL (dB).

Table 5: COMSOL simulation summary results for concrete pile

Concrete Pile Parameters	Peak Pressure (dB)	SEL (dB)
Small Diameter		
1 m	209	254
5 m	194	227
10 m	195	216
20 m	188	207
40 m	184	195
Large Diameter		
1 m	216	261
5 m	200	239
10 m	199	226
20 m	195	223
40 m	189	216
Small Diameter with Nylon		
1 m	206	241
5 m	194	222
10 m	193	215
20 m	186	199
40 m	183	194

Table 6: COMSOL simulation summary results for steel pile

Steel Pile Parameters	Peak Pressure (dB)	SEL (dB)
Small Diameter		
1 m	217	273
5 m	205	236
10 m	197	226
20 m	192	215
40 m	190	204
Large Diameter		
1 m	222	290
5 m	210	251
10 m	204	247
20 m	201	235
40 m	200	225
Small Diameter with Nylon		
1 m	206	235
5 m	196	226
10 m	189	212
20 m	188	208
40 m	184	191

The values presented in Tables 5 and 6 are comparable with the Suwannee River Bridge numerical data that is summarized in appendix B [5]. The steel pile large diameter calculations in Table 6 indicated an average 6% and 10% deviation for peak pressure and SEL, respectively, at the 1-meter distance in comparison with the Suwanee River Bridge measurements estimated at the pile wall. Additionally, for all three concrete and steel pile variations, the peak pressure threshold for fish onset of physical injury (206 dB), from Table 1, is satisfied at greater than 1m distances from the pile wall except for the large diameter steel pile, which is greater than 5 m distance from the pile wall.

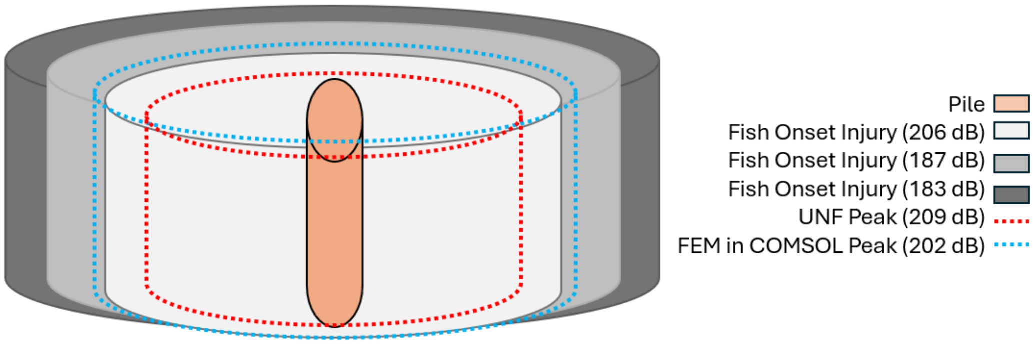


Figure 25: Bullseye schematic of FEM COMSOL results (steel pile with large diameter) and UNF results with NMFS impact pile driving guidelines at 15 meters

The bullseye schematic in Figure 19 provides a visual of the finite element modeling (FEM) through COMSOL Multiphysics and the University of North Florida (UNF) historical data results compared against the National Marine Fisheries Service (NMFS) guidelines for impact pile driving. The data for the FEM in COMSOL Multiphysics is represented by the dashed blue cylinder and the UNF data is represented by the red dashed cylinder. As summarized in Table 6 and Appendix B, visual assessment confirms that the UNF peak pressure at 15 meters from the pile wall remains above the NMFS threshold (206 dB) whereas the FEM at 15 meters from the pile wall is 202 dB, which is below the threshold for all fish. As a result, Figure 19 shows a 3.3% deviation between the two studies.

8. Conclusion

Overall, the historical data collection studies provided effective correlations of pile driving and sound levels in the vicinity of the construction projects in Florida. The University of North Florida field assessments improved with each study conducted, resulting in more advanced and accurate data collection. One common theme among each study was that the different types of piles and hammers used, which produced different levels of sound attenuation. Additionally, this thesis demonstrated that finite element modeling, via COMSOL Multiphysics, can predict comparable results to the numerical field data collected in the State of Florida, which provides an effective planning tool for construction companies and environmental policy personnel.

As indicated in the simulation section, the sound exposure level (SEL) was greatest near the pile wall, exceeding established guidelines. As Berube (2019) discussed, due to technical difficulties and construction constraints, it was not possible to obtain data closer than 7 m to the pile wall. Utilizing computer modeling, it was possible to predict sound data at 1 m from the pile wall. Additionally, SEL from the steel pile with the large diameter at 10 m from the pile wall equated to 247 dB. The simulated values produced are also comparable to the values reported by Berube (2019) and Reinhall and Dahl (2015). As the distance from the pile increased, the SPL decreased quickly. This sound propagation loss can most likely be associated with the various 24 independent variables that were considered, some of which included water and geotechnical conditions.

It is important to note that while the FEM via COMSOL Multiphysics did prove to be within 10% deviation of the UNF historical data, an adjustment factor of approximately 1.035 should be considered to the FEM simulation for calibration. This adjustment factor will ensure that the modeled results are comparable to the field measured data when considering the NMFS guidelines and thresholds for all fish.

8.1 Recommendations for Future Work

The finite element computer modeling provides preliminary predictions for Florida shallow waters, however, it would be valuable to evaluate the effects of computer modeling to demonstrate correlations between sound absorption and additional geotechnical conditions and sediment type, including deep water and associated temperature gradients. As previously discussed for COMSOL modeling, there are significant boundary conditions that are considered with the FEM via COMSOL Multiphysics, and future work to validate these parameters to further validate accuracy. Based on the simulated results of varying pile material properties, further work could determine if sound attenuation is greater for steel versus concrete due to steel's material properties acting as a wave guide into the sediment. Where concretes material properties and porosity may limit transmission into the sediment, but instead broadcast more readily to the surrounding water. Furthermore, being able to input more variables into the computer model allows for more accurate sound generation predictions. Having more accurate sound generation prediction models could allow construction companies and the Navy to maximize marine environmental policy satisfaction within different construction environments.

Additionally, collection of additional data from multiple buoys to model and compare the effects of the numerous variables including different pile materials, hammer impact forces, and site conditions could advance progress and methodology to better predict future marine guidance and environmental policies. Exploring the variables in the computer modeling simulations with field data, will allow for more accurate sound propagation prediction models. As a result, more advanced and precise models will help the U.S. Navy be respectable stewards of Florida waters and its marine environment as well as the many naval bases located around the United States.

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Appendix A:

A1. Suwannee River Bridge Impact Hammer Specifications [5]

APE Model D62-22 Single Acting Impact Hammer

operates on diesel or bio-diesel for all types of impact pile driving

Bottom drive system for large diameter piles

MODEL D62-22 (6.2 metric ton ram)

SPECIFICATIONS

Maximum Rated Energy	153,770 ft/lbs (208,484 Nm)
Minimum Rated Energy	78,956 ft/lbs (107,050 Nm)
Stroke at Rated Energy	11.24 ft (3.42 m)
Maximum Obtainable Stroke	12.5 ft (3.81 m)
Speed (blows per minute)	36-50

WEIGHTS (Approximate)

Ram	13,669 lbs (6,200 kg)
Anvil	2,833 lbs (1,285 kg)
Hammer Weight (includes trip device)	28,272 lbs (12,823 kg)
Hammer weight w/ DB-32 Drive Base	31,744 lbs (14,399 kg)
Typical Operating Weight w/ Drive Cap	Varies- consult factory

CAPACITIES

Fuel Tank (runs on diesel or bio-diesel)	25.89 gal (98 liter)
Oil Tank	8.32 gal (31.5 liter)

CONSUMPTION

Diesel or Bio-Diesel Fuel	5.28 gal/hour (20 liter/ hour)
Lubrication Oil	.84 gal/hour (3.2 liter/hour)
Grease	twice per day

DIMENSIONS OF HAMMER

a	Length overall	232.68 in (5,910 mm)
a	Length over cylinder extension	272 in (6,908 mm)
a	Length over trip tubes	308 in (7,823 mm)
b	Impact block diameter	27.91 in (709 mm)
c	Width over bolts	35.6 in (904 mm)
d	Hammer width overall	31.5 in (800 mm)
e	Width for guiding- face to face	32 in (812 mm)
f	Hammer center to pump guard	19.3 in (490 mm)
g	Hammer center to bolt center	15 in (381 mm)
h	Hammer depth overall	38.2 in (970 mm)
H	Minimum clearance for leads	19.7 in (500 mm)

Features

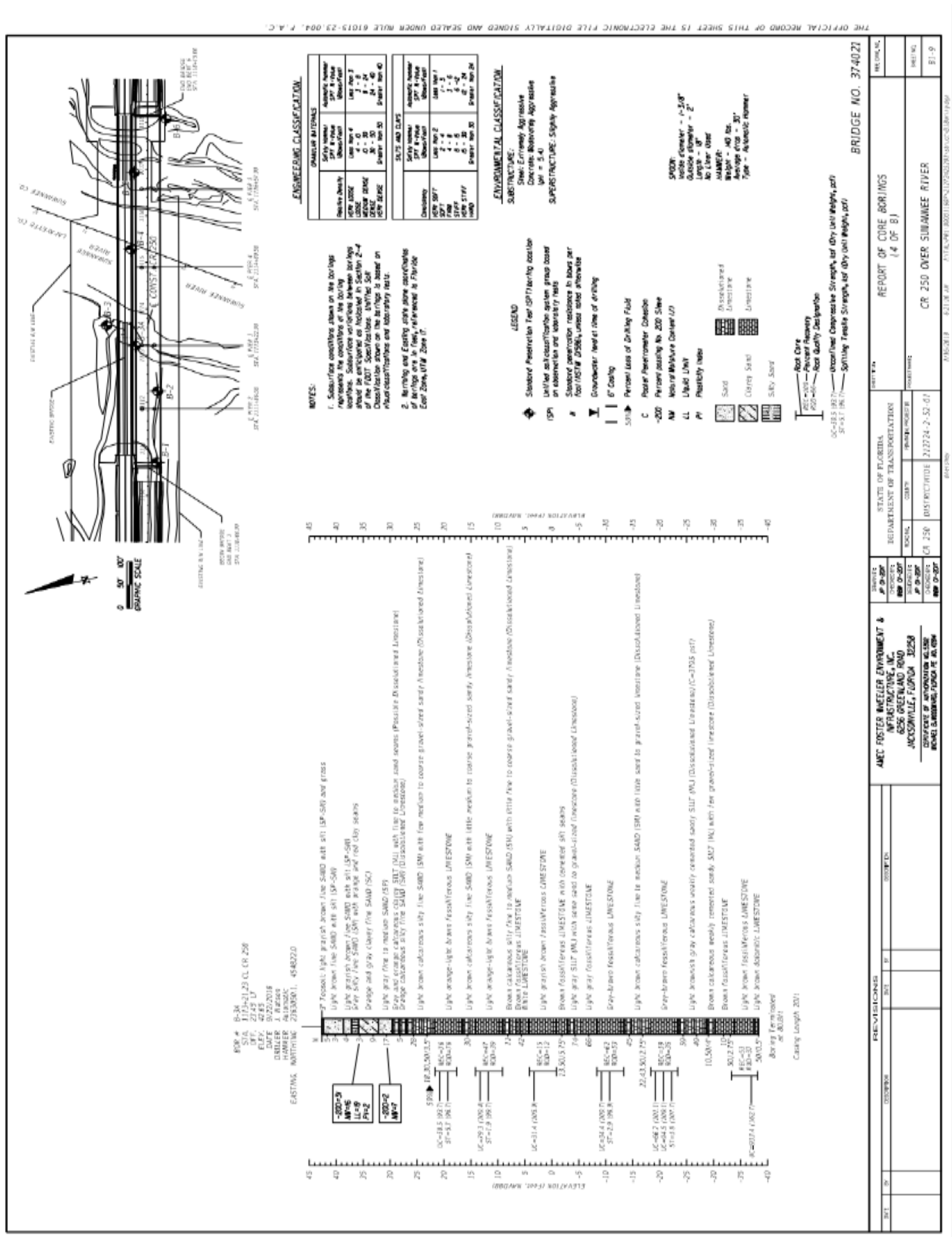
Fuel and lube pumps with 50% less parts than ICE
Hardened piston needs no high maintenance wear rings
Optional direct drive for high speed production on steel piles
Fuel pump mounted where heat will not harm it
Variable mechanical cam fuel pump- no air pistons or rings
Optional hydraulic variable fuel remote control
Heavy duty trip system for years of fault free operation
Chrome rings for super long life
Low maintenance and extremely low parts pricing
German design at a reasonable price
Two year APE warranty

AMERICAN PILEDRIVING EQUIPMENT, INC.
APE
Corporate Offices
7032 South 196th
Kent, Washington 98032 USA
(800) 248-8498 & (253) 872-0141
(253) 872-8710 Fax

2/06

Visit our WEB site:
www.apevibro.com
e-mail: ape@apevibro.com

A2. Suwannee River Bridge Geotechnical Boring Logs [5]



Appendix B:

Suwannee River Bridge Numerical Data Pile Summary [5]

Pile 1:

Buoy Name	RMS_{90} (dB)	$Peak_{90}$ (dB)	SEL_{90} (dB)	Peak (dB)	SEL_{cum} (dB)
Buoy 2	197.85	204.18	225.44	206.40	226.41
Buoy 3	185.49	189.38	211.58	185.89	212.55
Buoy 4	161.90	165.48	186.29	172.87	187.30
At Pile (from best-fit curve)	**227**	**235**	**257**	**229**	**258**
			Transmission Loss Coefficient, F =	**25**	

Pile 2:

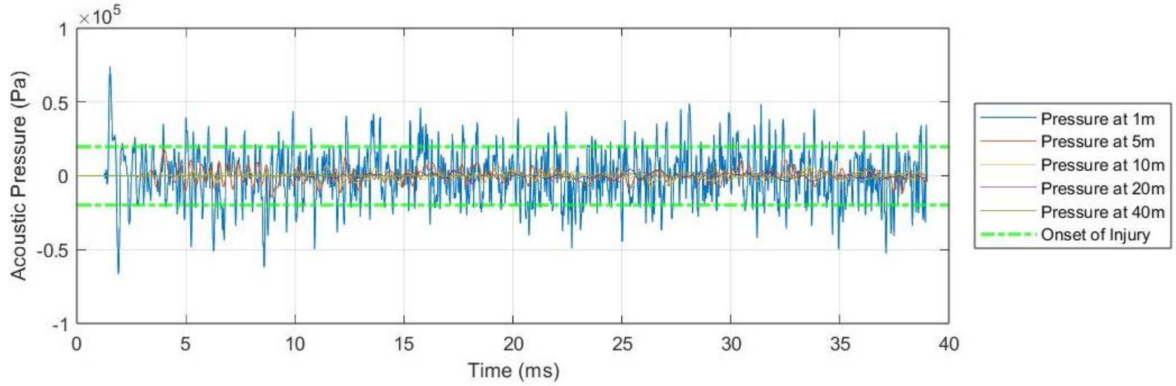
Buoy Name	RMS_{90} (dB)	$Peak_{90}$ (dB)	SEL_{90} (dB)	Peak (dB)	SEL_{cum} (dB)
Buoy 2	199.05	208.45	231.93	209.38	232.79
Buoy 3	187.09	187.29	218.01	187.59	218.94
Buoy 4	161.59	164.97	188.96	169.09	189.99
At Pile (from best-fit curve)	**230**	**241**	**267**	**238**	**268**
			Transmission Loss Coefficient, F =	**28**	

Pile 3:

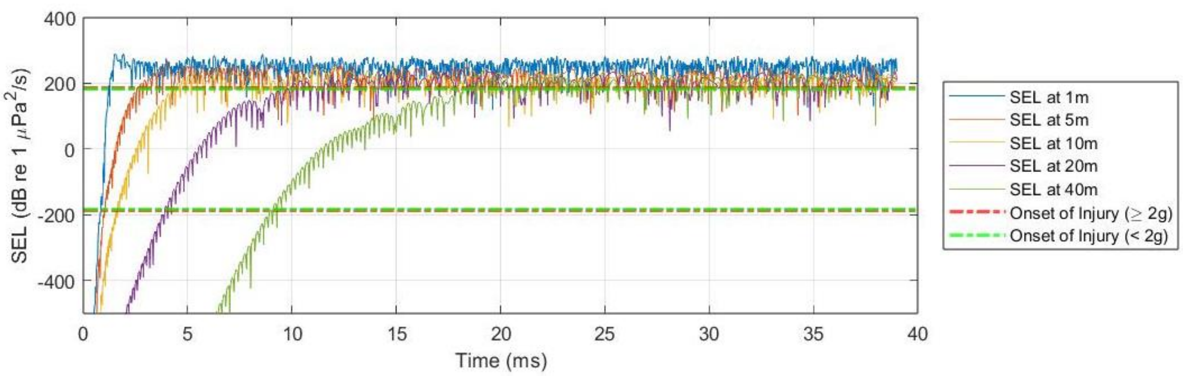
Buoy Name	RMS_{90} (dB)	$Peak_{90}$ (dB)	SEL_{90} (dB)	Peak (dB)	SEL_{cum} (dB)
Buoy 2	204.01	209.90	227.65	211.87	228.79
Buoy 3	188.75	160.36	212.01	187.92	213.02
Buoy 4	165.32	167.48	186.63	170.10	187.56
At Pile (from best-fit curve)	**234**	**228**	**260**	**241**	**261**
			Transmission Loss Coefficient, F =	**26**	

Appendix C:

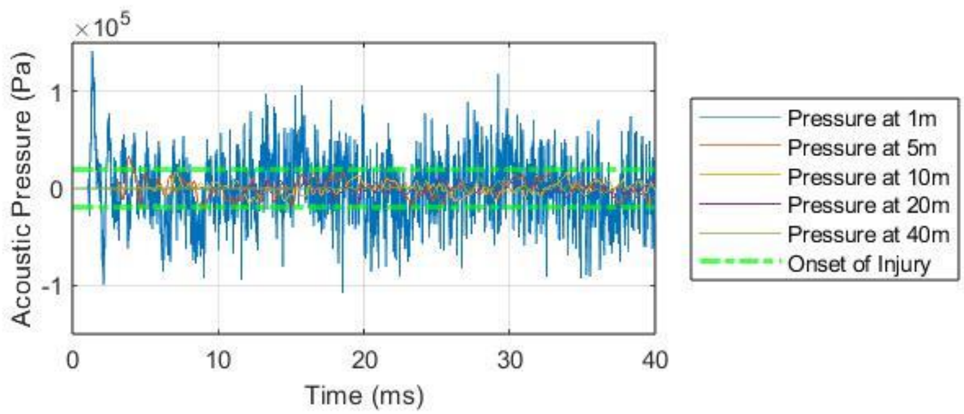
FEM via COMSOL Multiphysics Simulation Results at 1, 5, 10, 20, and 40 meters



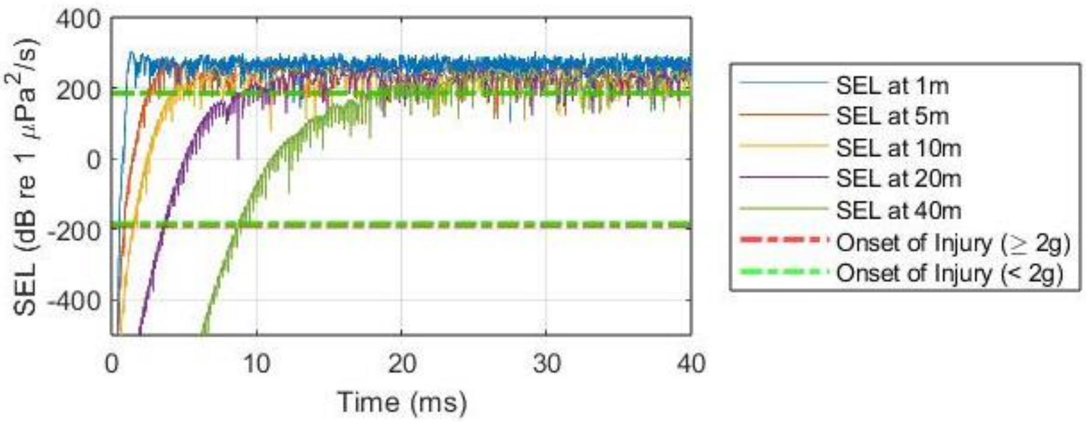
Steel pile with small diameter acoustic pressure (Pa)



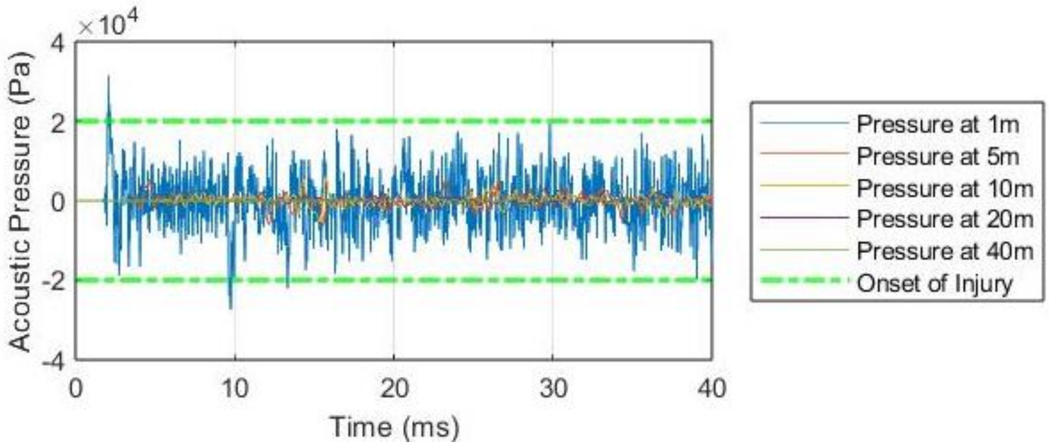
Steel pile small diameter sound exposure level (dB)



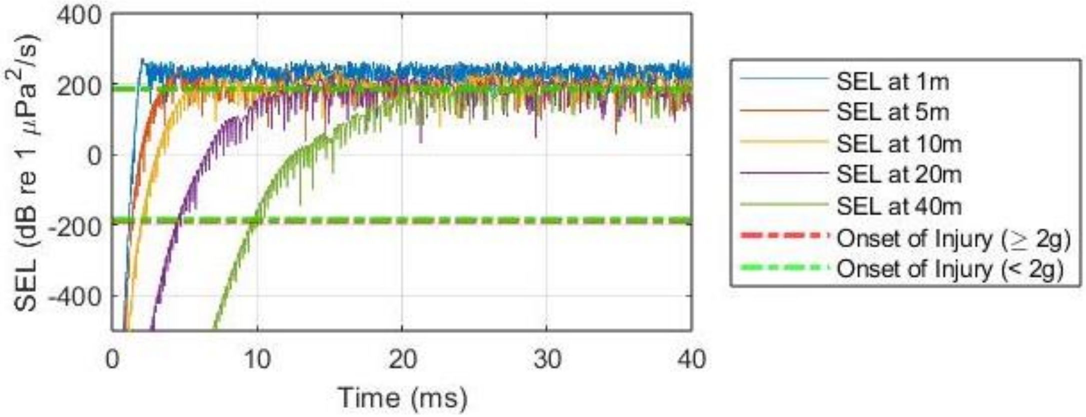
Steel pile with large diameter acoustic pressure (Pa)



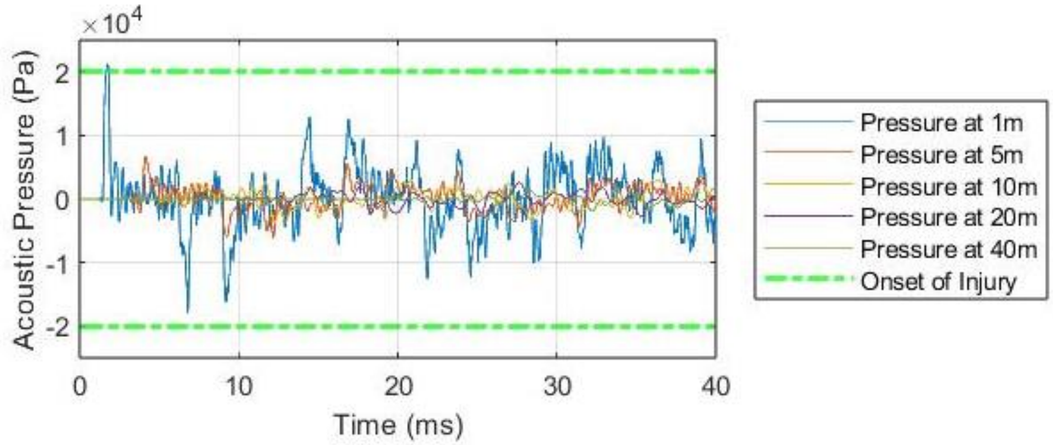
Steel pile large diameter sound exposure level (dB)



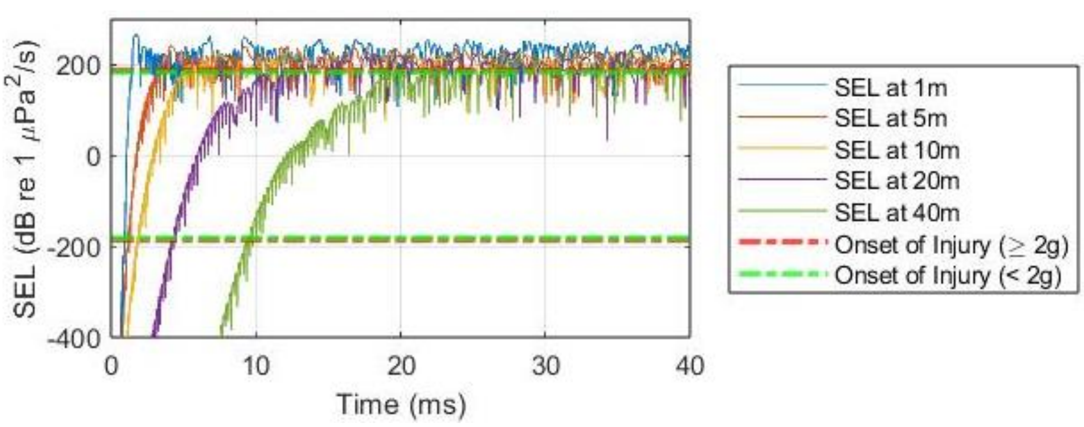
Concrete pile with small diameter acoustic pressure (Pa)



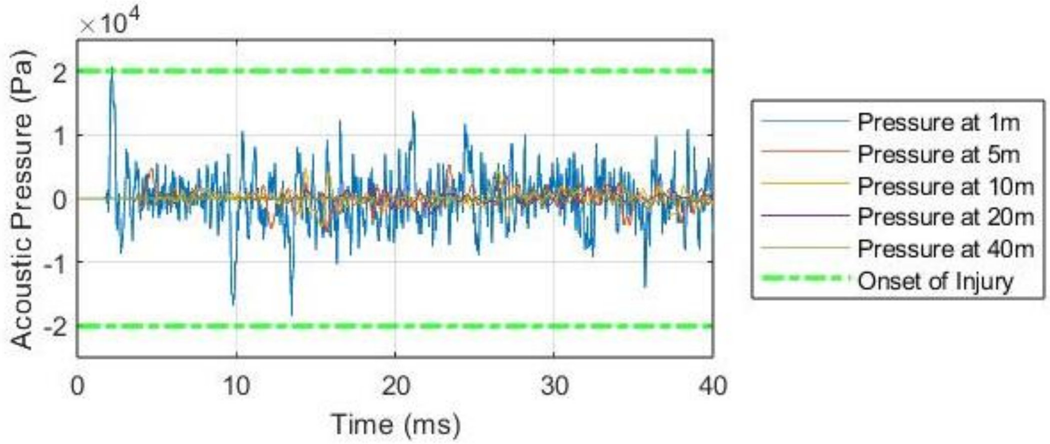
Concrete pile with small diameter sound exposure level (dB)



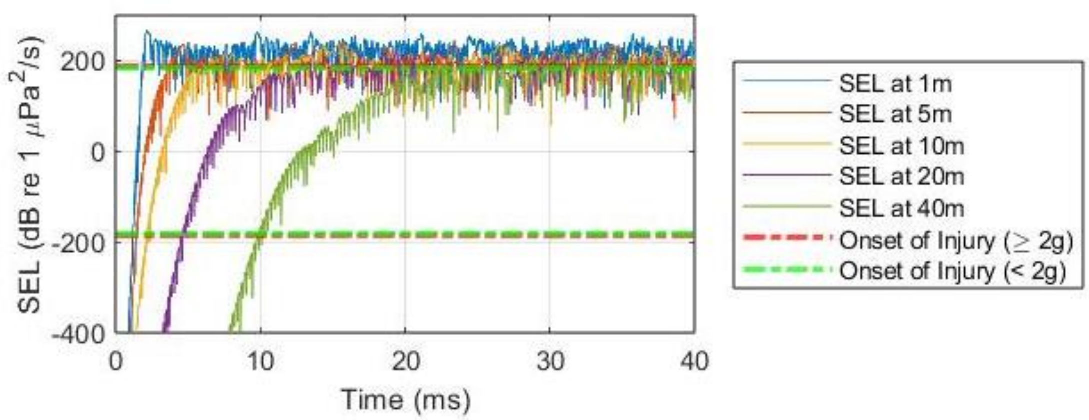
Steel pile with small diameter and nylon cushion acoustic pressure (Pa)



Steel pile with small diameter and nylon cushion sound exposure level (dB)



Concrete pile with small diameter and nylon cushion acoustic pressure (Pa)



Concrete pile with small diameter and nylon cushion sound exposure level (dB)

Vita
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Education

Masters of Science in Mechanical Engineering May 2024
Virginia Polytechnic Institute and State University, Arlington, VA, USA

Graduate Certificate in Additive Manufacturing and Design May 2022
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Experience

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Naval Construction Force Liaison Officer June 2021 - June 2023
U.S. Navy/ I Marine Expeditionary Force (MEF) Camp Pendleton, CA

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U.S. Navy/ Naval Mobile Construction Battalion (NMCB) 133 Gulfport, MS

Construction Manager/Contract Specialist May 2017 – September 2019
U.S. Navy/Public Works Department Newport, RI

Student CAPSTONE Project May 2016 - May 2017
Naval Research Laboratory Key West, FL

Science Aid June 2011- June 2012
Naval Research Laboratory Key West, FL

Student and Engineering Apprentice Program (SEAP) Internship June 2010 - August 2010
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