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DEVELOPMENT OF EQUIPMENT AND METHODOLOGY FOR THE MEASUREMENT OF UNDERWATER SOUND PRODUCED BY DEEP FOUNDATION CONSTRUCTION

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DEVELOPMENT OF EQUIPMENT AND METHODOLOGY FOR THE MEASUREMENT OF UNDERWATER SOUND PRODUCED BY DEEP FOUNDATION CONSTRUCTION

BY

JAMES BROWNE

B.S., University of New Hampshire, 2009

THESIS

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TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

ABSTRACT

DEVELOPMENT OF EQUIPMENT AND METHODOLOGY FOR THE MEASUREMENT OF UNDERWATER SOUND PRODUCED BY DEEP FOUNDATION CONSTRUCTION

By

James Browne

University of New Hampshire, September, 2016

Until the last decade, the underwater sound produced during marine pile driving and underwater drilling work was not considered a hazard to marine life. However, beginning with state environmental agencies on the West Coast, NOAA National Marine Fisheries Service has taken a national interest in this possible source of environmental disturbance to endangered species and marine mammals. Under Section 7 of the Endangered Species Act and the 1972 Marine Mammal Protection Act, “taking” of endangered species or marine mammals includes activities that could cause physical harm, harassment, or behavioral modification of a protected species. High intensity sound produced by construction activities can meet these legal standards of a “taking”.

Many northern New England rivers and coastal areas are known habitats for endangered fish species and marine mammals. In response, NOAA NMFS has added recently-developed limits on sound energy produced by construction activities to its permits for new bridges and coastal infrastructure in locations considered a habitat for protected species. The equipment and methodologies to determine compliance to sound limits are generally unknown to the construction and civil engineering industry in New England. The University of New Hampshire Department of Civil Engineering was approached by regional DOT’s and contractors to develop an approach to meet these monitoring requirements. Several types of hydrophone equipment and data analysis methods were evaluated to assist regional DOT’s and contractors with accurately meeting the monitoring requirements on several projects. The goal of this research was to develop a means to accurately meet project noise monitoring specifications while ensuring that projects were not unduly impacted by inaccurate or unreasonable analysis of the acquired data. Over the course of several years and a handful of pile driving and foundation drilling projects, regional expertise was demonstrated in this complex and emerging area of regulatory compliance. Several critical areas for future research were identified to provide owners and contractors with methods to predict possible impacts during the design and planning phases of a project and reduce project risk.

CHAPTER I

INTRODUCTION

1.1 – Problem Statement

Many northern New England rivers and coastal areas are known habitats for endangered and threatened fish species including the short-nosed sturgeon (Acipenser brevirostrum), alewife (*Alosa pseudoharengus*), and Atlantic salmon (*Salmo salar*). Additionally, many species of marine mammals are known to inhabit and migrate in costal habitats in northern New England. In response, NOAA National Marine Fisheries Service (NMFS) has added limits on sound energy produced by construction activities to its permits for new bridges and coastal infrastructure in some locations. These limits are based on preliminary research on the effects of underwater sound, or barotrauma, on fish caged near driven piles or exposed to high intensity sound in a laboratory (FHWG, 2009). More recent standards are also focusing on the possibility of behavioral modification or harassment of fish and marine mammals possibly resulting in legal "takings" of endangered species under the Marine Mammal Protection Act or Section 7 of the Endangered Species Act.

Owners and contractors on projects with noise specifications have very few standards or guidelines for noise monitoring equipment and procedures. Other than a single guidance document produced by CalTrans and NMFS, there is no guidance offered in the permit specifications issued to date. Contractors have almost no references for predicting the sound levels they might expect on their projects or how to go about assembling and operating a hydroacoustic monitoring system to verify compliance. Few consultants exist in the Northeast to provide these services on pile driving projects and established hydroacoustic equipment manufacturers are almost entirely focused on mapping applications at ultrasonic frequencies and not high intensity low frequency acoustic compliance surveys.

1.2 - Purpose of Study

UNH was approached by NHDOT to address these challenges on several projects in the Portsmouth, NH area in response to this lack of information. In 2012, UNH was asked to perform non-mandated measurements on drilling activities during the replacement of the Memorial Bridge carrying Rt. 1 over the Piscataqua River. At the time, no data existed on these types of drilling activities and NHDOT did not have a consultant experienced in this type of work. After this project, UNH was asked to continue providing and improving on the initial methods on larger and more complex projects.

This research involved developing familiarity with underwater acoustics and the equipment used in measuring underwater sound. Initial selection of equipment and guidance from the vendors was improved on subsequent projects as many areas were identified where necessary information was not clearly understood even by vendors themselves. Deficiencies in noise specifications and a lack of clarity on intent of various quantities and procedures were identified. Calibration standards were lacking and several concerns about the appropriateness of common low-intensity calibration techniques and equipment when certifying equipment for high-intensity, low-frequency performance were identified. A thorough understanding of common noise specifications and analysis methods were developed and the process of dialoging with various regulatory agencies about clarifying and improving future noise specifications is ongoing. Finally, key areas of future research that need to be performed to better understand pile driving noise generation, which equipment can and cannot be reliably used for monitoring, and the effects of pile driving noise on marine life were identified.

1.3 – Importance of Study

The following section describes why this research is important and relevant to current engineering and construction practices and to the maintenance of US civil infrastructure.

1.3.1 – Cost of Current Infrastructure Projects

Current noise monitoring requirements are adding substantial cost and risk of delay to many recent and ongoing projects in the Northeast and along the West coast. Due to a very limited field of qualified noise monitoring firms and high equipment and labor expense, noise monitoring work can cost hundreds to thousands of dollars per day. While this is in-line with labor intensive construction instrumentation activities (such as dynamic pile driving load tests), most of these kinds of on-site testing tasks are limited to only a few days out of an entire project. Many noise monitoring specifications require this work to be performed for the duration of any pile driving activities. Due to typical project logistics, even a few piles driven over an entire workday will require a full day of billed time due to the significant day to day and hour to hour uncertainties in pile driving work. Added up, sound monitoring can add hundreds of thousands of dollars to a large foundation project.

1.3.2 – Cost of Future Civil Infrastructure

UNH researchers have been informed by contractors, design engineering firms, and infrastructure owners that concerns over the schedule risk and costs associated with possible delays caused by noise limits are now influencing the selection of foundation systems for future infrastructure. Designers are often abandoning the use of driven piles altogether in favor of drilled-shaft and micropile types of systems. While there is still uncertainty about the noise impacts from the very diverse methods used to install drilled foundations, regulators have not expressed an interest in limiting sound from these activities thus far. Drilled shaft type systems are typically reserved for demanding applications due to their often significantly increased cost over driven piles. However, they are now being proposed extensively on new civil infrastructure in northern New England to avoid the perceived and actual cost and risk associated with noise limitations on driven pile systems.

1.3.3 – Risk To Contractors

Most sound specifications include a requirement to stop work when sound limits are reached or certain wildlife comes too close to a pile driving operation. Because there is currently no guidance for predicting the sound generated by various hammers, piles, and driving criteria, contractors have no way to predict the possible delays that might result on a project they are bidding. On projects with strict deadlines or limitations on any in-water work, contractors are forced to respond by adding money to their estimates to account for possible losses or delays. This adds significant cost to projects that might not actually have substantial cost or delay when the work is performed because the theoretical risk remains until the work is completed.

Additionally, on critical infrastructure projects where returning a civil asset to service is a top project priority, delays alone can impact the public to a tremendous degree. One of the most recent projects associated with this research involves the replacement of the main pier for fishing and tourism for the city of Eastport, Maine. The delays associated with pile driving noise limitations and marine mammal proximity have significantly affected the town's economy and UNH's efforts to ease restrictions based on actual measured sound and data-driven analysis have been reported in local newspapers. This project vividly demonstrates how any engineering research that reduces project risk is of tremendous relevance to US infrastructure.

1.4 – Scope of Study

The following section describes the scope of the work performed on several projects in northern New England from 2012-2015.

1.4.1 – Memorial Bridge Drilling Survey

During the summer of 2012, UNH was asked by NHDOT to research on hydroacoustic monitoring equipment and existing sound data on foundation drilling activities. Subsequently, UNH was asked to provide measurements of underwater sound generated during pier construction during the replacement of the Memorial Bridge carrying Rt. 1 over the Piscataqua River in downtown Portsmouth. As part of this project, the contractor was installing 30” diameter drilled shafts for the approach spans as well as 9” diameter micropiles through the existing piers. Initial selection of hydrophone equipment was performed and the equipment was operated it from a boat at various points around the site and a report was produced for NHDOT.

1.4.2 – Sarah Long Emergency Repairs Pile Driving Monitoring

In April of 2013, the Sarah Mildred Long Memorial Bridge which carries Rt. 1 Bypass over the Piscataqua River in Portsmouth, NH was damaged by a ship that broke free from its moorings at a nearby pier. The repair work required the driving of pipe piles for temporary support bents. UNH was approached to develop a way to deploy three hydrophones on the project and operate them simultaneously. This was the first time UNH had observed foundation work where results could be compared to other test data, as existing pile driving data was available. The observed information in the field varied considerably from published values. The issue was traced to an incorrect specification provided by the equipment rental company. Upon correction of the data with the revised calculations, the results showed correlation with known data. A report was provided to NHDOT.

1.4.3 – Sarah Long Bridge Replacement Pile Driving Monitoring

During the summer of 2014, UNH was asked to provide a proposal for mandated sound monitoring during pile driving on the Sarah Long Memorial Bridge replacement project. The scope focused on pile driving for several large temporary crane trestles. An automated system was proposed that could be monitored remotely, but site conditions and construction schedule required modification to an on-site system. Possible problems with the hydrophones selected on the project were identified requiring correction of the data based on reference measurements made with the hydrophones previously used in this research. Data is being corrected based on average SEL measurements taken from the reference data and sound measurements on permanent drilled-shaft installation was performed in late spring of 2016.

1.4.4 – Eastport Breakwater Replacement Hydroacoustic Isopleth Survey

In the summer of 2015, Maine DOT recommended that CPM Constructors approach UNH about providing broadband hydroacoustic survey services during pile driving on the Easport, Maine Pier and Breakwater replacement project. The contractor owned equipment to perform basic underwater acoustic surveys. On this project, the Contractor was required to determine “isopleths” of uniform maximum predicted sound pressure for each pile driving activity to determine zones of wildlife exclusion and zones of potential wildlife harassment. However, NOAA did not approve the use of the contractor’s equipment to produce these isopleths due to insufficient frequency response range. UNH was approached to conduct these isopleth surveys. During this research, a methodology was created to produce the isopleths by incorporating geospatial information as well as develop a way to rationally plot the data on a map. Over several site visits, in-situ measurements were produced that showed the default contract wildlife exclusion and potential harassment zones were too large, and showed that they could be reduced, thereby significantly reducing construction delays while maintaining the mandated buffers for wildlife sound exposure.

CHAPTER II

Literature Review

2.1 – Existing Research on the Effects of Pile Driving Sound on Fish

The following section is a review of significant research on the effects of pile driving sound on marine life over the past 15 years. Popper and Hastings provided a comprehensive and often-cited review of research to date in 2009 in their paper "The effects of anthropogenic sources of sound on fishes" published in the Journal of Fish Biology by the Fisheries Society of the British Isles.

The abstract of this report describes how a review of both peer-reviewed and grey literature up until 2009 shows that very little is known about the effects of pile driving sound on marine life (Popper & Hastings, 2009). The report includes references to a number of studies conducted to date on the West Coast of the United States and the UK coastline on live fish in the presence of pile driving sound. A number of these studies were poorly conducted, utilizing too few fish specimens and poor research methods (Popper and Hastings, 2009). These were usually the only studies that alleged injury due to barotrauma from typical pile driving sound. The intensity of the sound the specimens were exposed to was often not recorded, nor was any information about the pile driving operations or driving criteria reported. Of the few studies that were well constructed, little to no verifiable differences in physiological or behavioral condition were noted from exposure to typical pile driving conditions versus control specimens. A review of these studies are given below.

A study by CALTRANS in 2001 involved the exposure of caged shiner surfperch *Cymatogaster aggregate* near a pile being driven. Of the caged specimens, a general increase in mortality was observed the closer the cage was placed to the pile being driven, but this was often overshadowed by variations between cages of different distances. Mortality was observed in fish not included in the experiment, but the numbers were reported as quite low. A lack of consistency in the hammer being used and durations of exposure further obscured verifiable data. Additionally, the examination of fish allegedly killed by exposure to pile driving sound was not carried out by an expert in fish pathology (Popper & Hastings, 2009). The intensity of sound at each cage location was not measured.

A study by Abbot & Bing-Sawyer in 2002 involved the study of Sacramento Blackfish *Orthodon microlepidotus* caged from distances varying from 45 – 850m from a pile struck 43 times with an air bubble curtain and 45 times without the bubble curtain being active. After exposure, the fish were observed for 5 hours before being bagged and frozen. No mortality or obvious signs of behavioral changes were observed during the 5 hour observation period. After thawing in a lab, pathology was performed, but without controls for tissue damage that resulted from freezing and thawing (Popper & Hastings, 2009). The authors reported an increase in damage to fish exposed to sound levels exceeding 193dB re 1uPa, but this sound level was not measured in-situ, rather, extrapolated from assumed “typical” values. However, the variation in damage to fishes within each cage exceeded the variation in damage with respect to distance and assumed sound dosage.

A study conducted by CALTRANS in 2004 involved the exposure of shiner surfperch *Cymatogaster aggregate* and rainbow trout *Oncorhynchus mykiss* caged at distances ranging from 23 to 314m from a pile driving operation for durations from 1 to 20 minutes. Control fishes were placed in the same cages for 3 to 10 minutes without exposure to pile driving sound. After exposure, the fish were observed for behavior modification and then observed for 48 hours prior to sacrifice by freezing. Upon thawing and necropsy, fish were evaluated for tissue damage without the presence of anyone experienced in fish pathology (Popper & Hastings, 2009). Several fish died in the 48 hour observation window, but it was not possible to connect the mortality with the sound exposure. Additionally, all of the control fishes showed low level trauma. It was not possible to develop a statistical relationship between injuries observed for fishes at the various distances due to an insufficient sample size (Popper & Hastings, 2009).

These studies were typical of those conducted prior to 2005. While a general idea regarding a relationship between mortality and injury and sound exposure from pile driving existed, the studies were often too flawed to show any meaningful results. Particularly unhelpful was the lack of any useful information about the source intensity and the site conditions. This is especially noteworthy as many of the studies to date were conducted by CALTRANS which is known to drive unusually large piles to very high capacities due to the high seismic lateral foundation capacities required in the region. It is not likely that the results from these early studies can be directly related to pile driving operations in other areas of the country.

Popper and Hastings did cite several studies on fish observed in-situ that were better designed and conducted. Interestingly, these higher quality studies showed nearly no verifiable damage from sound intensities that greatly exceed some current regulatory limits (Ruggerone et al., 2008).

Abbot et al. conducted a study in 2005 on a pile driving project in the Port of Oakland where 24” square concrete piles were driven with a diesel hammer and jet-assist. Shiner surfperch *Cymatogaster aggregate*, Chinook salmon *Oncorhynchus tshawytscha,* and northern anchovy *Engraulis mordax* were caged at a distance of 9.75m from the pile and exposed to 4 minutes of driving or 200 blows. A control sample was not exposed to the pile driving sound. Behavior was observed for 1 minute following exposure after which the fish were sacrificed using excellent methods (Popper and Hastings, 2009). The fish were then observed in the lab by an expert in fish pathology who was not told which batches of fish were control or treated with sound exposure. The results showed no difference between the exposed fishes and the control samples in either mortality or tissue damage. No behavioral differences were reported, but the short observation period and lack of criteria for how such differences would be determined makes the behavioral portion of the experiment unreliable (Popper & Hastings, 2009).

The most complete study to the date of the Popper and Hastings paper was a study by Ruggerone et al. in 2008. Yearling coho salmon *Oncorhynchus kisutch* were caged 15 m from 14EA 20 inch diameter pipe piles and exposed to 1,627 blows over a period of 4.3 hours. A control group was caged far away from the pile driving operation. Sound exposure at the closest cage was measured at 208dB re 1uPa peak and a cSEL of 207dB re 1uPa^2*sec at the conclusion of the 4.3 hour exposure, exceeding the current NMFS limits of 206dB peak and 187dB cSEL by a significant margin. The caged fish were observed for 19 days and sampled at 10 and 19 days for pathology. No mortality was observed during the observation period (Popper & Hastings, 2009). No differences were reported between exposed and control specimens. Additionally, no differences in behavior were noticed between groups of specimens.

Popper and Hastings showed that through 2009 no well-controlled studies showed reliable evidence of mortality or significant barotrauma from typical pile driving sound exposure. From a civil engineering perspective, one absent piece of information from most reports and studies is a complete description of the pile driving equipment, materials, and driving criteria. While the hammer model and overall pile size were occasionally mentioned, more detailed information was usually absent. Hammer stroke, ram weight, ultimate pile capacity, blow count, energy per stroke, or pile wall thickness/weight per foot was almost never mentioned. In addition, researchers did not mention any awareness of dynamic load test (PDA) data which would provide blow by blow records of pile penetration, hammer stroke, energy delivery, hammer efficiency, energy loss along the length of the pile, or transmitted and reflected strain wave amplitude. These parameters are critical to understanding the mechanisms of pile driving noise generation but seem to be unknown to the marine biology research side of the bioacoustics community at this time.

Recently, research at the University of Maryland lead by marine barotrauma researcher Arthur N. Popper has focused on observing live specimens in a custom-built noise simulation chamber called the High Intensity Controlled Impedance Fluid Filled wave Tube (HICI-FT). This chamber allows researchers to expose fish to sound pressures as high as 223dB re 1uPa and then sacrifice and perform pathology on the specimens with no freezing or transport time. Casper et al performed research in the HICI-FT in 2013 on a variety of species including Hybrid Striped Bass, Nile tilapia, lake sturgeon, chinook salmon, and hogchoker fishes and found only a handful of barotrauma injuries at cSEL levels below 207dB re 1uPa^2xsec (Casper, et al., 2013). It was only at intensities higher than 207dB cSEL that injury counts began to rise rapidly. This is in comparison to the current NOAA NMFS cSEL limit of 187dB that has been applied to all noise-sensitive permits on the both the East and West Coasts. The well-conducted research of Casper et al. would suggest that this specification may be too conservative and needlessly burdensome to infrastructure owners and contractors. Further research is required.

2.2 – Existing Research On The Behavior Modification of Fishes Due To Pile Driving Sound

More recent research has focused on possible temporary or permanent behavioral modification of fishes and marine mammals in response to pile driving sound. Research on behavioral modification has been primarily driven by the concerns of European researchers on the effects of driving very large diameter mono-piles for the oil and offshore wind energy industries in Europe’s northern oceans. These projects involve the driving of extremely large diameter piles with some of the largest hammers available handled by some of the world’s biggest offshore construction and crane vessels. The over-ambient noise from this type of unusual pile driving work can extend for tens of kilometers from the pile driving operation (Mueller-Blenkle & Et. al, 2010). However, these kinds of pile driving operations are unusual and do not represent the scale of the typical pile driving project in the US or northern New England.

Figure 1 – HLV (Heavy Lift Vessel) "Svanen" Installing Monopiles in the North Sea

Figure 2 –"Thialf" World's Largest Crane Vessel Handling 800' Piles for an Offshore Platform Jacket

In 2003, Nedwell et al. observed brown trout *Salmo trutta L.* caged near a pile driving operation at the Red Funnell Southampton ferry terminal in the UK at distances of 25 to 400 meters. The fish were observed by video cameras for behavior modification. The sound levels at the cages were not measured, but estimated to be 134dB at the 400m cage. No behavioral response was noted during vibratory driving of the unspecified pile, and behavioral modification was only reported at the 400m cage for impact driving (Popper & Hastings, 2009). No injuries or other effects were observed.

One of the best-controlled studies to date on the behavioral effects of pile driving sound on fish was conducted in 2010 by Mueller-Blenkle et al. in the UK. In this study, two 40m diameter by 5m deep pens termed "mesocosms" were used to study the reaction of cod and sole to pile driving sound produced by a transducer. The pile driving sounds were previously recorded during the construction of the German research platform Fino 1 and were recorded during the driving of a 1.5m diameter pile driven in ~30m of water. No other information on the project, hammer, driving criteria, or pile was given.

Both cod and sole of sufficient size were tagged with acoustic beacons and tracked with a Vemco Radio Acoustic Positioning (VRAP) system. This system was comprised of three receiving buoys that triangulate the position of tagged fish once every 22-90 seconds depending on the number of fish being tracked in a given test. The tags transmitted at ultrasonic frequencies between 63 and 84kHz which presumably did not interfere with the lower frequency pile driving noise (Mueller-Blenkle & Et. al, 2010).

The pile driving sound transducer was placed at either end of the pair of in-line mesocosms with two hydrophones placed on the perimeter of each mesocosm (also in-line with the transducer) producing a good measurement of the gradient of sound intensity across the two mesocosms. The transducer was capable of producing sounds up to 170dB re 1uPa but it was reported that the maximum sound pressure presented to the fish was 156dB and the minimum was 133dB. The fish were presented with randomized sections of the original 50 minute pile driving recording.

The results of the testing showed that tagged fish showed greater movement during the playback of pile driving sounds.

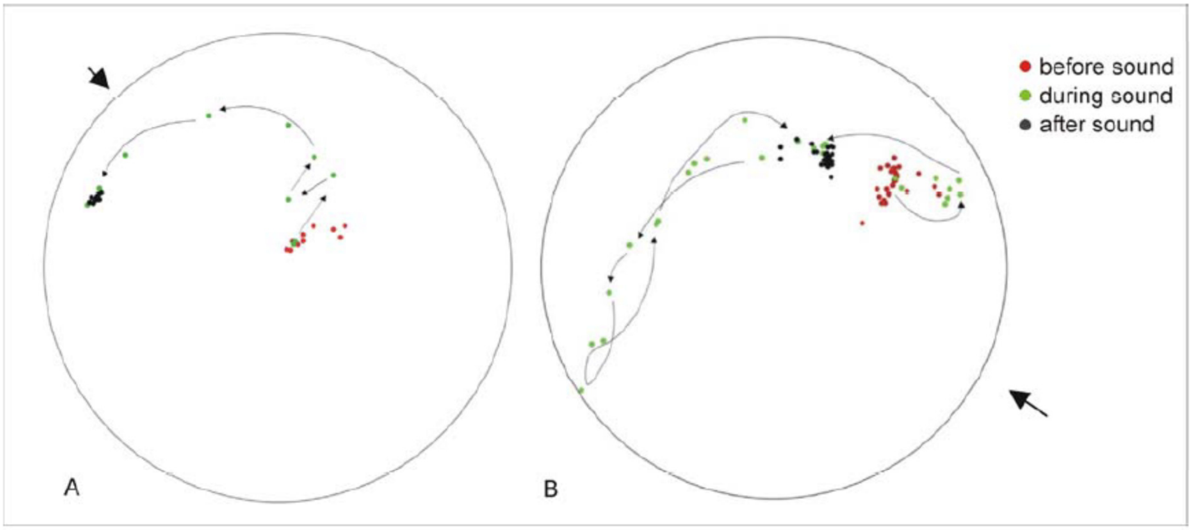


Figure 3 - Typical Fish Motion Plot from Mueller-Blenkle et al. 2010

It was reported that almost half of the cod (45%) and 32% of the sole showed responses to pile driving noise (Mueller-Blenkle & Et. al, 2010). It was also reported that both species tended to swim in a direction that reduced sound exposure upon initial ensonification of the mesocosms, but this response was downplayed by the researchers because the fish tended to swim in a chaotic pattern that roughly included the extents of the mesocosm. The effect of the relatively small confinement area was not addressed. Of interest, it was found that by the time playbacks reached the 27th or 28th exposure for a given group of fish their responses were marginal compared to initial exposure with a few specimens swimming slightly toward the noise transducer as if interested. The researchers determined that this was a general group behavior and that this "habituation" was not able to be correlated to an individual fish's behavior (Mueller-Blenkle & Et. al, 2010).

The researchers stated that this research has "immense" implications for fisheries management and that the precautionary sound mitigation measures applied thus far in the UK and elsewhere were, in fact, addressing a "real problem" (Mueller-Blenkle & Et. al, 2010). However, it is difficult to extract such conclusions from an objective evaluation of the data. First, no long term harm to the fish was observed in this study, and it was not demonstrated that pile driving sound, usually briefly produced in most locations, has any long-term effect on fish populations. Secondly, the study did not demonstrate that fish would not flee from dangerous levels of sound because their relatively small confinement area prevented this. Third, while researchers stated that their study confirmed that the "costs imposed by some mitigation measures" were apparently justified by the study, no support for this statement was given. The researchers did, however, provide several crucial points of further study requirements, including the study of a much larger range of fish and the use of a real pile driving rig to produce sound *in situ*.

Overall, research to date on the effects of pile driving sound on fish and marine life vary widely in their results and none have demonstrated a strong case for significant environmental harm from pile driving sound. In particular, the research to date lacks any discussion of the significant variation in the duration of pile driving sound production on a typical project, the variation in pile type, wall thickness, and peak strain wave amplitude during driving (which is available on most projects from dynamic test data), and no discussion of the significant variation in driving criteria which relate directly to how hard a pile is hit and how much energy may have been lost to sound in the immediate vicinity. Further research into this area would appear to benefit from the integration of bio-acoustic research and engineering research on the installation of driven piles. This research project provides a preliminary discussion of this information as it relates to the projects included in this study. However, due to the limited variations in pile types and hammers observed, this research is not a complete treatment of these topics.

Hawkins and Popper in 2014 produced a comprehensive overview of the research to that date and a discussion of the current NOAA NMFS guidelines for maximum fish and wildlife sound exposure. Historically, NOAA NMFS and US Fish and Wildlife Service use 150dB RMS re 1uPa as the threshold for behavioral modification in endangered or threatened fish. However, Hastings in 2008 reported that the scientific origin of this value is not known nor was variation in species taken into consideration (Hawkings & Popper, 2014). Currently, NMRS guidance suggests sound exposure limits of 206dB RMS peak and 187dB cSEL re 1uPa^2 x sec as recommended by the Fisheries Hydroacoustic Working Group (FHWG) in 2009 (Hawkings & Popper, 2014). Hawkins and Popper note that these metrics are likely not capable of fully distinguishing between sounds that are potentially harmful and those that are not. They note that while experimental data suggest that injury results from a combination of energy per strikes and number of strikes, these are not linearly related (Hawkings & Popper, 2014).

Hawkins and Popper also point out that these values do not take into account the tendency of fish and marine organism to avoid sounds that might cause harassment and harm. While NMFS seems to indicate that their guidance level for cSEL are to be measured over a 24 hour period before being “reset” to zero and have allowed this interpretation in pile driving reports, elsewhere NOAA suggests that this approach is inappropriately conservative. NOAA also touches on this issue in their 2013 guidance paper for hydroacoustic harm and behavioral modification to marine mammals. In section 2.3.1.1 of the “Draft Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammals”, NOAA says that it is not appropriate to use 24 hours as the period over which sounds are accumulated unless the location of the mammal in question is known throughout the period of interest and if it is known what sound levels the mammal was exposed to during that time (NOAA, 2015). If the location of organisms are not known, NOAA recommended that a period of only 1 hour be used to accumulate cSEL as the organism is not likely to stay in the same location and may flee sounds that produce harassment.

Hawkins and Popper also note that the current guidelines do not include frequency weighting, which is typically applied to sound measurements for humans and other organisms to account for the variations in sensitivity based on frequency (Hawkings & Popper, 2014). Humans, for example, are most sensitive to sounds with a frequency of 1kHz with decreasing sensitivity on either side of this value. Hawkins and Popper point out that research on frequency sensitivity is limited.

Finally, Hawkins and Popper note that current sound exposure criteria do not account for “strong avoidance responses” which are reported for nearly all fishes, although of varying degrees (Hawkings & Popper, 2014). This would suggest that more complete guidelines should fall under the NOAA 1-hour accumulation period (or less) for cSEL due to the documented tendency for fishes to avoid dangerous sources of sound.

Overall, Hawkins and Popper conclude that significant research on the effects of underwater sound on fish species and marine life is needed before more complete guidelines can be set. What is absent, though, is a discussion of the costs associated with the current incomplete guidelines and its effect on America’s infrastructure funding availability.

2.2 – Acoustic Physics Review

2.2.1 – CALTRANS Guidance Manual

The most complete guiding document available on the acquisition and analysis of pile driving sound data is the “Final Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish” prepared for the California Department of Transportation in 2009. UNH references this document in the development of its hydroacoustic monitoring methods and interpretation of project specifications. This document is not yet referenced by DOT project specifications directly, but is the most reliable and comprehensive guiding document available for this area of study.

This manual will be referenced for the following overview of acoustic physics as it pertains to pile driving sound analysis.

2.2.2 – Sound Pressure

Sound is fundamentally a pressure wave that propagates through a medium. Sound pressure, typically measured in Pascals (Pa), has the fundamental properties of amplitude, frequency, and speed in a given material. Sound propagates through a medium and shows a decrease in amplitude as distance from the source increases and the total acoustic energy is distributed into an ever-growing volume, thereby decreasing the total energy in a given unit of volume.

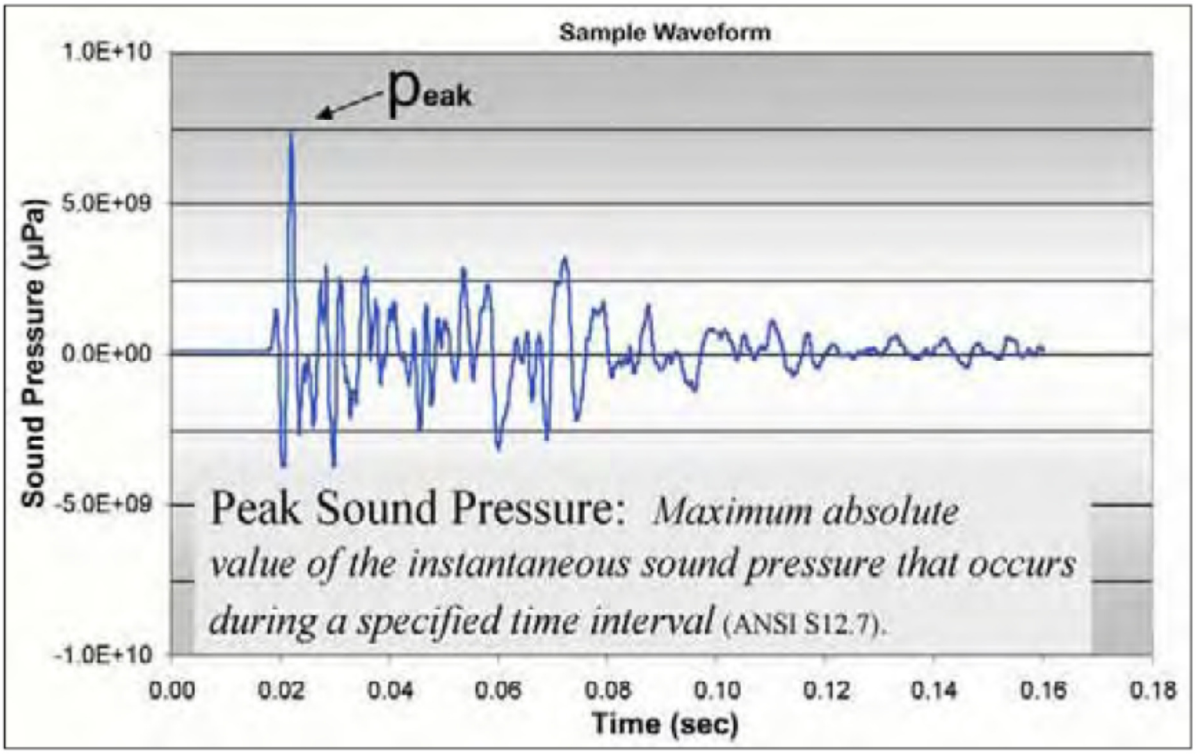


Figure 4 - Typical Pile Strike Pressure Waveform (Caltrans 2009)

The underwater sound pressure pulse from a typical impact pile strike is created when the strain or compression wave travels down the pile at a speed that typically exceeds the speed of sound in water, depending on the pile material. This supersonic pulse forms a “Mach cone” pressure shockwave that radiates into the surrounding water volume (Dahl & Reinhall, 2011). This initial pulse is typically followed by a “ring” from the pile resonating or other reflections of the initial pulse that eventually subsides to background levels just before the next strike.

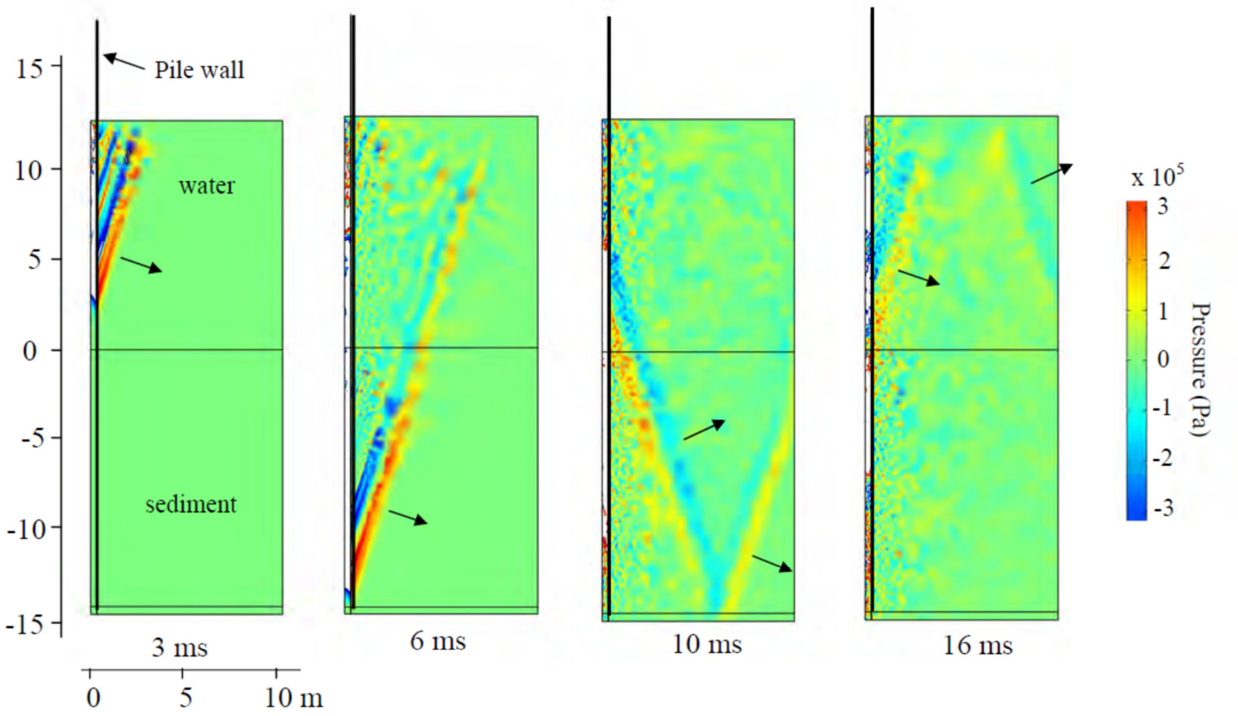


Figure 5 - Sound Pressure Propagation From Typical Pile Strike (Dahl 2011)

During vibratory pile driving, sound pressure is primarily produced by the displacement of the pile by the hammer with pronounced frequency peaks at the hammer's fundamental frequency (typically between 15 and 25Hz) and subsequent harmonics. Other noise can be created by rattling of the pile or template steel and transmitted into the surrounding water body.

2.2.3 – Decibel Scale

Sound pressures in the hydroacoustic environment can vary from only a few micropascals in very deep water to tens of kilopascals from large pile driving work or the detonation of high explosives (FHWG, 2009). In areas of study that require the comparison of signal measurements over a very large range, such as sound or electronic signal analysis, measurements are often compared to standard reference values and expressed as a logarithmic ratio defined as the bel. The bel is considered a discrete unit of measurement under the SI system and is named after Alexander Graham Bell due to its origin in telephone transmission line energy loss calculations (Harley, 1928). Each bel represents an order of magnitude increase in power. The decibel (dB), or 1/10th of a bel, is commonly used; therefore 10dB represents a 10-fold increase in power. The mathematic definition of the decibel is given below, showing the level of power (Lp) in dB is related to 10 times (to convert from bels to decibels) the logarithmic ratio of the measured power value P to the reference value P_0 (Pozer, 2004). Therefore, a measurement that equals the reference value produces log(1) = 0dB. A measurement below the reference value would produce a negative dB value.

$$L_P = \frac{1}{2}\ln\left(\frac{P}{P_0}\right)\ \mathrm{Np} = 10\log_{10}\left(\frac{P}{P_0}\right)\ \mathrm{dB}.$$

Figure 6 - Definition of Decibel Power Quantity

For all signals, the power of the signal is related to the square of its amplitude. Therefore, to use the decibel to describe amplitude measurements (F), the measurement is squared and compared to the square of the reference value (F_0) (Moore, 1995). These amplitude measurements in dB are called “field quantities” and their definition is given below.

$$L_F = \ln\left(\frac{F}{F_0}\right)\ \mathrm{Np} = 10\log_{10}\left(\frac{F^2}{F_0^2}\right)\ \mathrm{dB} = 20\log_{10}\left(\frac{F}{F_0}\right)\ \mathrm{dB}.$$

Figure 7 - Definition of Decibel Field Quantity

It is important to note that for power quantities a doubling of power is 3dB and an order of magnitude increase in power is 10dB. However, for field quantities a doubling of amplitude is 6dB and an order of magnitude increase in amplitude is 20dB.

A measurement of sound pressure is a field quantity as sound power cannot be measured directly, only pressure amplitude or particle velocity amplitude. Therefore a reading of 180dB represents a doubling of sound pressure amplitude from 174dB. A reading of 200dB represents an order of magnitude increase in sound pressure from a reading of 180dB.

For acoustic readings in air, 20 micropascals is used as the reference level of 0dB and is generally considered the lower threshold of human hearing (Roeser & Valente, 2007). After the development of hydroacoustic measurement equipment and the establishment of underwater acoustic science, it was found that a reference pressure of 20uPa commonly produced negative decibel values when working in the extreme quiet of deep water. The underwater reference pressure was revised to be 1uPa and this should be noted on charts or graphs of an underwater sound recording presented in decibels as "re 1uPa" to note that the reference (re) pressure is 1uPa (FHWG, 2009). There is no consistent linear comparison between decibel values for sound in air verses sound in water as they are non-linear scales with different origins. Ambient sound conditions in air are typical around 60dB and very loud sounds are around 100dB. In water, ambient conditions in a typical estuarine or river environment might be 120dB – 150dB and very loud sounds are anywhere from 160dB to 200dB (FHWG, 2009). Typical impact pile driving peak pressures measured at 10m ranges from 170dB for small timber piles up to 205dB for very large pipe piles.

2.2.4 – RMS (Root Mean Square) Sound Presssure Level

RMS Sound Pressure Level (SPL) is the time-varying RMS (root-mean-square) pressure recording expressed as a decibel field quantity. For noise compliance monitoring, the raw sound signal is typically not presented as SPL. Rather, an RMS moving average is performed and this time-varying RMS or instantaneous sum is given as the RMS SPL. The definition of the RMS of a set of discrete measurements is given below (Oxford, 2010).

$$x_{\mathrm{rms}} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots + x_n^2\right)}.$$

Figure 8 - Root Mean Square Computation

The RMS window can vary depending on application or desired information for compliance testing. The shortest window possible takes the RMS of a single data point as the raw measurement value divided by the square root of two. This means that the “RMS SPL Trace” of the recording is roughly 3dB below the raw data trace. This methodology is limited in application to broadband noise compliance testing which focuses on energy or intensity measurements over a large range of sound frequencies. This is opposed to a classic signal mechanics approach where measurements of very limited frequencies might be compared and phase information is required to calculate the net energy at any given instant. However, as noise compliance monitoring is not looking at the power interactions of specific signals in the broadband noise measurement, this is not a problem as both approaches converge over many signal cycles.

In the area of noise monitoring and compliance testing, all SPL values should be assumed to be RMS SPL. The current guidance from NOAA NMFS and other agencies for fish protection imposes a limit on peak SPL of 206dB re 1uPa regardless of duration at a distance of 10m.

2.2.5 – Sound Exposure Level and Cumulative Sound Exposure Level

Construction and engineering professionals are familiar with OSHA noise limits for humans being based not only on intensity but also duration of exposure at a given intensity. There are many metrics for calculating sound dosage, but researchers on bioacoustics have generally used Sound Exposure Level (SEL) and cumulative Sound Exposure Level (cSEL) to calculate a time-dependent sound dosage. This metric is based on SEL which has its origin in analyzing gunshots or other very brief, but intense events. However, it is easier to understand SEL by working backwards from cSEL.

cSEL is the double integral of pressure over time during a recording period, or the integral of pressure squared over time and has the units of Pascals squared x seconds. Due to the squaring of pressure, SEL and cSEL are measurements of power and can be expressed in basic power quantity decibels relative to a reference, typically taken as 1 uPa^2 x sec (FHWG, 2009).

SEL is a bit less intuitive to understand. Classically defined in the context of acoustic safety, it is the constant sound energy over one second that contains the total sound energy of the event that occurred in that second (Bernard, 1995). Originally, this unit was meant to classify events with a very short duration that had a high intensity, such as a gunshot or explosion. It can be thought of as the average energy of the original event if spread out over an entire second. This relationship to impulsive type sounds is likely why SEL is used in the field of bioacoustics relative to the effects of impact pile driving.

cSEL and SEL are related in that cSEL can be calculated as the logarithmic sum of the SEL of the events within that time period (FHWG, 2009). The final answer will be very similar to the cSEL calculated directly by integrating the entire data set. Both approaches are used and accepted in pile driving monitoring, although some consultants prefer to calculate the SEL of a “typical” strike and then perform the logarithmic sum on the total number of strikes. This requires marginally less computing power than the direct method.

The current guidance from NOAA NMFS and other agencies places a limit on cSEL of 187dB re 1uPa^2 x sec at a range of 10m. However, the duration allowed before this dosage is reset is generally not given. Many agencies take it as per 24 hour period, but others interpret it as per pile. NOAA has suggested in its marine mammal noise guidance in 2013 that a period of 1 hour may be more rational than 24 hours (NOAA, 2015). This duration period has been generally interpreted on a project by project basis.

CHAPTER III

Methodology

3.1 – Project Methodology

Each case study was approached with a three step process to develop a hydroacoustic monitoring solution. First, existing research and technical information was evaluated to develop a data acquisition and analysis approach for the project requirements. Second, a software and hardware configuration was assembled and implemented to meet the required technical and logistical criteria. Finally, the acquired data was compared with published results, when available.

The initial research focused on researching hydrophone electrical parameters and evaluating data acquisition devices to provide adequate performance for a given sensor. The data acquisition device must be selected to provide adequate frequency response based on its input impedance relative to the sensor and must have a minimum voltage range to provide adequate resolution at the expected output of the sensor.

Secondly, a custom LabVIEW application was written to acquire, process, and display, and store the data. Data was acquired as voltage and converted to sound pressure using the receiving sensitivity of the hydrophone in use. The data was then filtered by frequency to eliminate very low frequency offsets from wave action and very high frequency data that did not contain significant pile driving sound energy. NOAA recommended a frequency range from 20Hz to 10kHz which was used on most case studies. The data was then displayed to the user as a time domain histogram and a frequency spectrogram, updated constantly. Finally, the software saved the data to a .lvm LabVIEW Measurement File which is a text-based, tab delineated file containing a header with all measurement information and columns for time and the channels of sound pressure acquired.

Third, the acquired data was imported into MATLAB to be further processed and plotted for presentation. Various scripts were written and employed throughout these case studies to process data files sequentially and streamline plot figure creation. The LabVIEW data acquisition programs used on these case studies did not compute cSEL in real time, so most projects involved computing and plotting the time-domain accumulated sound energy and the final cSEL for each test in MATLAB. More complex data processing operations were also performed and explained in the relevant case studies. Sample scripts are included in the Appendix to this thesis.

3.1 – Memorial Bridge Foundation Drilling Survey

As of the summer of 2012, the UNH Department of Civil Engineering had no previous experience with underwater sound monitoring of construction activities or hydroacoustic measurements. At that time, sound monitoring requirements and in-water work restrictions were just beginning to show up in NOAA permit documents on several large bridge projects in the Merrimack River in Massachusetts. There were few experienced consultants or hydroacoustic monitoring firms in the region, as almost all sound monitoring and mitigation work to date had been performed on projects on the West Coast.

NHDOT approached UNH about investigating hydroacoustic monitoring methods and performing some preliminary measurements on the recently begun Memorial Bridge Replacement Project in downtown Portsmouth, NH. This historic lift bridge carried US Rt. 1 over the Piscataqua River to Kittery, ME. The foundation design involved the drilling of 30” diameter drilled shafts on the Kittery side approach and 9” diameter micropiles through the existing granite masonry piers which were being rehabilitated to carry the proposed bridge. NHDOT was interested in gathering data on the underwater sound produced by these activities due to the fact that sound data on foundation drilling methods was generally unavailable, unlike data on pile driving work being generated on West Coast projects. Future NHDOT projects on the Piscataqua River would involve the use of drilled foundations and the DOT was concerned about the possibility of limits being placed on future projects as the Piscataqa River was identified as a habitat for short-nosed sturgeon (*Acipenser brevirostrum)*.

Existing data acquisition experience was drawn upon and a rental source of industry-standard hydrophone equipment was identified. The proposed survey methods involved the use of a single Reson TC4013 hydrophone deployed at various locations from a small UNH boat with location and range information to be estimated from Google Earth and a test log describing the measurement locations. The TC4013 is a high-impedance piezoelectric device that produces a voltage linearly related to the sound pressure it is exposed to. The hydrophone signal was amplified by a gain of 30dB by a Reson VP2000 preamplifier that also provided a high pass filter at 10Hz to filter out wave action and a low-pass filter at 10kHz to filter out very high frequency sound. The data was acquired by an NI USB-9334 DAQ device at a sample rate of 20kHz.

Data was recorded and displayed by a custom LabVIEW application. The application was configured using LabVIEW’s express VI to automatically convert the voltage data to SPL. The express VI was configured with a hydrophone receiving sensitivity of 2.2 µV/Pa (per the rental supplier) and a reference pressure of 1.0 µPa. The data produced by the module was presumed to be SPL in decibels. To correct for the 30dB amp gain, 30dB was subtracted from the SPL data before the data was displayed to the user and saved to a data file. A flowchart of the VI is given below.

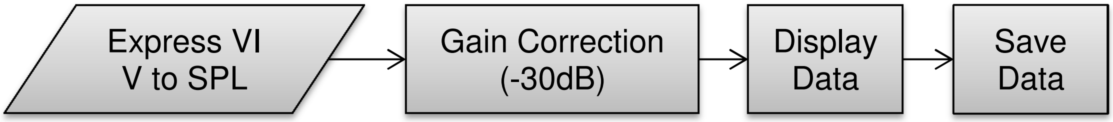


Figure 9 - Initial Labview Program Block Diagram

The field survey was conducted on August 6th, 2012. Micropile installation was in progress on Pier 4 using a Soilmec PSM-1350 hydraulic drill rig. During the measurement period, drilling crews were completing installation of a 9-5/8” diameter casing to a depth of 44’ below the top of pier and transitioned to installing the 9” diameter micropile at the same depth. The drill tool was a pneumatic down-hole-hammer (DHH) with spoil removal by the returning hammer exhaust air.

Figure 10 - PSM - 1350 Hydraulic Drill Rig Installing Micropiles on Pier 4

Drilled shaft installation was ongoing with a Soilmec R-930 rotary drill rig using a toothed auger bit at a depth of approximately 5’ below the top of rock. During all measurements where drilling was in progress, drilling speed was slow. The shaft in progress was located on the western end of the second most northerly pier in a tidal zone. The drilling location was dry at the beginning of the measurement period and was under several feet of water by the final test. The shaft diameter was 36” and was being installed within a 6’ diameter steel casing.

Figure 11 - Soilmec SR-930 Installing a 36” Diameter Drilled Shaft

A map of the measurement locations is given below.

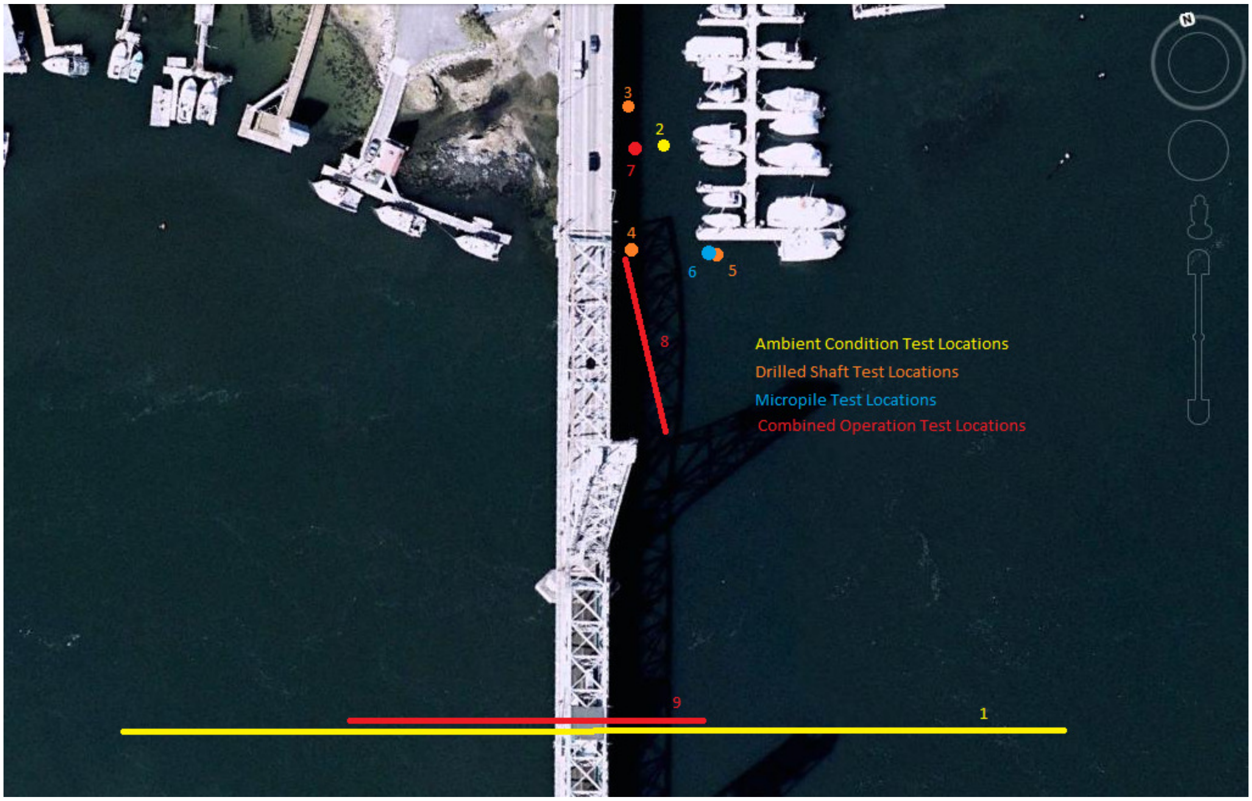


Figure 12 - Map of Memorial Bridge Measurement Locations

A summary of the original results are given below. A report was submitted to NHDOT on Nov. 28th, 2012.

No.	Time	Location	Distance From Source (feet)	Depth (feet)	Micro pile	Drilled Shaft	Boat Engine	Ambient Sound (dBa)	Max Submerged SPL (dbA)
1	10:40am	400' W to 400' E	450	20	No	No	No		20
2	12:41pm	Near Trestle	100	5	No	No	No		15
3	12:34pm	Near Trestle	75	5	No	Yes	Yes	84	95
4	10:53am	20' Off Pier 4	150	5	No	Yes	No		100
5	10:47am	Fixed at Marina	200	5	No	Yes	No		55
6	1:12pm	Fixed At Marina	90	10	Yes	No	No	75	240
7	10:34am	Between DS and MP	100	5	Yes	Yes	No		93
8	12:48pm	At Pier 4	30	10	Yes	Yes	No		105
9	1:06pm	100' E to 200' W	450	10	Yes	Yes	No		130

Table 1 - Memorial Bridge Sound Data Summary

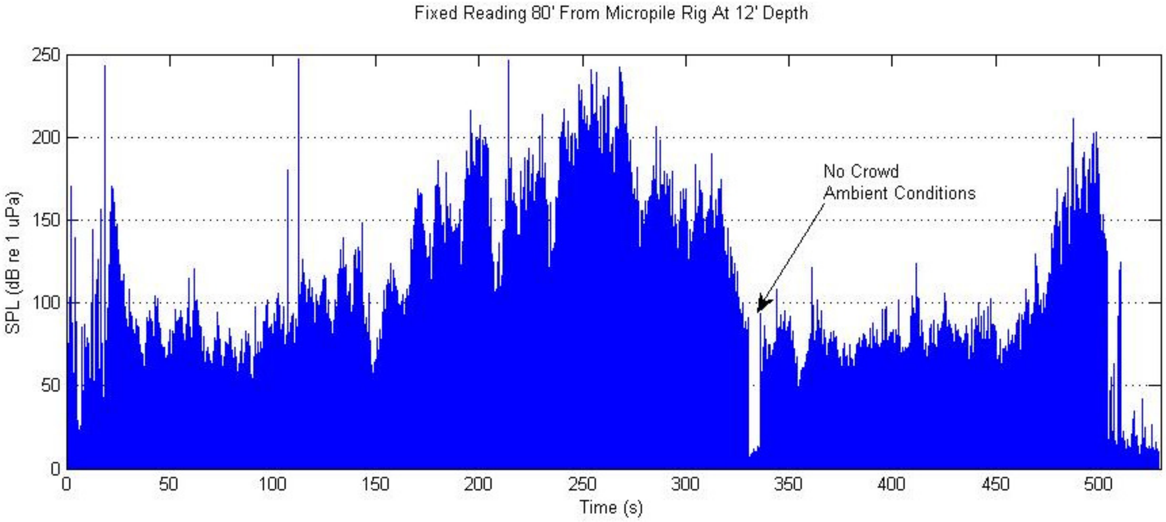


Figure 13 - Plot of Maximum Sound Pressure Recording of Micropile Drilling on Test No. 6

3.2 – Sarah Mildred Long Bridge Emergency Repairs

UNH was approached by NHDOT to provide non-mandated sound monitoring on repair work to the Sarah Mildred Long (SML) Bridge in Portsmouth after it was damaged by a ship collision. On April 4th, 2013 at roughly 1:30pm, a 473 foot tanker drifted from its moorings at the NH State Pier and collided with the SML Bridge that carries Route 1

Bypass over the Piscataqua River from Portsmouth, NH, to Kittery, Maine. The stern of the ship damaged several critical structural members, including the lower chord, on the southernmost 224' truss span. After NHDOT engineers and engineers from Cianbro Corporation inspected the damage, it was determined that temporary pile bents would be required to support the truss while repairs were made. Motivation for the sound monitoring came from the fact that Cianbro was expected to begin replacement of the SML bridge through the use of an extensive temporary trestle system that was to use the same size pipe piles. NOAA sound limits and mandatory monitoring was expected on the replacement project, and NHDOT along with Cianbro was interested in preliminary data.

The new noise specifications included requirements to monitor sound levels at 10m, 20m, and 40m from the pile being driven. The same hydrophone equipment used previously was proposed, but with three channels to be acquired at the same time. Due to the SML Bridge being a double deck structure with railroad tracks on the lower deck, deployment was proposed from the railroad deck. However, due to the swift tidal currents in the area around the bridge, the use of 30' sections of EMT (electrical metallic tubing) conduit, painted bright orange, was used to keep the hydrophones from drifting in the current. The height of the bridge over the water level meant that there could be up to 25 feet of vertical distance between the deck and the water surface, which would cause extreme horizontal displacement of the hydrophone.

Figure 14 - Deployment of Hydrophone Through EMT Conduit Below the SML Bridge

Researchers coordinated with Cianbro field personnel to schedule the roughly eight days of monitoring required. The initial vibratory and final impact driving of 8EA 30" diameter by half inch wall pipe piles was recorded. The vibratory driving was performed with an APE Model 200 vibrator/extractor which can provide a maximum dynamic driving force of 181 tons at a frequency of 0-28.3Hz. The impact driving was performed with an APE Model D62-42 diesel hammer capable of delivering up to 179,000 ft-lbs at maximum stroke with a 6.2 metric ton ram. Both hammers were handled by a Manitowoc Model 4000 crawler crane working off a sectional crane barge.

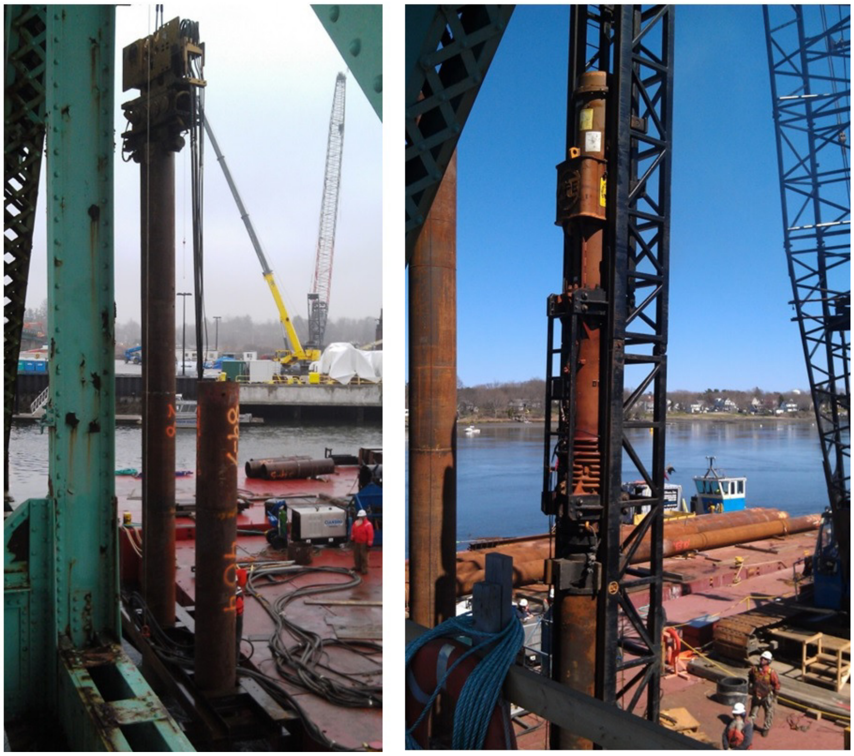


Figure 15 - Driving 30" Pipe Piles with an APE Model 200 (left) and Model D62-42 (right) Hammers

A map of the monitoring locations and truss panel points being repaired is given below.

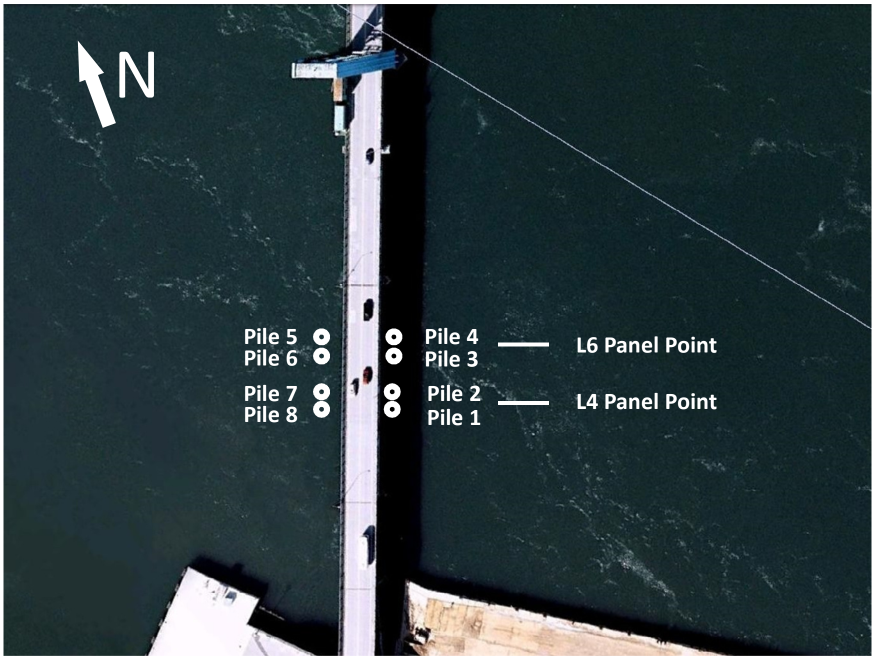


Figure 16 - Map of Pile Locations

While observing the data displayed in the field, it was noticed that the results for impact driving greatly exceeded published values (170dB-200dB). Investigation of the equipment in the field showed no apparent wiring faults or discrepancies in the response of the sensors. Attention was turned to checking the hydrophone sensitivity value, as this was the only other user-inputted parameter into the LabVIEW sound pressure express VI. The rental supplier reported a receiving sensitivity of 2.2 µV/Pa, but the hydrophone data sheet showed a sensitivity of "-212dB re 1V/µPa". After discussion with the supplier, it was demonstrated by the researcher that the correct conversion of this specification is:

$$-212dB\ re\frac{1V}{\mu Pa} = 20 * \log\left(\frac{Receiving\ Sensitivty}{\frac{1V}{\mu Pa}}\right)$$

$$Receving\ Sensitivty = 2.51x10^{-11}\frac{1V}{\mu Pa}$$

$$Receiving\ Sensitivity = \ 25.1\frac{\mu V}{Pa}$$

Figure 17 - TC4013 Hydrophone Receiving Sensitivity Calculation

The same calculation steps provided the correct conversion from dB re 1V/µPa to µV/Pa on other hydrophone specification sheets where both formats were provided.

After applying this correction to the data after the fact in MATLAB, the results still exceeded published values. After inspecting the data file headers, it was noticed that the measurement columns generated by the SPL express VI had only converted the voltage data to pressure in Pascals, not SPL referencing the reference value the VI was configured with. The fact that the data was saved in Pascals meant that the intended gain correction performed by subtracting amp gain in dB from the assumed SPL data head really only subtracted 30Pa from the pressure readings.

A MATLAB script was written to add 30Pa back to the original data files, then convert the pressure readings back to voltage using the incorrect sensitivity value the files were created with, remove the 30dB gain by dividing the voltage reading by three orders of magnitude (30dB or 3 bel), then convert the data to pressure using the correct sensitivity. The final readings converted to SPL ranged from 170dB to 185dB, indicating that the data was within the range expected from a survey of existing impact driving data.

Peak SPL from the vibratory driving varied from 150dB to 180dB at a distance of 10m. The propagated sound in the water varied due to a number of factors including the operating power of the hammer, the depth of the pile, and the resistance of the soil layers encountered. It was observed that during periods of hard driving, there was a noticeable increase in the vibration felt in the bridge structure, and this corresponded to the highest SPL underwater. The typical driving time varied between 6 and just over 20 minutes.

A summary of the test results is given below.

Date	**Location**	**Hammer**	**Begin Time**	**End Time**	**Ch. 1 Distance**	**Tide**	**Speed**	**Max SPL @ 10m**
4/20/2013	Pile 1	Vibro	N/A	N/A	N/A	N/A	N/A	N/A
		Diesel	3:53pm	5:08pm	30'	Out	2.6fps	165
	Pile 2	Vibro	2:23pm	2:24pm	30'	Out	2fps	150
		Diesel	5:37pm	5:43pm	30'	Out	2.5fps	170
4/21/2013	Pile 3	Vibro	12:50pm	1:10pm	30'	Out	1.5fps	173
		Diesel	1:56pm	2:14pm	30'	Out	2.5fps	170
	Pile 4	Vibro	1:16pm	1:26pm	30'	Out	2fps	170
		Diesel	2:26pm	2:34pm	30'	Out	3fps	170
4/22/2013	Pile 5	Vibro	N/A	N/A	N/A	N/A	N/A	N/A

		Diesel	2:04pm	2:14pm	30'	Out	2.5fps	169
	Pile 6	Vibro	1:18pm	1:24pm	30'	Out	2fps	180
		Diesel	2:30pm	2:42pm	30'	Out	3fps	170
4/23/2013	Pile 7	Vibro	N/A	N/A	N/A	N/A	N/A	N/A
		Diesel	2:55pm	3:05pm	30'	Out	3fps	182
	Pile 8	Vibro	1:45pm	2:06pm	30'	Out	2fps	170
		Diesel	2:34pm	2:45pm	30'	Out	2.5fps	180

Table 2 - Summary of SML Emergency Repair Sound Data

A plot of a typical vibratory driving SPL is given below. The drops to ambient conditions of ~142dB indicate periods when the hammer was shut off.

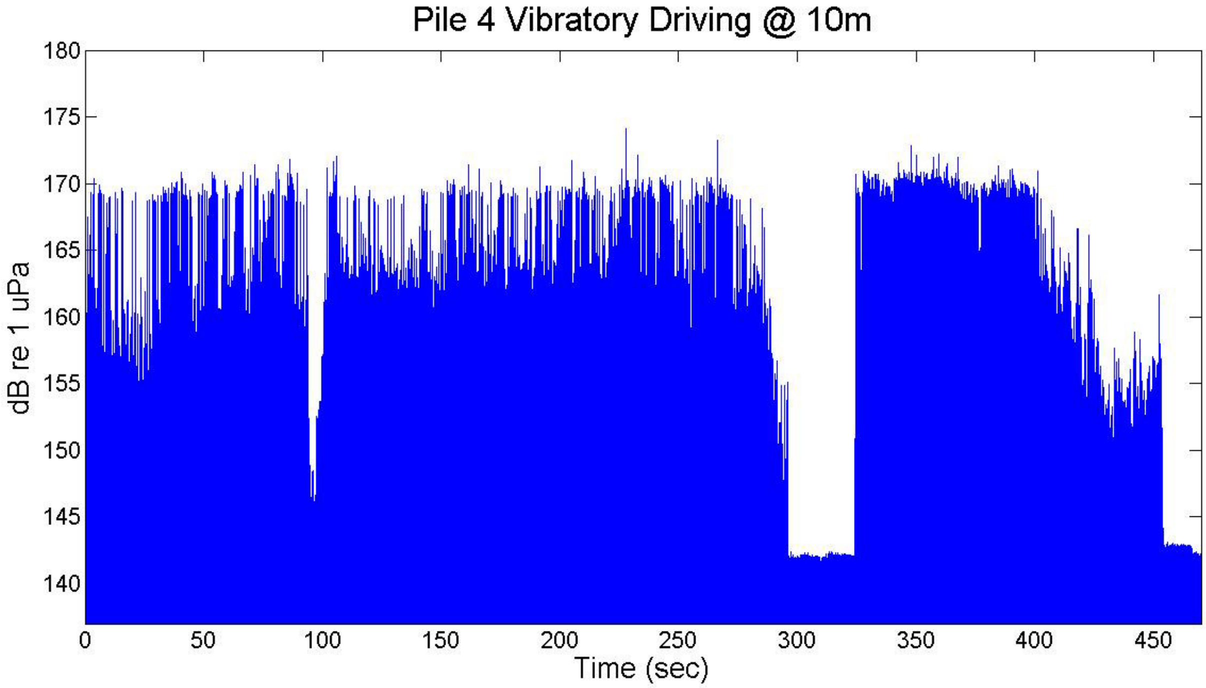


Figure 18 - Plot of Sound Data During Vibratory Driving on Pile 4 at 10m

Pile Type	Pile Size	Hammer Model	Driving Force	Max Frequency	Pile Length	Pile Penetration
Steel Pipe	30" Diameter x ½" wall	APE 200 Vibratory	181 Tons	28.3 Hz	105ft	Approx. 40ft

Table 3 - Summary of Pile Driving Information

A plot of the same recording at the 40m location is shown below and gives a sense of the attenuation over distance. Notice how the dynamic range of the data is similar, but scaled differently due to the logarithmic nature of the decibel scale.

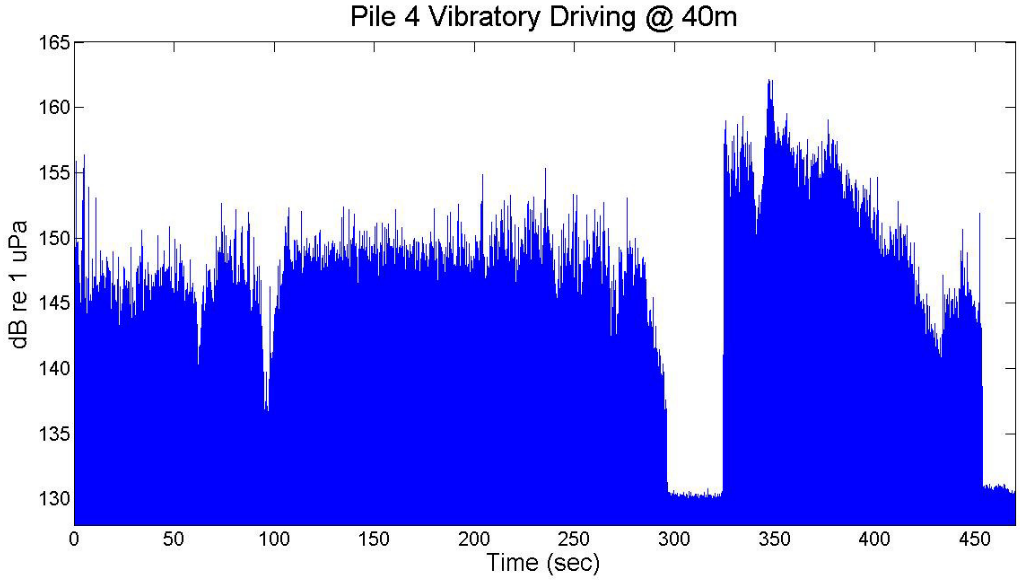


Figure 19 - Plot of Sound Data During Vibratory Driving on Pile 4 at 40m

Pile Type	Pile Size	Hammer Model	Driving Force	Max Frequency	Pile Length	Pile Penetration
Steel Pipe	30” Diameter x ½” wall	APE 200 Vibratory	181 Tons	28.3 Hz	105ft	Approx. 40ft

Table 4 – Summary of Pile Driving Information

The impact driving seemed to vary between 170dB and 185d at 10m. A plot of a typical impact driving recording is shown below. While cSEL and duration limits were not given as a criteria of this study, the driving cycles were kept relatively brief by the initial driving with the vibratory hammer and the relatively shallow bedrock depths in this area. The results of the survey seemed to show that exceeding the peak limit of 206dB was not likely with these piles or hammer.

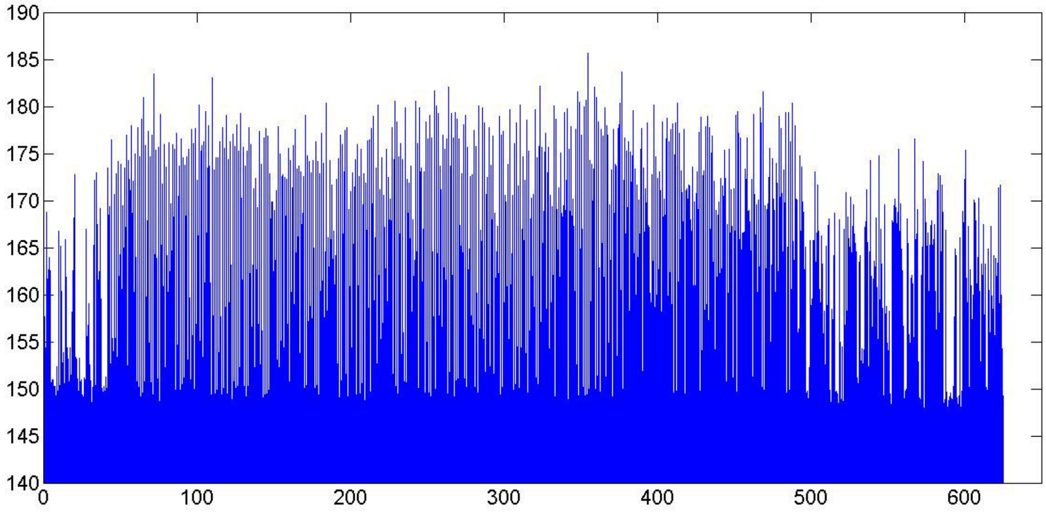


Figure 20 - Plot of Sound During Impact Driving Data On Pile 7

Pile Type	Pile Size	Hammer Model	Ram Weight	Max Stroke	Pile Length	Pile Penetration
Steel Pipe	30" Diameter x ½" wall	APE D62-42 Diesel Impact	13,700lb	Approx. 7ft	105ft	Approx. 40ft

Table 5 – Summary of Pile Driving Information

3.3 – Sarah Mildred Long Bridge Trestle Installation

Following the submission of the previous test data, UNH was asked to provide a general hydrophone system proposal to NHDOT for purchase instead of rent. This request was expanded to include a proposal to provide hydrophone monitoring for the SML bridge replacement project. The permanent bridge foundations are proposed as large diameter drilled shafts that are not included in the NOAA sound monitoring and mitigation requirement. NOAA's permit specifications apply only to piles driven with impact hammers. Therefore, the focus of the UNH proposal was monitoring the installation of several large temporary crane trestles to provide access to pier locations for the drilled shaft installation. UNH was required to monitor SPL and cSEL at 10m, 20m, and 40m from each pile as it was driven. cSEL was to be calculated for each individual pile.

The proposed trestle design was sized for 230-300 ton capacity crawler cranes. To support this equipment, the trestle would be based on 40 foot spans with three vertical 30” diameter by ½” wall pipe piles per bent. Additionally, to resist lateral loads imposed by the area’s swift tidal currents and horizontal reactions from heavy drilling equipment, most of the bents included two battered driven piles with drilled rock anchors installed through them. A typical bent cross section is shown below.

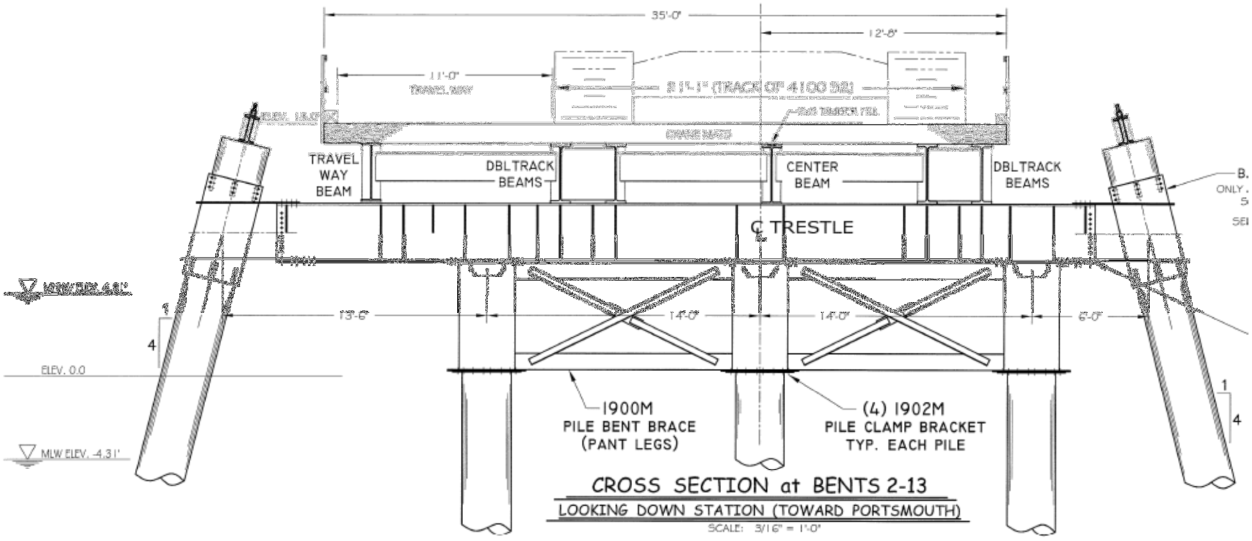


Figure 21 - Cross Section of Typical Trestle Bent

An aerial picture looking north of the completed trestle system in service in early 2016 is shown below. Top to bottom is the “Kittery-side trestle”, the “Portsmouth-side trestle”, and the shorter “Cutt’s Cove trestle” at the bottom of the frame. The proposed bridge alignment follows the location of the trestle “fingers”, passing east of the Kittery trestle and west of the Portsmouth trestle.

Figure 22 - Overview of Completed Temporary Crane Trestles

Due to the extensive nature of the trestle system and simultaneous construction sequence, it was initially propose to use hydrophone monitoring stations that could be accessed remotely via the internet and record sound data automatically. It was expected that simultaneous monitoring might be required at up to 7 points at once, three each per pile on each side of the river at 10m, 20m, and 40m and one proposed "far" station to provide attenuation data of a higher quality than the projection from the previous project.

A recently introduced model of piezoelectric hydrophones intended to provide cost-effective performance for pile driving applications was selected. To save the cost of voltage preamplifiers, a data acquisition device was specified to acquire the low voltage hydrophone signals directly without amplification. This required selecting a DAQ device with a sufficiently high input impedance to provide adequate response at low frequencies and a low voltage range to ensure adequate resolution. The hydrophone manufacturer supplied the following equation to compute minimum required input impedance (Z) to ensure linear operation down to a given linear low frequency cut-off (Fc).

$$Z = \frac{1}{0.000000038 * Fc}$$

To ensure linear operation down to 20Hz, for example, the DAQ device must have a minimum input impedance of 26 megaohms (MΩ). The National Instruments NI-9205 module was selected as it is a 16 bit multifunction DAQ device with a minimum voltage range of +/- 200mV at 250 kilosamples per second and an input impedance of 1 gigaohm. The module was proposed to be used to acquire a set of three hydrophones in a self-contained monitoring station for each of the two trestles. The DAQ modules were to be integrated with NI-9181 Ethernet carriers allowing them to be connected to industrial grade wireless routers for communication back to a base station in the DOT field office. The system would allow monitoring to be triggered remotely and simultaneously on both sides of the river if pile driving operations were happening concurrently. The monitoring stations could be relocated as time and access permitted while each trestle span was erected after driving each successive bent. Together the cost of the proposed hydrophone system was just under $36,000.00. The general arrangement of the proposed monitoring stations is shown below.

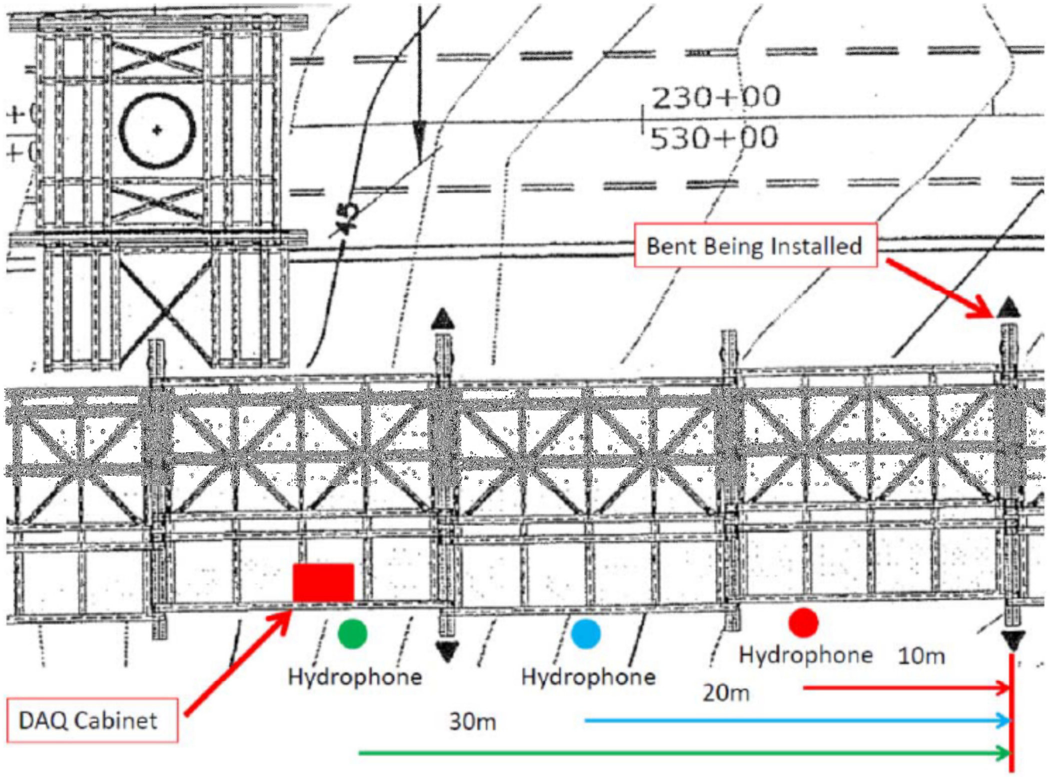


Figure 23 - Proposed Hydrophone Deployment Plan

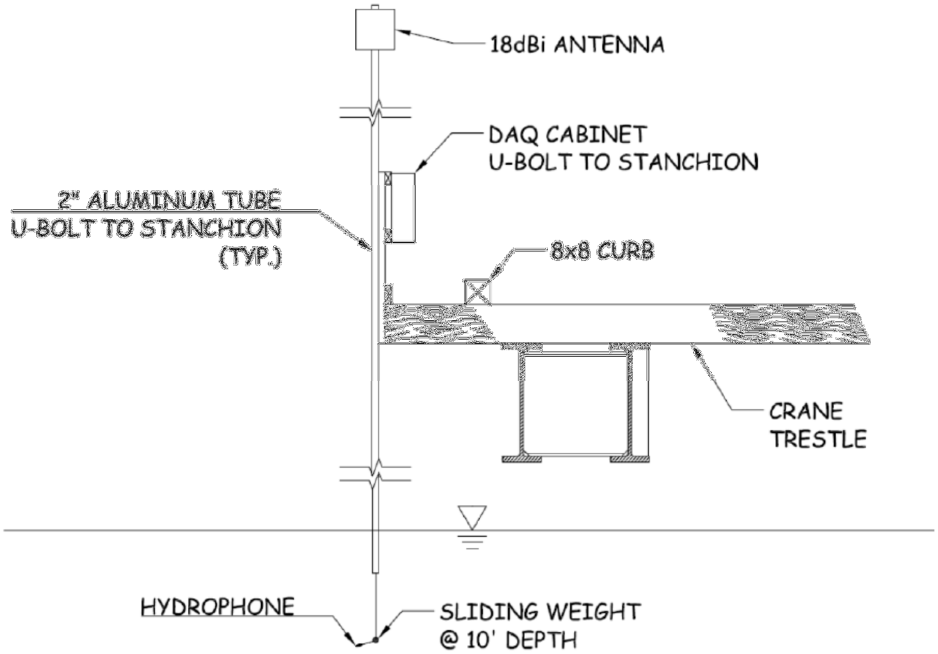


Figure 24 - Proposed Hydrophone System Elevation on Trestle

A preliminary data acquisition system was put together to handle monitoring before any trestle spans were complete to attach the proposed stations to. This consisted of the data acquisition equipment placed in a small waterproof box and connected to a laptop computer located in a vehicle with a 300’ ruggedized Ethernet cable. However, after observing the site conditions, it became apparent that the swift tidal currents would prohibit the use of continuously deployed equipment, due to the hazards of floating ice and floating debris. Additionally, the contractor planned to only have one pile driving hammer available on site meaning that the initial concerns about simultaneous work on both sides of the river were not likely to occur. Therefore, the monitoring plan was changed to use the portable system exclusively.

The first piles were driven on January 26th, 2015. The three piles comprising the abutment bent of the Kittery trestle were driven to capacity and PDA tested with a Bermingham B64 diesel impact hammer which can deliver a maximum energy of 162,260 ft-lbs at a max 11.5 foot stroke with a 14,110lb ram. The piles were advanced as far as practical prior to impact driving with an APE Model 200 vibratory hammer. The piles proposed for the temporary trestle and both hammers used for the duration of the trestle were very similar to those used on the repair project two years prior.

Based on PDA testing, the piles were recommended to be driven with the diesel hammer to a blow-count of 10 blows per inch at a stroke of 6.5 feet. This is just over half the maximum stroke of the B64 hammer and not much more than its minimum sustainable stroke. The results of the first test showed a maximum SPL of 190dB and a maximum cSEL of 181dB per pile. These values were slightly higher than those found on the testing in 2013 which showed a maximum SPL of 185dB.

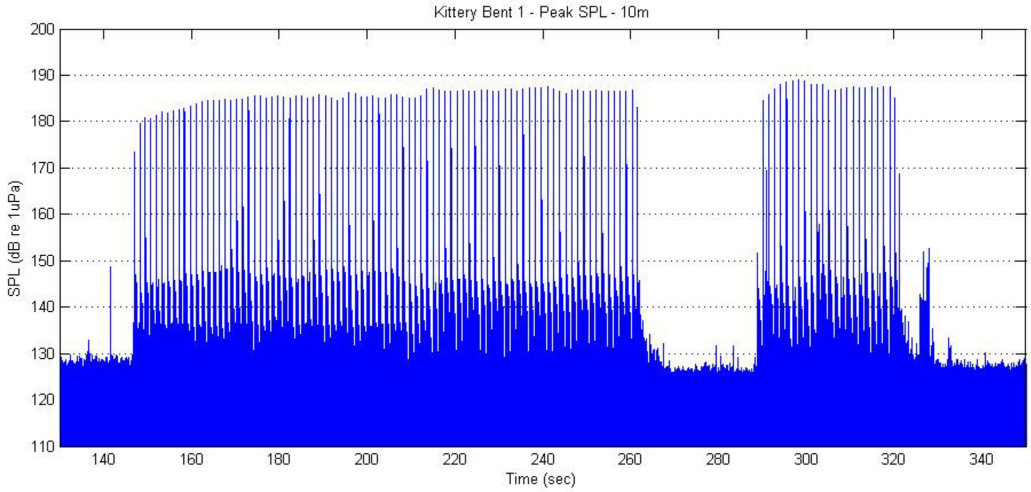


Figure 25 - Plot of Sound During Driving Of the Center Pile on Kittery Bent No. 1

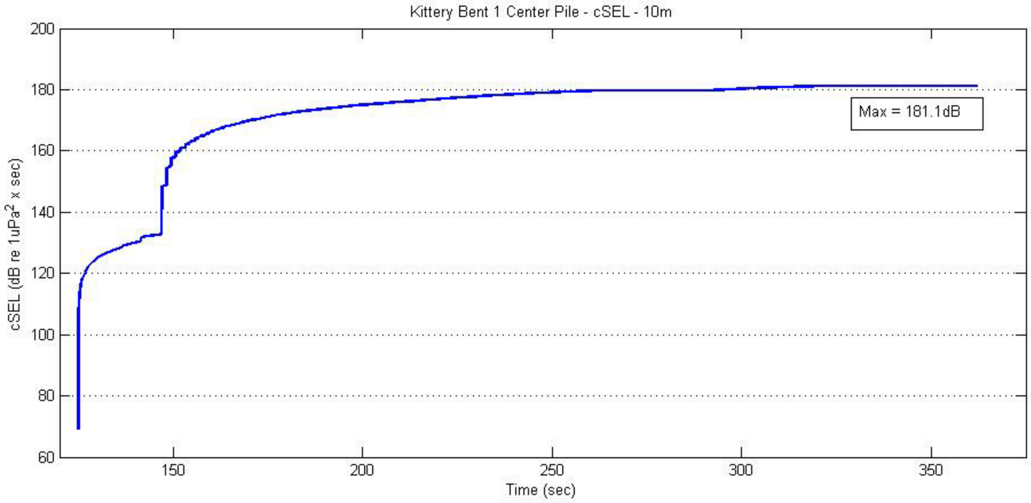


Figure 26 - Plot of cSEL During Driving Of the Center Pile on Kittery Bent No. 1

Pile Type	Pile Size	Hammer Model	Ram Weight	Max Stroke	Pile Length	Pile Penetration
Steel Pipe	30” Diameter x 5/8” wall	Bermingham B64 Diesel Impact	14,100lb	Approx. 7ft	55ft	Approx. 25ft

Table 6 - Summary of Pile Driving Information

From this test, a single-strike SEL of 160.0dB was calculated and the contractor was informed that the maximum cSEL of 187dB would likely be reached after 500 blows.

Figure 27 - Piles in Cantilevered Template After Driving

Subsequent to the first test, abnormally high and inconsistent data were recorded despite there being no change to the physical pile driving system. Readings as high as 210dB peak were seen with no discernable cause. Recordings continued as the trestle construction advanced with the expectation that the cause of the data inconsistencies would be discovered and corrected. Eventually, failure of some of the hydrophone sensors suggested a design defect as the data from these sensors become noisy and a substantial loss of sensitivity was noticed. As of the date of this report, the cause of the issue has not been resolved with the hydrophone manufacturer, and correction of the data acquired by them is likely not possible as the magnitude of the correction cannot be ascertained from the now-failed sensors.

To acquire representative data and project the sound impacts based on the number of blows per pile recorded by the original hydrophones, the previously used and standard Reson equipment was rented and a series of recordings were made on the Portsmouth No. 16 bent. A single Reson TC-4013 hydrophone was placed at the 10m location and the data acquired by an NI-USB 9334 DAQ module and a Reson VP1000 voltage amplifier. Additionally, a GRAS Model 42AC pistonphone was used to verify the performance of the Reson TC-4013 hydrophone and showed the system was within 1dB of calibration. The Model 42AC uses a series of cam-driven pistons to produce a displacement of air in a sealed coupler, into which the hydrophone is inserted and exposed to the pressure signal. The Model 42AC produces an RMS SPL of 164.5dB with the coupler designed for use with the Reson TC-4013 hydrophone. The calibration test showed an RMS SPL of 163.5dB with an amplifier gain of 20dB.

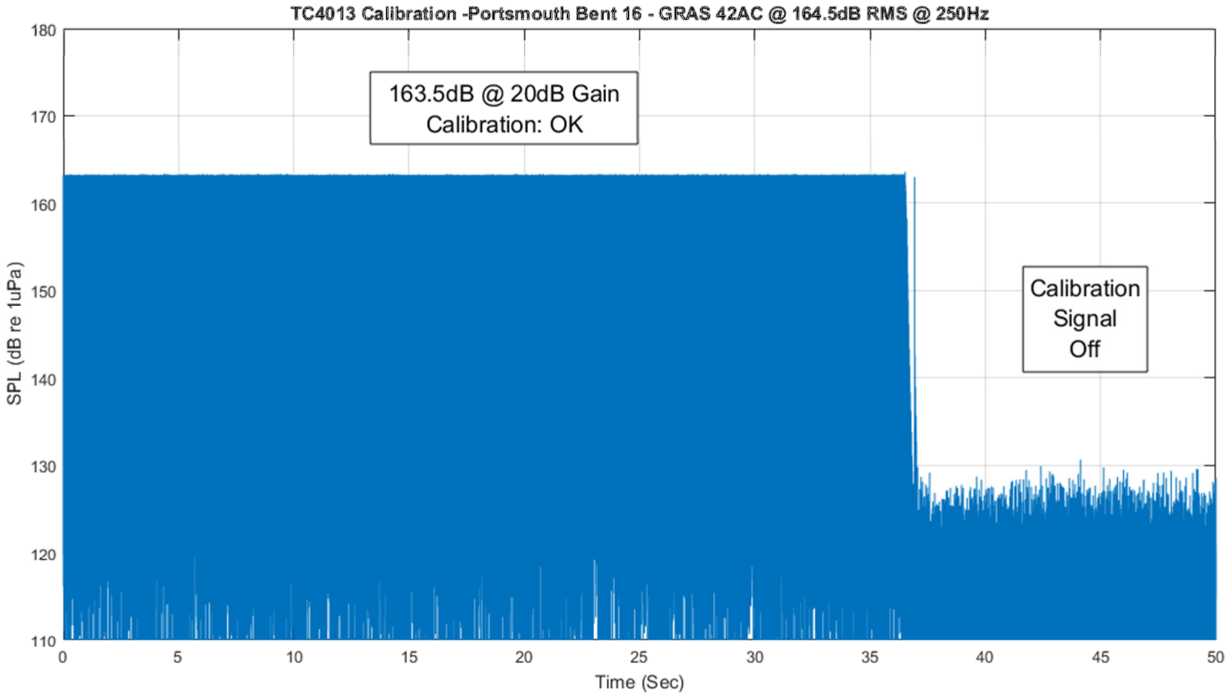


Figure 28 - Plot of Calibration Recording

These recordings showed similar results to those on the Kittery No. 1 bent with a peak SPL of 194dB and an average single-strike SEL of 161dB over the three piles driven. The following plots show the results for the south pile, which were similar to the center and north piles.

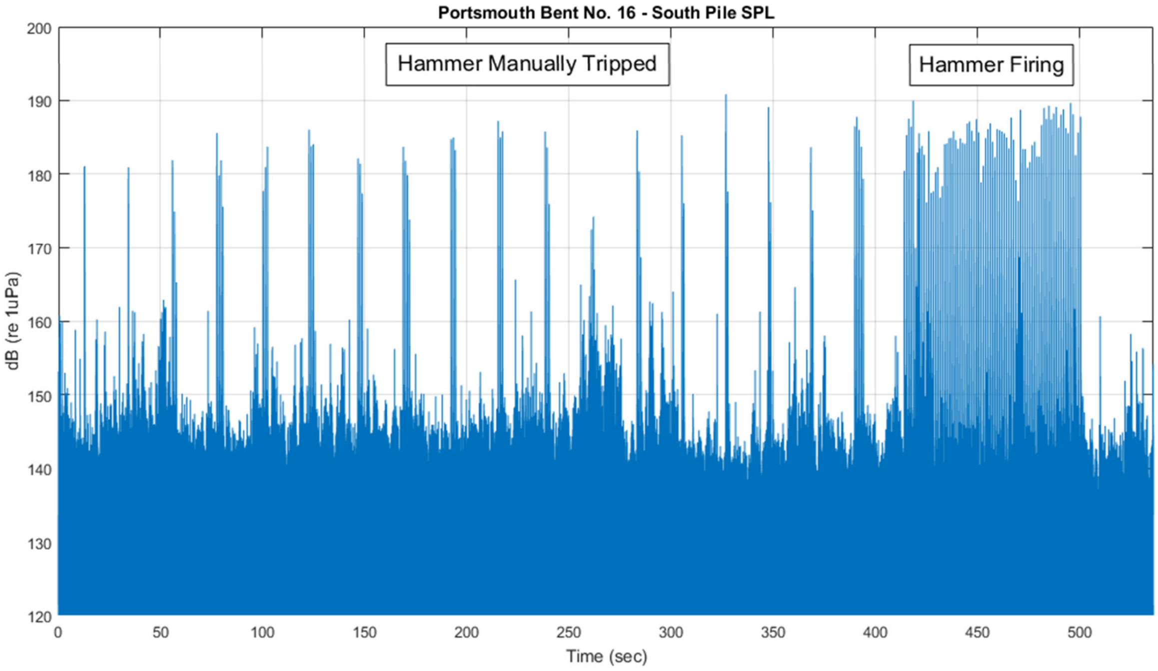


Figure 29 - Plot of Sound During Driving of the South Pile from TC4013 Hydrophone

The Bermingham B64 would not fire continuously until the pile reached substantial resistance. Until that point, the hammer was manually tripped using hydraulics. The accumulated energy cSEL plot is shown below. The final cSEL was 181.4dB after 122 blows, giving a single-strike average SEL of 160.5dB.

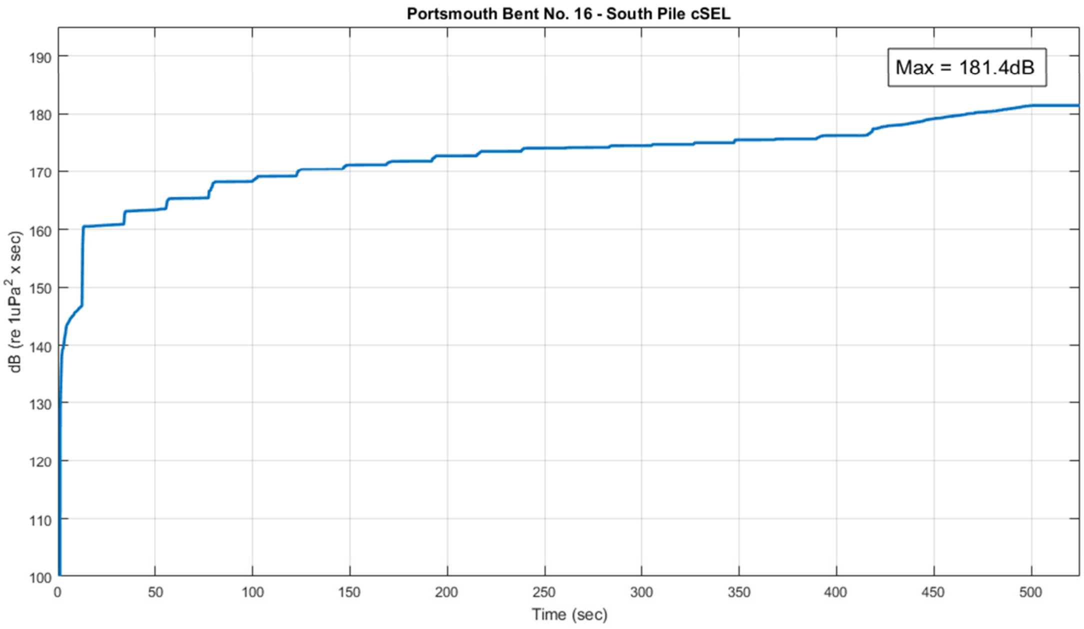


Figure 30 - Plot of cSEL During Driving of the South Pile from TC4013 Hydrophone

A summary of the three tests on Portsmouth Bent. No. 16 are shown below.

Date	Bent	Pile	Size	No. Blows	Peak SPL (dB)	cSEL (dB)	ssSEL (dB)	Mean ssSEL (dB)
July 29 2015	Portsmouth No. 16	Center	30" Dia. X 1/2"	163	194	182.4	160.3	161
July 29 2016	Portsmouth No. 17	North	30" Dia. X 1/2"	151	191	184.2	162.4	
July 29 2017	Portsmouth No. 18	South	30" Dia. X 1/2"	122	191	181.4	160.5	

Table 7 - Summary of Calibrated Data from Portsmouth Bent No. 16

One of the original hydrophones was also deployed at the same location connected to the portable DAQ system used previously on the project, but with the data acquired by software installed on a secondary laptop. The data displayed on screen from this hydrophone showed substantially higher results than the Reson hydrophone. As soon as the third pile in the Portsmouth No. 16 bent was driven, both hydrophones were retrieved and the calibration tests were performed on both hydrophones and showed in-specification performance at 166dB of the original hydrophone. However, due to a software error discovered later, the recordings of these tests were lost. Pile driving work on the temporary trestles was completed shortly thereafter and prevented further comparison of the two systems.

The data acquired on the project using the failed hydrophones represented an unreliable record of sound pressure, but did provide a record of the number of strikes for each pile. Because the driving criteria, hammer model, and general project conditions were consistent across all piles driven on site, it was possible to use the single-strike SEL of 160-161dB to project the cSEL for each pile. The data acquired by the calibrated Reson hydrophone on the Portsmouth No. 16 bent showed that the peak limit of 206dB was likely not exceeded on any piles as it was not closely approached in that calibrated test, the Kittery No. 1 test, or the tests performed in 2013. As a result, the cSEL limit of 187dB per pile was the limit most likely to be exceeded based on each pile’s driving duration.

As of the writing of this report, the post-processing of the data for the Cutt’s Cove trestle has been completed and showed no exceedance of the 187dB cSEL limit on any piles driven on that trestle. The maximum cSEL was 186.6dB on a pile that ran long on the final bent, nearest to Market St, where the APE Model 200 vibratory hammer was not used to initially drive the piles. This practice continued for the remainder of the work, and some exceedances of the 187dB cSEL limit is likely to be shown at the 10m location on some piles where significant depth of overburden was encountered. No exceedance was observed during the Portsmouth No. 16 test, as the overburden depth dropped off rapidly near the River's dredged navigation channel and driving durations were quite brief.

Because only one calibrated hydrophone was used on the Portsmouth No. 16 calibrated test, attenuation information in-situ was not directly observed. However, NOAA NMFS has recently published the GARFO acoustic calculator spreadsheet that includes a compendium of pile driving data and methods of calculating attenuation based on observations on historical projects. For confined water bodies, such as the Piscataqua River, the GARFOS tool suggests an attenuation of 5dB per 10m as observed during the driving of 30" diameter pipe piles on several projects in California and recommends this attenuation rate be used in similar confined water body conditions. For the post-processing of the SML data, 5dB per 10m is being used to compute the estimated cSEL at the 20m and 40m ranges from each pile.

Date	Bent	Pile	Size	No. Blows	SPL Peak (dB)	cSEL - 10m (dB)	cSEL - 20m (dB)	cSEL - 40m (dB)
Jan 29 2015	No. 7	North	30"ø x 5/8"	74	< 206	178.9	173.9	163.9
Feb 2 2015	No. 6	Center	30"ø x 5/8"	120	< 206	181.0	176.0	166.0
Feb 2 2015	No. 6	South	30"ø x 5/8"	139	< 206	181.6	176.6	166.6
Feb 2, 2015	No. 6	North	30"ø x 5/8"	145	<206	181.8	176.8	166.8
Feb 19 2015	No. 5	North	30"ø x 5/8"	61	< 206	178.1	173.1	163.1
Feb 19 2015	No. 5	Center	30"ø x 5/8"	87	< 206	179.6	174.6	164.6
Feb 19 2015	No. 5	South	30"ø x 5/8"	113	< 206	180.7	175.7	165.7
Feb 27 2015	No. 4	North	30"ø x 5/8"	44	< 206	176.6	171.6	161.6
Feb 27 2015	No. 4	Center	30"ø x 5/8"	80	< 206	179.2	174.2	164.2
Feb 27 2015	No. 4	South	30"ø x 5/8"	78	< 206	179.1	174.1	164.1
Mar 5 2015	No. 3	North	30"ø x 5/8"	61	< 206	178.1	173.1	163.1
Mar 5 2015	No. 3	Center	30"ø x 5/8"	47	< 206	176.9	171.9	161.9
Mar 5 2015	No. 3	South	30"ø x 5/8"	45	< 206	176.7	171.7	161.7
Mar 11 2015	No. 2	North	30"ø x 5/8"	41	< 206	176.3	171.3	161.3
Mar 11 2015	No. 2	Center	30"ø x 5/8"	81	< 206	179.3	174.3	164.3
Mar 11 2015	No. 2	South	30"ø x 5/8"	115	< 206	180.8	175.8	165.8
Mar 19 2015	No. 1	North	30"ø x 5/8"	127	< 206	181.2	176.2	166.2

Mar 19 2015	No. 1	Center	30"ø x 5/8"	359	< 206	185.8	180.8	170.8
Mar 19 2015	No. 1	South	30"ø x 5/8"	358	< 206	185.7	180.7	170.7

Table 8 - Summary of Sound Data from the Cutt's Cove Trestle

3.5 – Eastport Pier and Breakwater Replacement Project

UNH was approached by Maine DOT and CPM Constructors to assist with advanced monitoring requirements on the replacement of the central pier and breakwater for the city of Eastport, Maine. The pier's main sheet pile and retained earth wall collapsed in December of 2014 and its loss has severely affected the city's economy as it is no longer able to receive fishing and tourism vessels. Eastport is the easternmost city in the continental US and highly dependent on marine commerce for revenue.

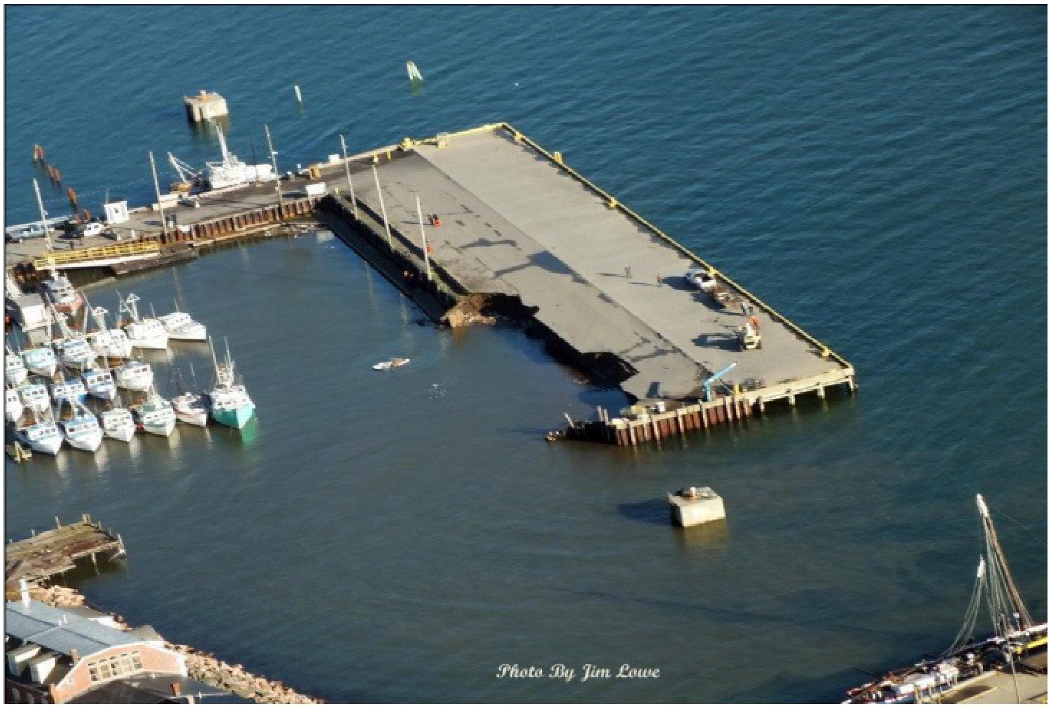


Figure 31 - Overview of Collapsed Eastport Breakwater

Due to its location on Cobscook Bay, the region is a habitat for seals, porpoises, whales, and other marine mammals. NOAA's research into the effects of anthropogenic sound on mammals indicated that hearing loss or shifts in hearing sensitivity are possible in mammals exposed to pile driving sound. The design of the replacement pier and breakwater required extensive driving of sheet piles and pipe piles and NOAA implemented limits on sound from these activities.

NOAA's research to date has indicated that harm to marine mammals was related to continuous RMS sound intensity as opposed to brief bursts of sound pressure or accumulated sonic energy that are the focus of fish protection limits. For the Eastport project, the following limits were set on RMS sound based on various construction activities. Level A sound intensities were those likely to cause permanent harm to marine mammals while Level B intensities were considered likely to cause harassment and possible temporary disruption to natural activities.

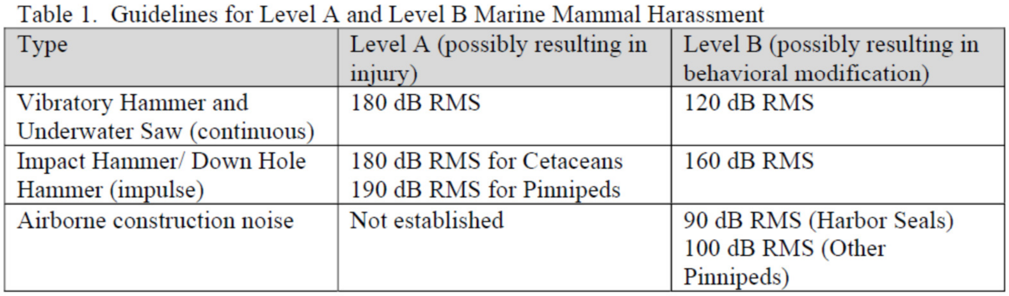


Table 1. Guidelines for Level A and Level B Marine Mammal Harassment

Type	Level A (possibly resulting in injury)	Level B (possibly resulting in behavioral modification)
Vibratory Hammer and Underwater Saw (continuous)	180 dB RMS	120 dB RMS
Impact Hammer/ Down Hole Hammer (impulse)	180 dB RMS for Cetaceans 190 dB RMS for Pinnipeds	160 dB RMS
Airborne construction noise	Not established	90 dB RMS (Harbor Seals) 100 dB RMS (Other Pinnipeds)

Figure 32 - Eastport Project Underwater Noise Limits

The RMS SPL for impact hammers was to be calculated by the "90% Energy Window Method" where the RMS SPL is computed for the portion of each strike that excludes the first 5% and last 5% of the total energy of the strike.

Based on existing sound data, NOAA indicated the following preliminary zones where marine mammal monitoring and exclusion were required during the indicated construction activities.

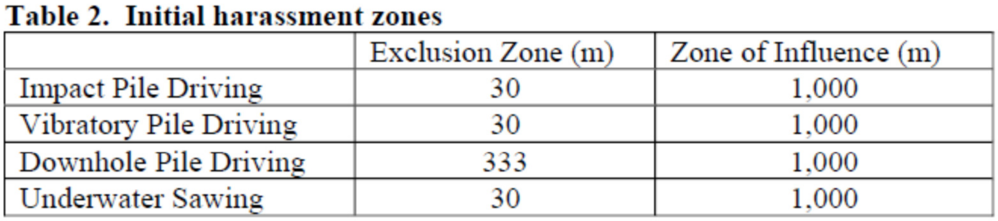


Table 2. Initial harassment zones

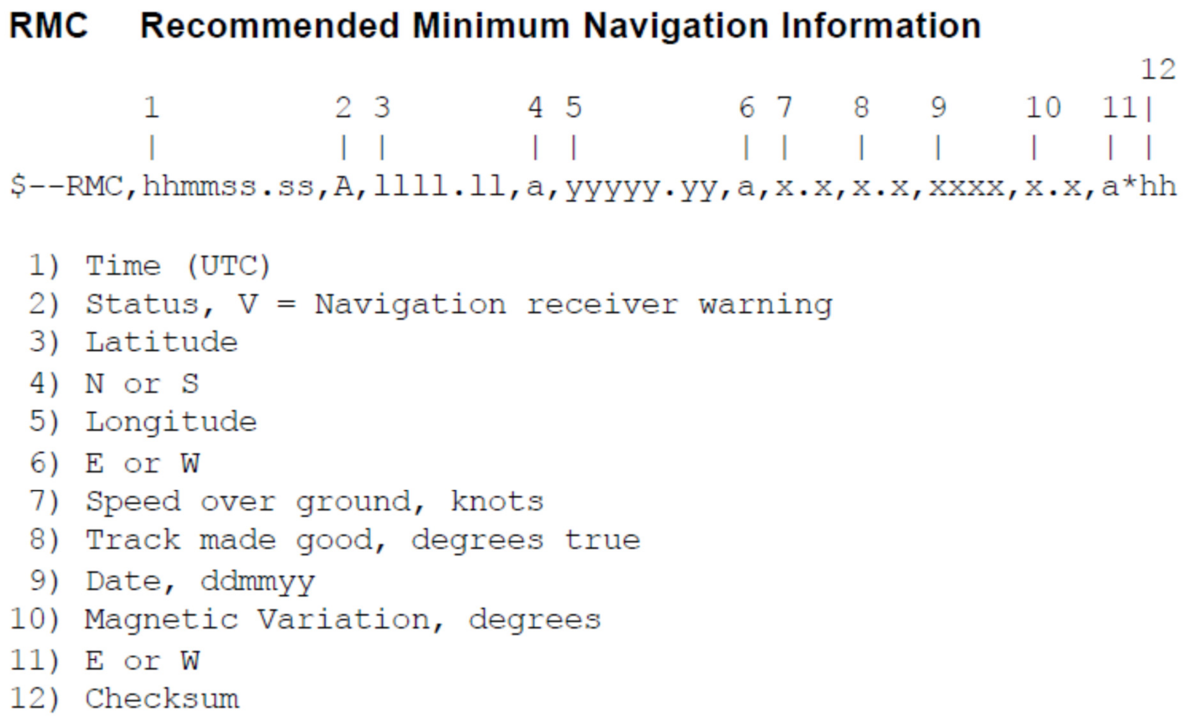
	Exclusion Zone (m)	Zone of Influence (m)
Impact Pile Driving	30	1,000
Vibratory Pile Driving	30	1,000
Downhole Pile Driving	333	1,000
Underwater Sawing	30	1,000

Figure 33 - Project Initial Harassment Zones

NOAA allowed the option of reducing the size of the zones if a map of sound "isopleths" or regions of maximum sound pressure were developed on site. However, the equipment originally proposed by the contractor to make the measurements was not approved due to having an insufficient frequency response range. Based on a recommendation from Maine DOT to the contractor, UNH was approached to perform the isopleth surveys as UNH's equipment met the NOAA required minimum frequency range of 20Hz-10Khz.

To support the spatial mapping requirements, UNH integrated a Garmin 18x USB GPS unit into the instrumentation package to provide real-time location information as the hydrophone was moved around the entire project area in a small boat. Integrating the GPS device required modifying the software to read the NMEA 0183 data stream produced by the Garmin 18x and store it in the sound data file at the proper lines to ensure synchronization. The NMEA 0183 protocol is used by GPS “talker” devices to produce a serial string of ASCII “sentences” that convey navigation information to “listener” devices on the network. A number of sentence formats can be sent depending on the application.

Labview does not support the use of the USB GPS receiver directly and required the use of a splitter program to read the GPS data and export it to a virtual COM port via the RS-232 protocol. The Franson GPSGate splitter application was used to receive a “ Global Positioning Recommended Minimum Navigation Information” (GPRMC) sentence format that provides a comma delineated string of the following information and export it to LabVIEW.



RMC Recommended Minimum Navigation Information

```
                                                            12
       1         2 3        4 5         6 7    8    9    10  11|
       |         | |        | |         | |    |    |    |   | |
$--RMC,hhmmss.ss,A,llll.ll,a,yyyyy.yy,a,x.x,x.x,xxxx,x.x,a*hh
```

```
 1) Time (UTC)
 2) Status, V = Navigation receiver warning
 3) Latitude
 4) N or S
 5) Longitude
 6) E or W
 7) Speed over ground, knots
 8) Track made good, degrees true
 9) Date, ddmmyy
10) Magnetic Variation, degrees
11) E or W
12) Checksum
```

Figure 34 – NMEA 0183 RMC GPS Data Sentence Format

The Garmin 18x refreshes this data sentence once per second. To record this information into the sound data file being written at 20,000 lines per second, the architecture of the LabVIEW application had to be changed substantially. Instead of a simple linear program, the architecture would need to be changed to a “data producer, data consumer” loop architecture. Three parallel execution loops were written to provide the following functionality: two data producer loops to record and process the sound data and to receive the GPS information and a data consumer loop to display the sound data spectrum (Fast-Fourier Transform) information and write a synchronized data file containing the sound and GPS information. A first in-first out (FIFO) data queue was used to move and buffer data between the data producer loops (Sound, GPS) and the data consumer loop (sound spectrum display and data file write).

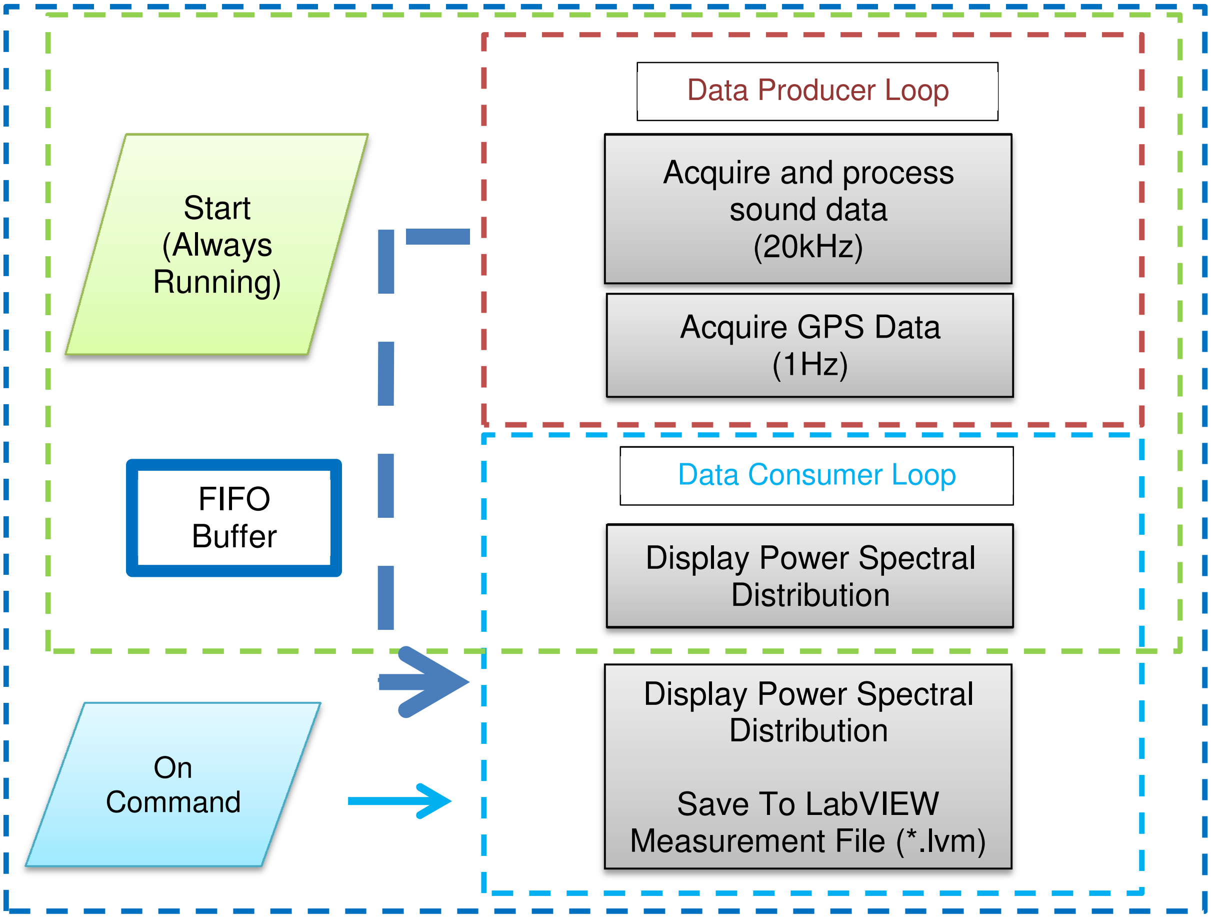


Figure 35 - Eastport Labview Software Block Diagram

Figure 36 - Hydrophone Recording System Showing (l-r) Hydrophone, Computer, and GPS Receiver

The hydrophone system consisted of a single Reson TC-4013 hydrophone amplified with a Reson VP1000 variable-gain amplifier with data acquired with an NI USB-9234 DAQ device. A calibration test was performed with the GRAS model 42AC pistonphone which produces an RMS SPL of 164.5dB. With the VP1000 voltage gain set to 20dB, the system indicated an RMS SPL of 165.5dB, within the +/- 1.5dB range of the nominal calibration signal indicating that the system was within calibration. A recording of a typical calibration test on this project is show below.

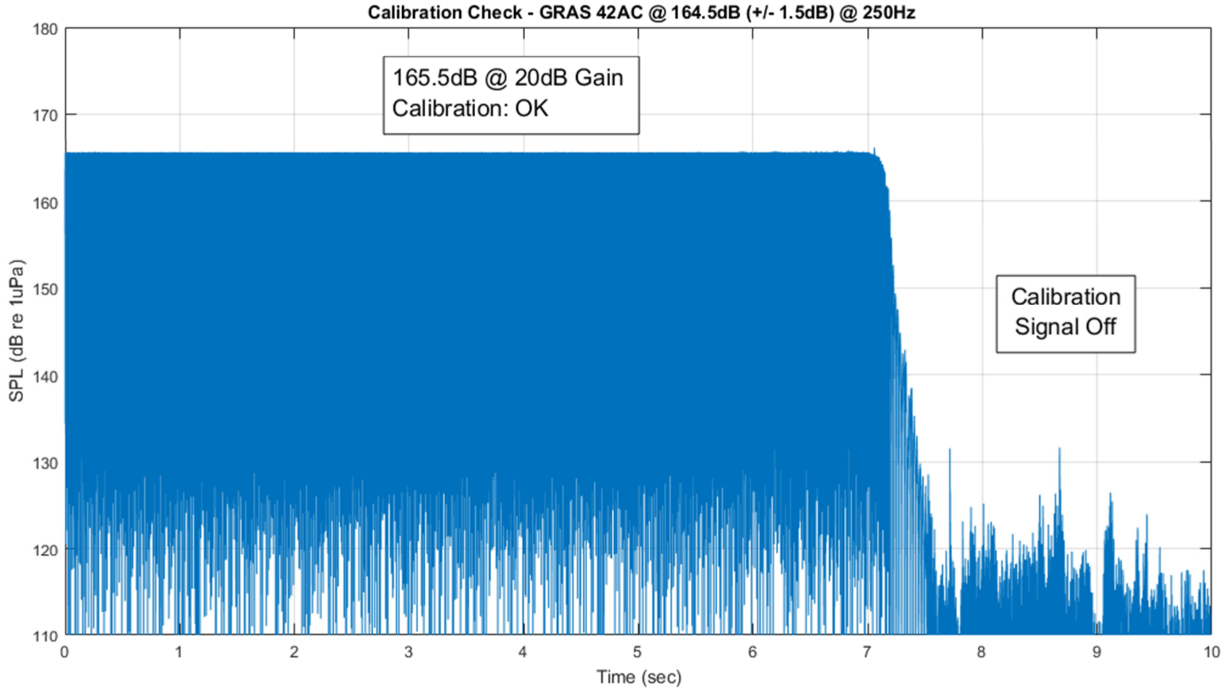


Figure 37 - Plot of Typical Calibration Test

A survey of vibratory sheet pile driving was performed with two different hammers between July 22nd and July 24th, 2015. Sixty-four separate recordings were taken at various locations around Eastport Harbor and included recordings of the ambient sound conditions, an APE Model 100 Driver/Extractor driving PZC-18 sheet piles, and an H&M 3400 Vibratory Hammer driving both PZC-18 and PZC-26 sheet piles.

Figure 38 - Driving PZC-18 Sheet Piles with an H&M 3400 Hammer

The method to produce the RMS isopleths was not prescribed in the project specifications. Due to the moment to moment variation in the intensity of the pile driving sound, it was not clear what sound intensity should be associated with a given location or distance. Initially, the data was processed to create a series of points based on a one second moving average where the RMS sound pressure over that second was associated with the average latitude and longitude. This data was imported to AutoCAD Civil 3D and plotted with sound pressure color coded to elevation. The following plots show the relationship between a raw SPL trace, the maximum sound intensity, and the one-second moving average RMS.

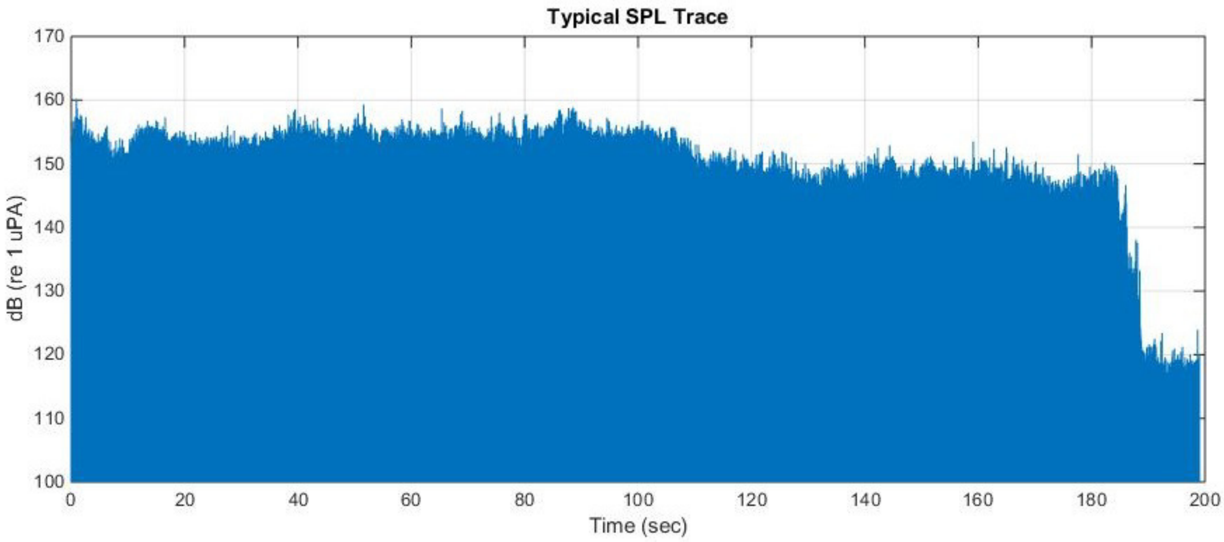


Figure 39 - Typical Vibratory Driving SPL

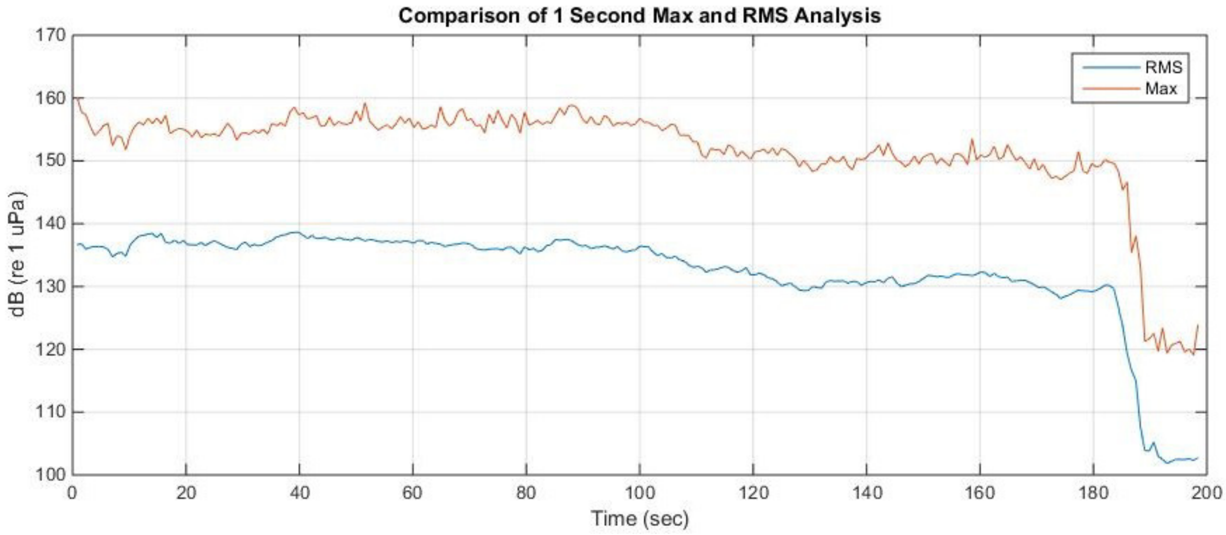


Figure 40 - Comparison of 1 Second Max and RMS SPL

The following plots show a recording of the typical ambient RMS sound pressure with no pile driving followed by a composite map of all ambient recording generated with the one-second moving average approach described above.

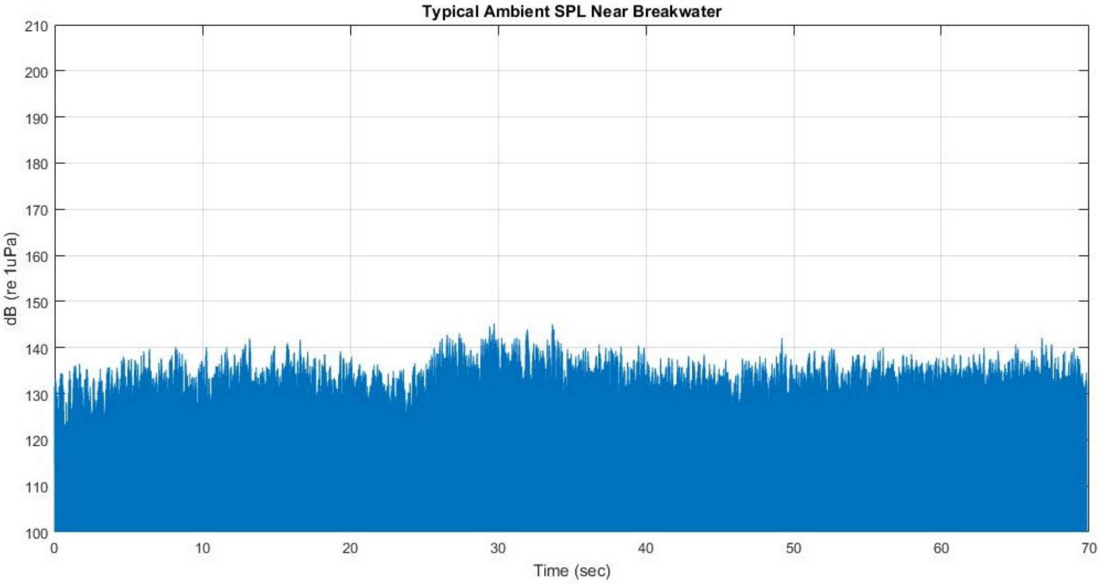


Figure 41 - Typical Ambient SPL

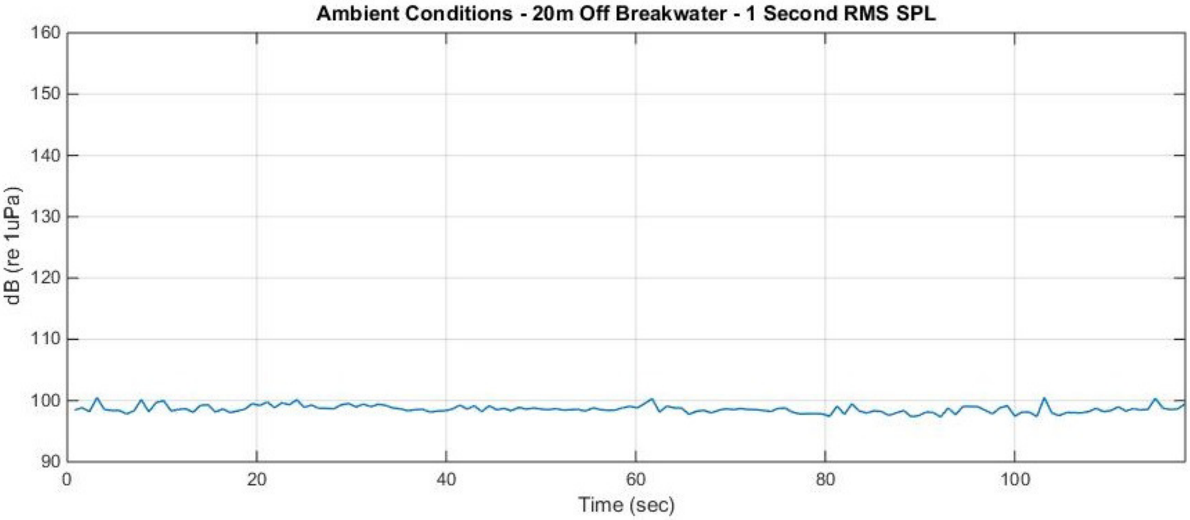


Figure 42 - Typical Ambient SPL 1 Second RMS Analysis

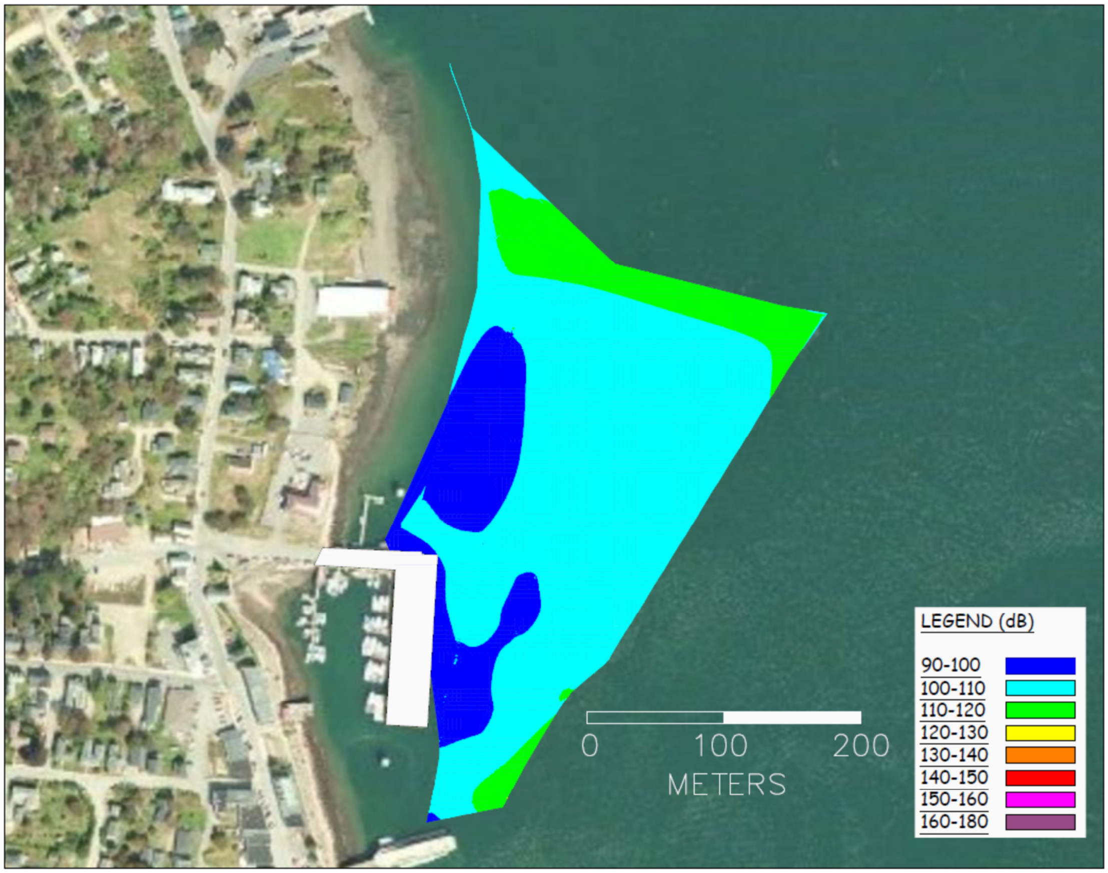


Figure 43 - Map of RMS Ambient SPL

A plot of the sound pressure generated while driving PCZ-26 sheet piles is shown below.

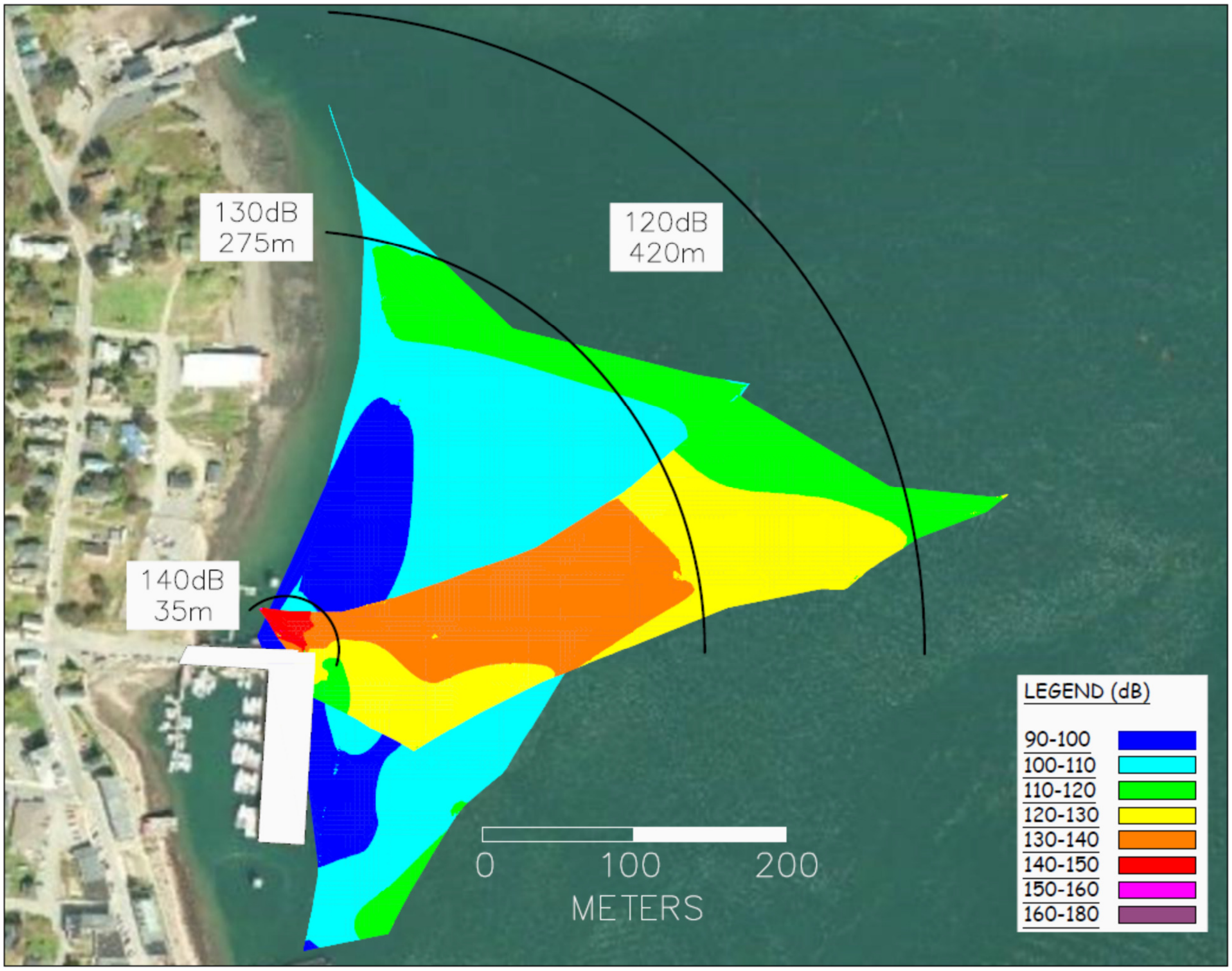


Figure 44 - Map of RMS Pile Driving Sound and Isopleth Locations

Pile Type	Pile Size	Hammer Model	Driving Force	Max Frequency	Pile Length	Pile Penetration
Steel Sheet	PZC-26	H&M 3400 Vibratory	90 Tons	20.8 Hz	60ft	Approx. 35ft

Table 9 - Summary of Pile Driving Information

Discussions with NOAA and Maine DOT indicated that for mammal protection NOAA's concern is the RMS sound pressure over long periods of time. While the initial approach preserved second-to-second variations in the RMS sound pressure, NOAA indicated that this level of detail was not necessary. It was recommended by the researcher that each separate recording be processed to display the RMS sound pressure of the entire recording and associate this intensity with the average latitude and longitude of the recording. MaineDOT concurred with this approach. For particularly long recordings, the recording was split into two pieces with each piece processed separately. An example of the relationship between a typical driving recording SPL and the average RMS of the entire recording is shown below.

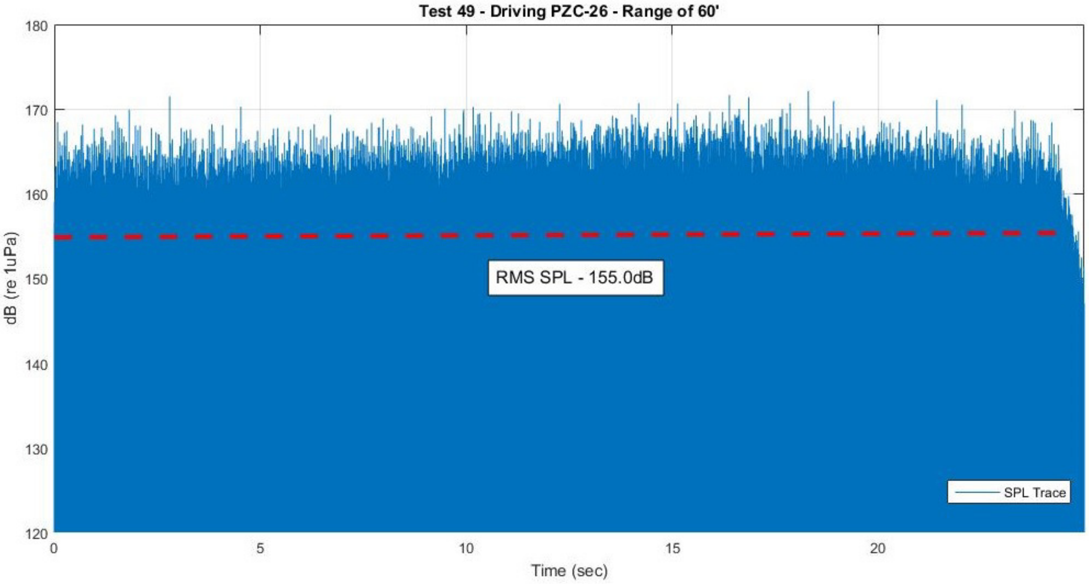


Figure 45 - Typical Recording And RMS SPL

A total of 16 recordings at various locations around the project site were conducted during the driving of PZC-18 sheet piles with the H&M 3400 hammer. A map of the measurement locations is given below and a summary of the test results is given in Appendix A.

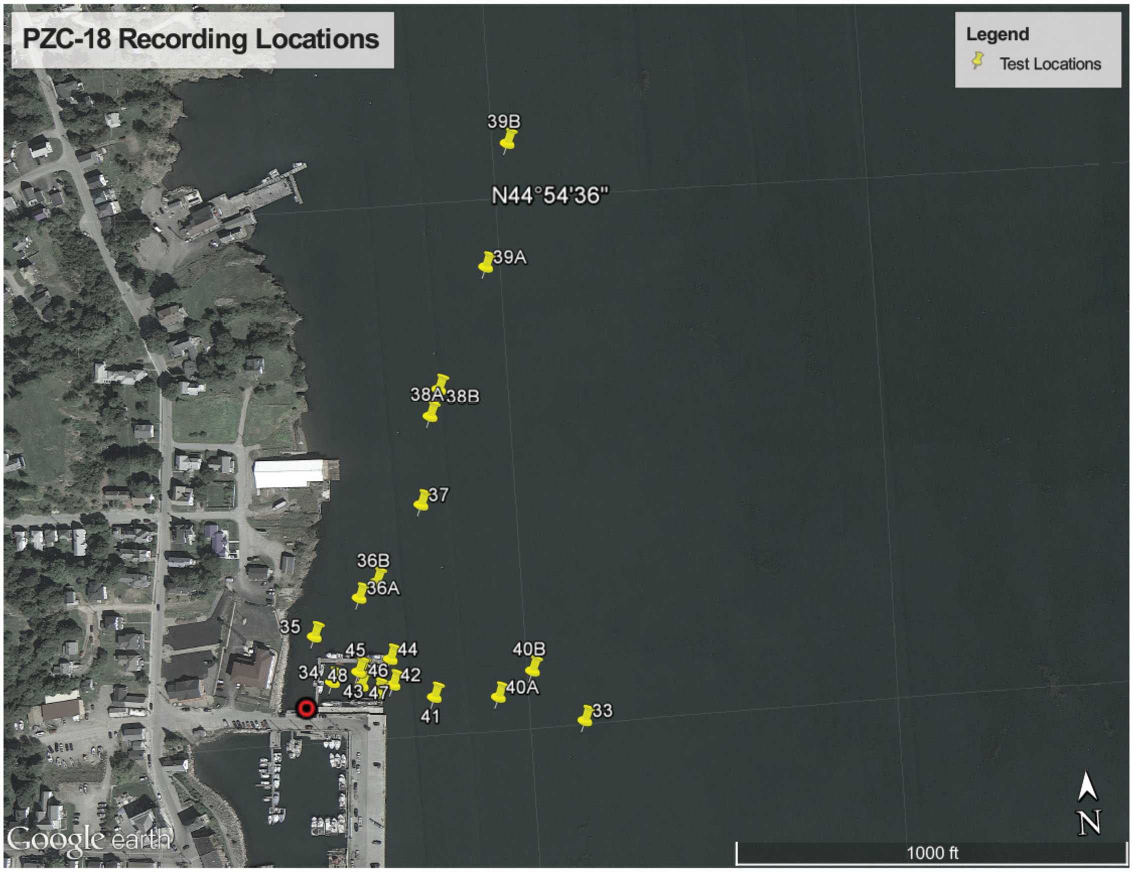


Figure 46 - PZC-18 Sound Measurement Locations

The RMS results of these measurements were plotted based on range from the pile being driven and a regression analysis was performed on the sound pressure data. The results of this regression analysis were used to predict the Level A and Level B isopleth locations.

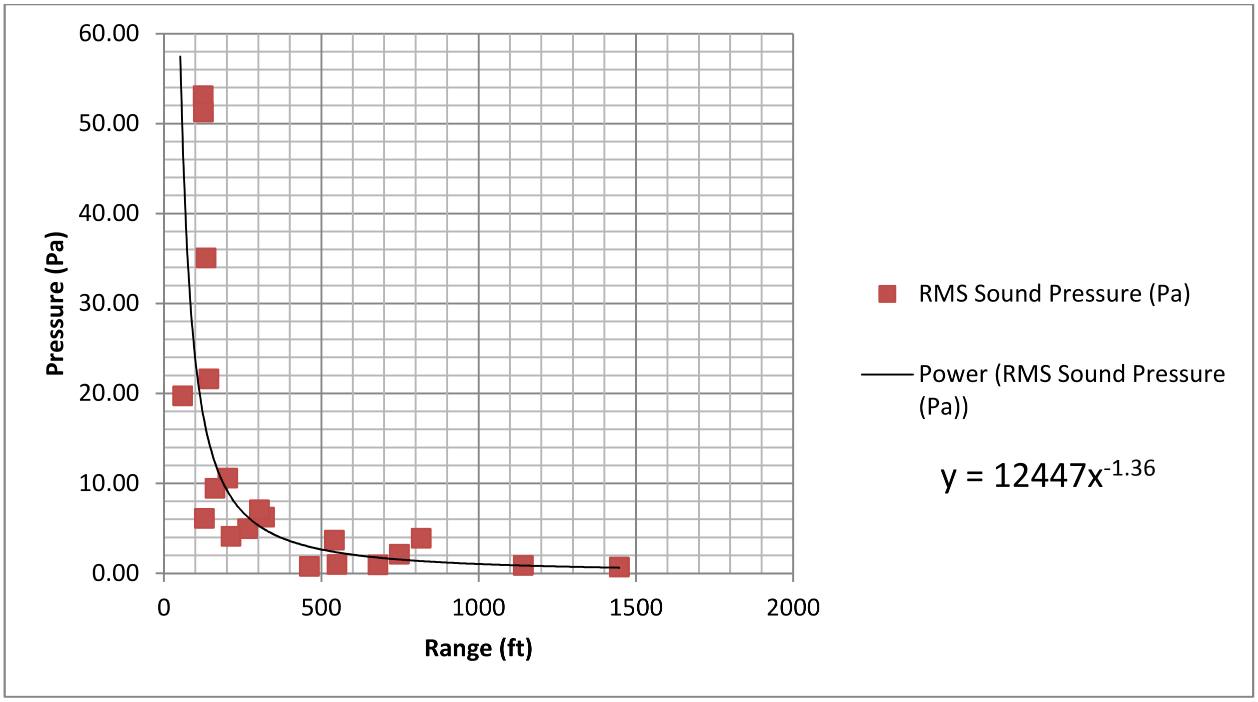


Figure 47 - Regression on PZC-18 RMS Sound Data

Based on the regression results, the Level A exclusion zone for all marine mammals where RMS sound pressure likely exceeds 180dB (1,000 Pa) RMS is 10ft (3m). Detailed information at this close range was not available due to the safety issues associated with approaching directly beneath the hammer while driving. The Level B zone of influence (ZOI) where RMS sound pressure likely exceeds 120dB (1.0 Pa) is 1,025ft (310m).

A total of 16 recordings at various locations around the project site were conducted during the driving of PZC-26 sheet piles with the H&M 3400 hammer. A map of the measurement locations is given below and a summary of the test results is given in Appendix A.

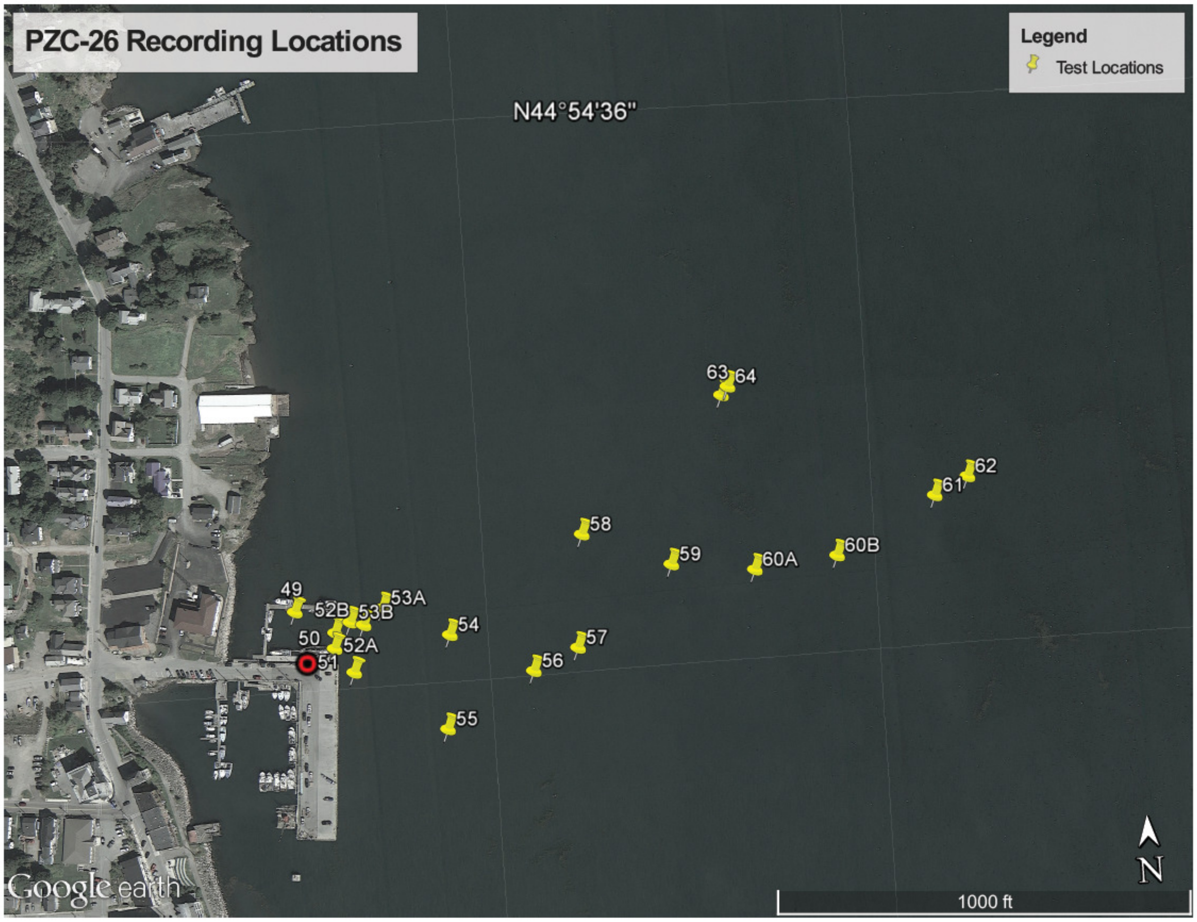


Figure 48 - Map of PZC-26 Sound Measurement Locations

The results of these measurements were plotted based on range from the pile being driven and a regression analysis was performed on the sound pressure data. The results of this regression analysis were used to predict the Level A and Level B isopleth locations.

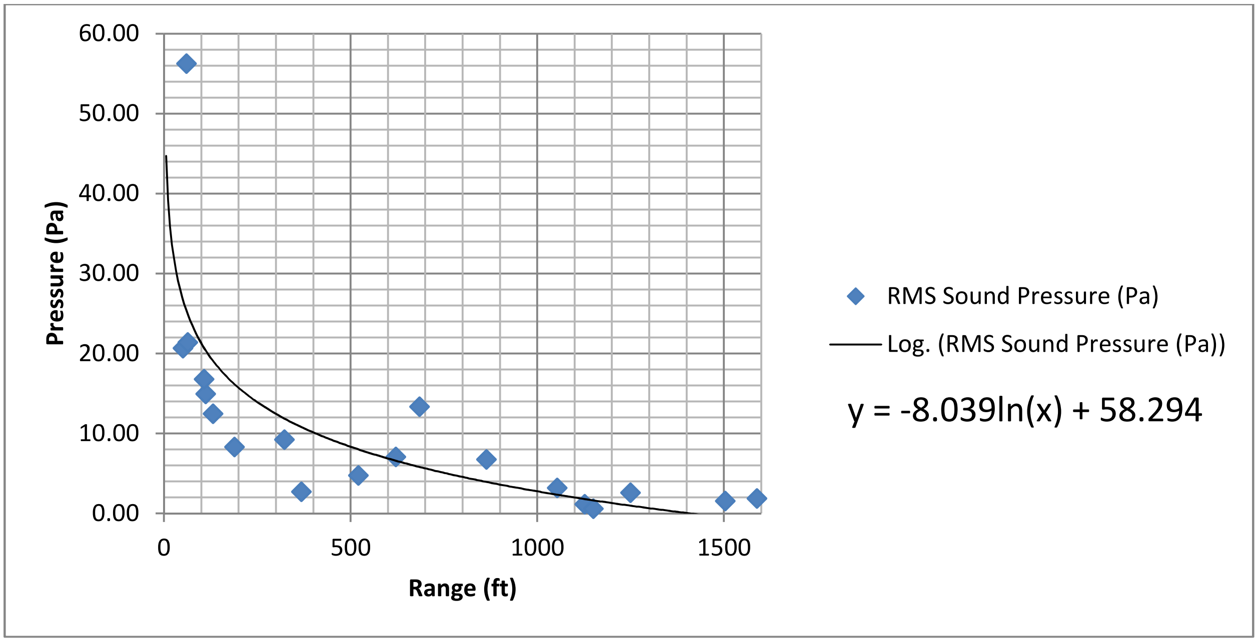


Figure 49 - Regression on PZC-26 RMS Sound Data

Based on the regression results, the Level A exclusion zone for all marine mammals where RMS sound pressure likely exceeds 180dB (1,000 Pa) RMS is 10ft (3m). Detailed information at this close range was not available due to the safety issues associated with approaching directly beneath the hammer while driving. The Level B zone of influence (ZOI) where RMS sound pressure likely exceeds 120dB (1.0 Pa) is 1,245ft (380m).

The regression curves for the PZC-18 sheets differ somewhat in mathematical definition and shape from the PZC-26 sheets despite being driven by the same hammer and being similar pile types. The PZC-18 data dropped off faster initially than the PZC-26 data and was slightly quieter overall. Despite all recorded piles being in the same general location, a material barge was positioned between the PZC-18 piles and the measurement locations that was not present while driving the PZC-26 piles and may have provided a slight acoustic shadowing effect that caused the change in attenuation behavior. Additionally, the measurement locations for the PZC-18 sheets were generally grouped north of the site while the locations for the PZC-26 sheets were generally grouped east. Slight differences in the bottom geometry and sound propagation near shore may also account for the difference in behavior.

In November and December of 2015, surveys were conducted during the driving of pipe piles for the main pier structure with vibratory and diesel impact hammers. The piles were initially driven with an H&M 3700 vibratory hammer and driven to capacity with a Pileco D12 diesel impact hammer. Two Spin-Fin piles were also observed.

Figure 50 - Driving 20" Pipe Piles with a Pileco D12 Diesel Impact Hammer

Field measurements were performed while CPM was driving pipe piles on the first and second bents (Bent 1 and Bent 2) of a new section of elevated pier that will expand the existing pier and breakwater further east. This section of pier consists of precast concrete deck panels and precast pile caps supported on 29' centers by bents of four PP20x0.625 ASTM A252 Grade 3 Modified pipe piles. These vertical piles are driven to ultimate capacities ranging from 278 kips (Row E) to 612 kips (Row G). Berthing load resistance and east/west stability are provided by pairs of PP20x0.625 Spin-Fin piles at each bent on a 1:4 batter. These piles are driven to a minimum ultimate compression capacity of 439 kips. The depth of water in the area around Bent 1 and Bent 2 is approximately 50' with a tidal change of roughly 20'. Top of bedrock, where all piles reached capacity, is located at an approximate depth of 100' below MSL. All pipe piles observed were driven open-ended and PDA dynamic load tests were conducted on all piles monitored in this report.

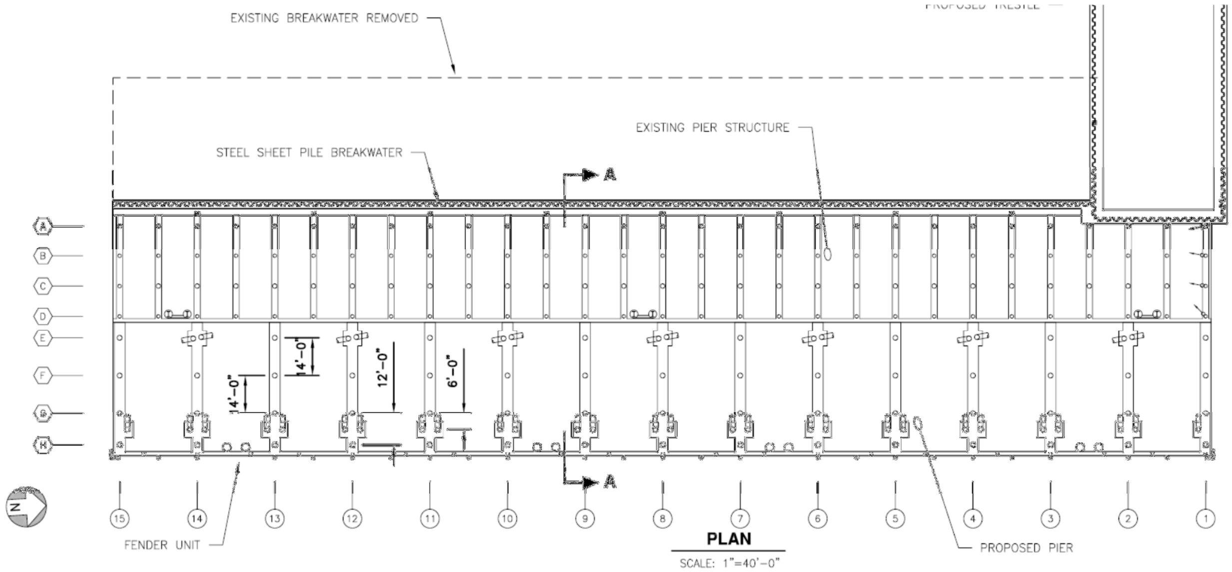


Figure 51 - Propose Pier Pile Plan

Figure 52 - Battered Piles in Template at Low Tide

Figure 53 - Driving Battered Piles at High Tide

For impact hammer strikes, the RMS sound pressure is computed for the portion of the strike between the time when 5% of the total final energy has been created and the time when 95% of the energy has been created. This is the central 90% of the total energy of the strike. The following three plots show the relationship between the pressure trace from a typical pile strike, the 90% energy window relative to the original pressure trace, and the 90% energy window relative to the strike accumulated energy.

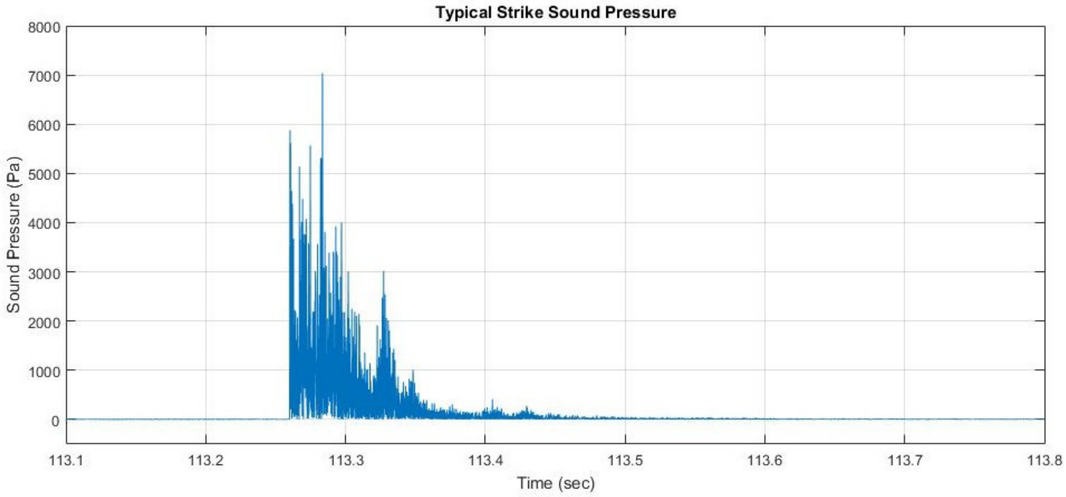


Figure 54 - Typical Strike Sound Pressure Trace

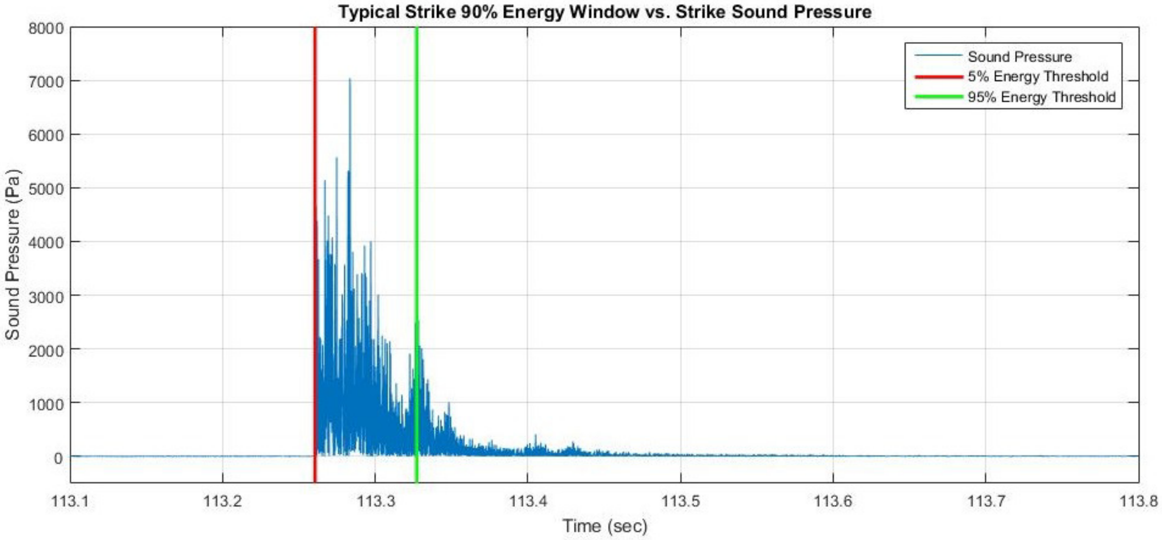


Figure 55 - Typical Strike Sound Pressure with 5% and 95% Energy Thresholds

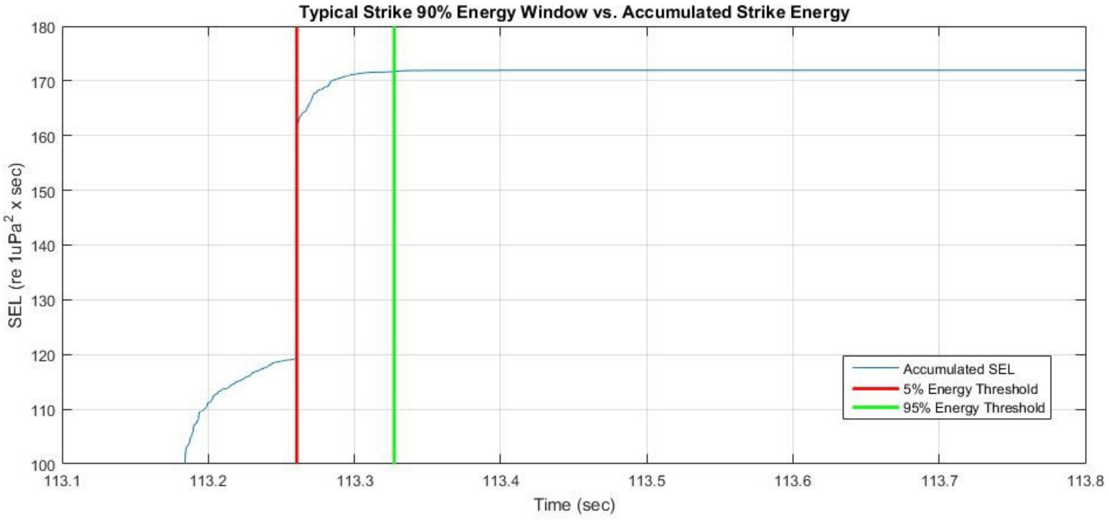


Figure 56 - Accumulated Strike Energy with 5% and 95% Energy Thresholds

The following plot shows the RMS SPL trace for the first pile observed by UNH and the 90% energy window RMS SPL computed for each strike. The mean 90% energy window RMS SPL is shown on each plot. The first pile driving recording on Bent 1, Pile E was done with the hydrophone located at 33' (10m) from the pile and shows the entire driving cycle.

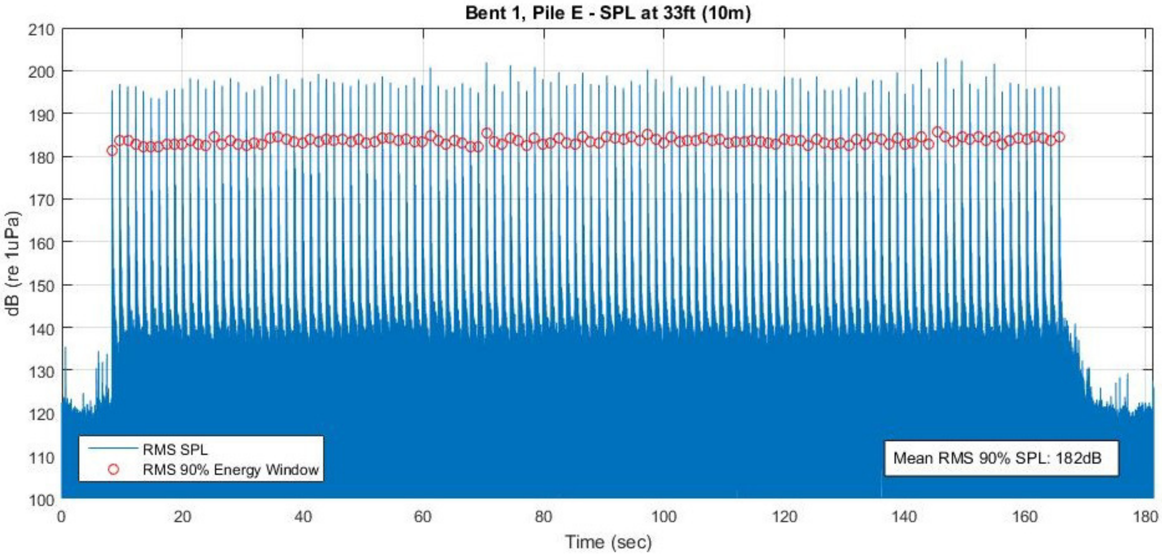


Figure 57 - Bent 1, Pile E SPL Plot Showing 90% RMS SPL

Each subsequent test was performed with the hydrophone located in a quasi-static position. A map of the measurement locations is shown below.

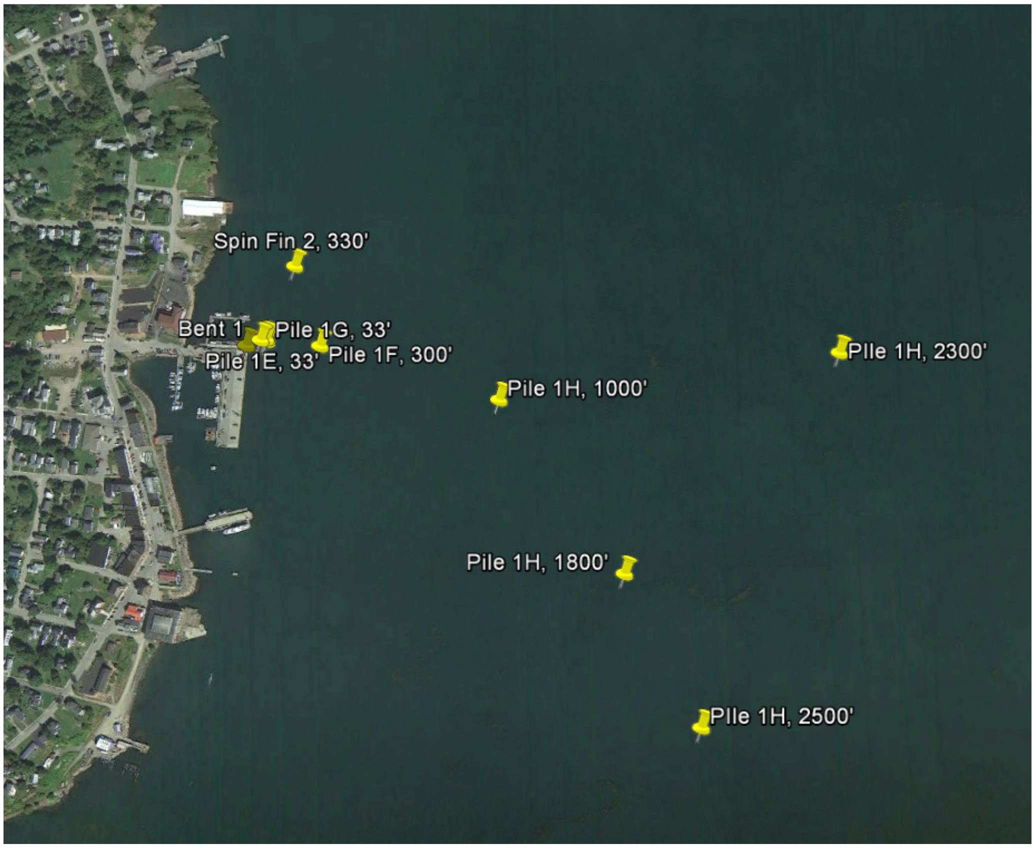


Figure 58 - Map of Impact Driving Measurement Locations

The following table shows the results from these tests.

Test No.	Lat (deg)	Lon (deg)	Average RMS	Pressure RMS	Desc.	Range (m)	Range (ft)
1	44.90651176	-66.98277301	182	1258.9	I1	10	32.8
2	44.90624983	-66.98158893	172	398.1	I2	103	337.84
3	44.90648705	-66.98274184	182	1258.9	I3	8	26.24
4	44.90488382	-66.97976343	166	199.5	I4	302	990.56
5	44.90368999	-66.97706345	157	70.8	I5	553	1813.84
6	44.90583337	-66.97380767	153	44.7	I6	716	2348.48
7	44.90194051	-66.97591951	149	28.2	I7	745	2443.6
8	44.90647763	-66.98307659	186	1995.3	SF1	10	32.8
9	44.90717668	-66.98224127	172	398.1	SF2	88	288.64

Table 10 - Summary of Impact Pile Driving Data

The results of the above mean 90% RMS strike intensities were plotted by their average distance from the pile and the following regression gives an equation that closely approximates the attenuation and dispersion of the impact pile driving sound pressure in the area around the Eastport pier. Note that the regression is performed on sound pressure, not the sound pressure level in decibels. Because the transformation from pressure to decibels is non-linear, any regression or arithmetic must be performed on the original pressure data.

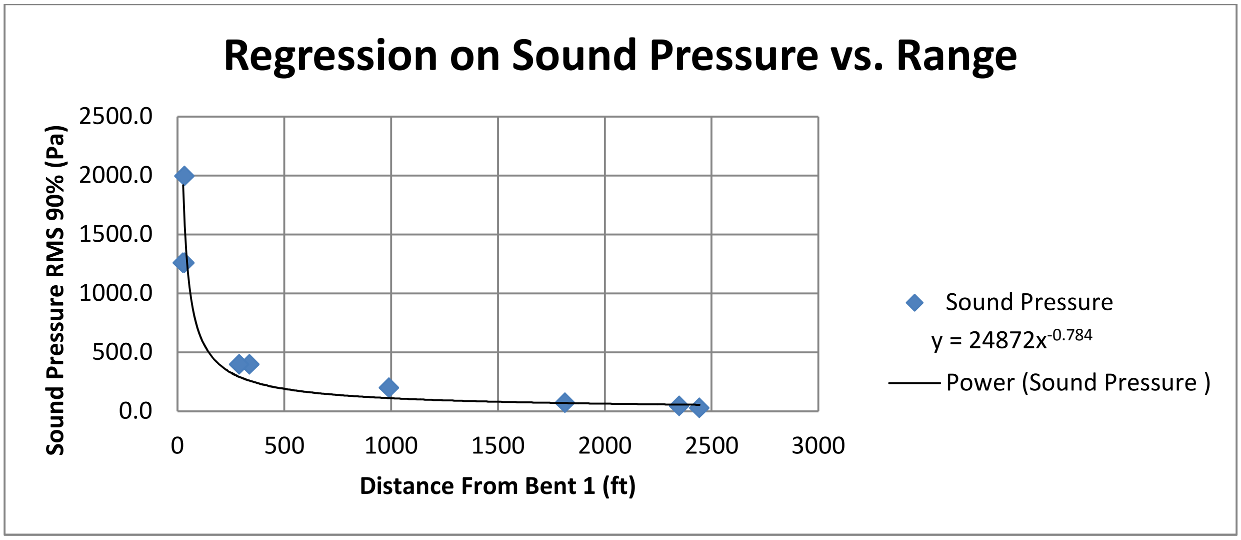


Table 11 - Regression on Impact Driving 90% RMS SPL

Based on the regression equation, it is possible to calculate the location of the 190dB, 180dB, and 160dB isopleths to establish the Level A and Level B harassment zones per the measured data. UNH recommended the following locations for the revised zones. The Level A Exclusion Zone for Pinnipeds where RMS 90% SPL exceeds 190dB is 16 feet (5m). The Level A Exclusion Zone for Cetaceans where RMS 90% SPL exceeds 180dB is 66 feet (20m). Finally, the Level B Zone of Influence (ZOI) for all marine mammals where RMS 90% SPL drops below 160dB is 1,150 feet (350m).

CHAPTER IV

Summary of Results

4.1 – Summary of Sound Data

The following shows a summary of all sound data acquired to date and the parameters it was acquired under.

Due to the revised hydrophone sensitivity value, the drilling data from Memorial Bridge is presented below revised with a similar method given in Chapter 3, section 2 for the Sarah Long Bridge emergency repairs. The first two tests show peak ambient sound around in the low 150dB range, which is typical for estuarine conditions. Peak sound from the drilled shaft installation reached the low 160dB range and the down-hole hammer reached a peak SPL near 170dB. This data was acquired without field calibration of the data acquisition system.

No.	Time	Location	Distance From Source (feet)	Depth (feet)	Micropile	Drilled Shaft	Boat Engine	Peak Submerged SPL (dbA)
1	10:40am	400’ W to 400’ E	450	20	No	No	No	153
2	12:41pm	Near Trestle	100	5	No	No	No	152
3	12:34pm	Near Trestle	75	5	No	Yes	Yes	161
4	10:53am	20’ Off Pier 4	150	5	No	Yes	No	161
5	10:47am	Fixed at Marina	200	5	No	Yes	No	157
6	1:12pm	Fixed At Marina	90	10	Yes	No	No	168
7	10:34am	Between DS and MP	100	5	Yes	Yes	No	161
8	12:48pm	At Pier 4	30	10	Yes	Yes	No	161
9	1:06pm	100’ E to 200’ W	450	10	Yes	Yes	No	163
Micropile installation with a pneumatic down-hole-hammer at a depth of ~45 feet								
Drilled Shaft installation with a 30” diameter toothed auger bit at a depth of ~5 feet								

Table 12 - Summary of Revised Memorial Bridge SPL Data

The following two plots show the original erroneous recording of the highest micropile recording compared with the same plot recalculated correctly.

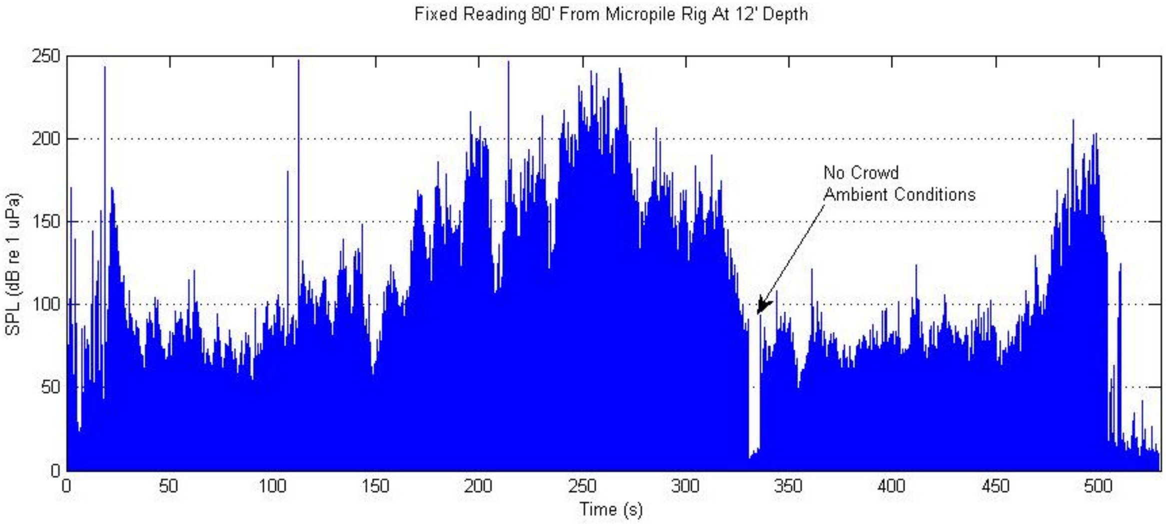


Figure 59 - Test 6 Original SPL Plot

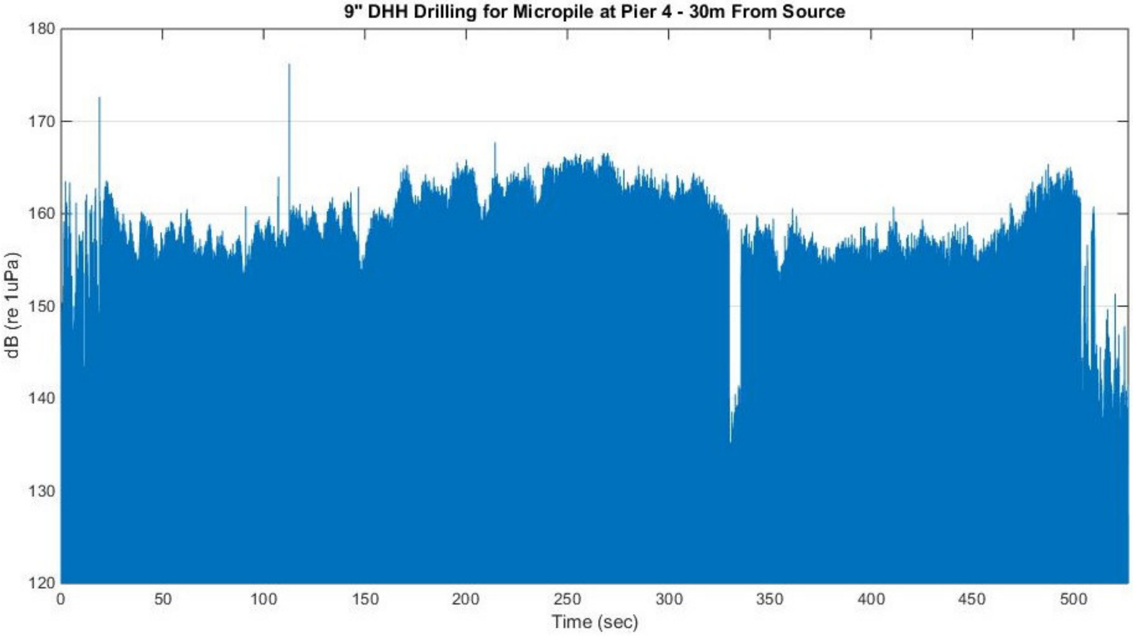


Figure 60 - Test 6 Revised SPL Plot

A summary of the Sarah Long Emergency Repair data is given below. This data was acquired during driving of 30” diameter x ½” wall pipe piles with an APE Model 200

Vibratory hammer and final driving with an APE Model 62-42 diesel impact pile hammer. This data was acquired without a field calibration test on the data acquisition system.

Date	Location	Hammer	Begin Time	End Time	Ch. 1 Distance	Tide	Speed	Max SPL @ 10m
4/20/2013	Pile 1	Vibro	N/A	N/A	N/A	N/A	N/A	N/A
		Diesel	3:53pm	5:08pm	30'	Out	2.6fps	165
	Pile 2	Vibro	2:23pm	2:24pm	30'	Out	2fps	150
		Diesel	5:37pm	5:43pm	30'	Out	2.5fps	170
4/21/2013	Pile 3	Vibro	12:50pm	1:10pm	30'	Out	1.5fps	173
		Diesel	1:56pm	2:14pm	30'	Out	2.5fps	170
	Pile 4	Vibro	1:16pm	1:26pm	30'	Out	2fps	170
		Diesel	2:26pm	2:34pm	30'	Out	3fps	170
4/22/2013	Pile 5	Vibro	N/A	N/A	N/A	N/A	N/A	N/A
		Diesel	2:04pm	2:14pm	30'	Out	2.5fps	169
	Pile 6	Vibro	1:18pm	1:24pm	30'	Out	2fps	180
		Diesel	2:30pm	2:42pm	30'	Out	3fps	170
4/23/2013	Pile 7	Vibro	N/A	N/A	N/A	N/A	N/A	N/A
		Diesel	2:55pm	3:05pm	30'	Out	3fps	182
	Pile 8	Vibro	1:45pm	2:06pm	30'	Out	2fps	170
		Diesel	2:34pm	2:45pm	30'	Out	2.5fps	180

Figure 61 - Summary of SML Emergency Repairs SPL Data

Some runs are omitted due to equipment setup/modification issues.

A summary of the Sarah Long Cutt's Cove Temporary Crane Trestle data is given below. This data was acquired during driving of 30" diameter x ½" wall pipe piles with a Bermingham B62 diesel impact pile hammer operated at a maximum stroke of 7 feet. This data is the result of field-calibrated tests.

Date	Bent	Pile	Size	No. Blows	SPL Peak (dB)	cSEL - 10m (dB)	cSEL - 20m (dB)	cSEL - 40m (dB)
Jan 29 2015	No. 7	North	30"ø x 5/8"	74	< 206	178.9	173.9	163.9
Feb 2 2015	No. 6	Center	30"ø x 5/8"	120	< 206	181.0	176.0	166.0
Feb 2 2015	No. 6	South	30"ø x 5/8"	139	< 206	181.6	176.6	166.6
Feb 2, 2015	No. 6	North	30"ø x 5/8"	145	<206	181.8	176.8	166.8
Feb 19 2015	No. 5	North	30"ø x 5/8"	61	< 206	178.1	173.1	163.1
Feb 19 2015	No. 5	Center	30"ø x 5/8"	87	< 206	179.6	174.6	164.6

Feb 19 2015	No. 5	South	30"ø x 5/8"	113	< 206	180.7	175.7	165.7
Feb 27 2015	No. 4	North	30"ø x 5/8"	44	< 206	176.6	171.6	161.6
Feb 27 2015	No. 4	Center	30"ø x 5/8"	80	< 206	179.2	174.2	164.2
Feb 27 2015	No. 4	South	30"ø x 5/8"	78	< 206	179.1	174.1	164.1
Mar 5 2015	No. 3	North	30"ø x 5/8"	61	< 206	178.1	173.1	163.1
Mar 5 2015	No. 3	Center	30"ø x 5/8"	47	< 206	176.9	171.9	161.9
Mar 5 2015	No. 3	South	30"ø x 5/8"	45	< 206	176.7	171.7	161.7
Mar 11 2015	No. 2	North	30"ø x 5/8"	41	< 206	176.3	171.3	161.3
Mar 11 2015	No. 2	Center	30"ø x 5/8"	81	< 206	179.3	174.3	164.3
Mar 11 2015	No. 2	South	30"ø x 5/8"	115	< 206	180.8	175.8	165.8
Mar 19 2015	No. 1	North	30"ø x 5/8"	127	< 206	181.2	176.2	166.2
Mar 19 2015	No. 1	Center	30"ø x 5/8"	359	< 206	185.8	180.8	170.8
Mar 19 2015	No. 1	South	30"ø x 5/8"	358	< 206	185.7	180.7	170.7

Figure 62 - Summary of Cutt's Cove Trestle SPL Data

A summary of the impact driving of 20” diameter pipe piles in Eastport, Maine is given below. This data was acquired while driving with a Pileco D12 diesel impact pile hammer operated up to its maximum stroke of approximately 12 feet. This data is the result of field-calibrated tests.

Test No.	Lat (deg)	Lon (deg)	Average RMS	Pressure RMS	Desc.	Range (m)	Range (ft)
1	44.90651176	-66.98277301	182	1258.9	I1	10	32.8
2	44.90624983	-66.98158893	172	398.1	I2	103	337.84
3	44.90648705	-66.98274184	182	1258.9	I3	8	26.24
4	44.90488382	-66.97976343	166	199.5	I4	302	990.56
5	44.90368999	-66.97706345	157	70.8	I5	553	1813.84
6	44.90583337	-66.97380767	153	44.7	I6	716	2348.48
7	44.90194051	-66.97591951	149	28.2	I7	745	2443.6
8	44.90647763	-66.98307659	186	1995.3	SF1	10	32.8
9	44.90717668	-66.98224127	172	398.1	SF2	88	288.64

Figure 63 - Summary of Eastport Impact Pile Driving SPL Data

CHAPTER V

Conclusion

5.1 – Hydrophone Data Acquisition System

The primary goal of this research project was the development of a hydrophone data acquisition and analysis system for use in pile driving applications. Following the described projects, a hydrophone system was assembled using the Reson TC4013 hydrophones that provided stable, reliable data that could be field calibrated.

The final hydrophone system is capable of acquiring up to three channels of hydrophone data at various distances from the pile driving operation. The data is amplified by three Reson VP1000 pre-amplifiers to provide a high signal-to-noise ratio before being digitized by a high-impedance National Instruments 9205 DAQ Module contained in an NI-9181 Ethernet chassis. All of this equipment is contained in a waterproof Pelican brand case with a battery capable of running the system for at least 12 hours forming a self-contained instrumentation package.

The data is outputted from the DAQ package to a 300’ ruggedized CAT5 Ethernet cable that can be ran from the DAQ equipment near the pile driving operation to a location suitable for a laptop computer, such as a vehicle or field office. This laptop computer runs a custom LabVIEW VI that records and displays the hydrophone data using a buffered FIFO loop as developed on the Eastport project. This provides robust performance and the ability to monitor the underwater sound level and system condition with the equipment active without recording data. It also allows the GPS receiver to be used, if desired, when operating a single hydrophone on a boat at many locations.

The data files are written as .lvm LabVIEW measurement files with a single header containing the measurement information followed by the columns of data in a tab delineated format. The files can become very large when multiple channels are recorded for long periods of time, and good data organization practices must be followed. An example of a measurement file and header is given in Appendix A, “Example of Data Record”.

The GRAS 42AC pistonphone should be used to calibrate the system during each day of field measurements and the calibration data should be recorded.

5.1 – Hydrophone Data Analysis Methodology

The second goal of this research project was to develop methods of hydrophone data analysis to meet the requirements of projects with sound limits. NOAA sound limits fall into two categories: those with the purpose of protecting fish from barotrauma (206dB peak, 187dB cSEL) and those with the purpose of protecting marine mammals from harm or harassment, which vary by project and type of mammal likely to be affected. Two significant MATLAB scripts were written to import, process, and plot the data files produced by the LabVIEW DAQ application to produce reports. Many smaller scripts were written to perform various miscellaneous tasks and are not presented in this report.

The first script presented is useable on projects with fish protection limits. The script imports the data using the MATLAB “dlmread” file load command that reads the file line by line without loading the entire file into memory, as the more standard “load” command would do. It was found that using the basic file load tools in MATLAB with the large text files produced by LabVIEW would tend to cause a memory crash, even on computers with up to 16GB of RAM. The script then repopulates the time and GPS columns (if used) to create a continuous sequence of entries if gaps exist from discontinuous recordings, as LabVIEW records time entries relative to the creation of the file. The script then saves this data as a new file. The data is then plotted for review by the operator and trimmed, if required. The new data file is plotted and the plot file is saved for editing later. cSEL is then computed and plotted and saved as a separate figure file for editing later. This script can run through many data files sequentially, if configured to do so. This script is given in Appendix B “MATLAB Data Processing Scripts”.

The second script computes the 90% energy window RMS intensity of a series of impact hammer strikes on projects with RMS limits for mammal protection. It imports data using the “dlmread” command and converts the SPL data back to pressure. From there, peaks from impact strikes are found based on a minimum expected threshold of 500Pa. The vector of peak locations is then indexed to accumulate the sound energy of each strike and determine the time when the 5% and 95% energy thresholds are crossed. The RMS sound pressure between these times is then computed and the result converted to SPL. The RMS 90% energy window values are then plotted over the original SPL trace and the plot figure is saved. This script can run through many data files sequentially, if configured to do so. This script is given in Appendix B “MATLAB Data Processing Scripts”.

The final equipment selection and software has been proven to provide robust performance on projects with multiple variations of noise limits currently placed on projects by NOAA or measurement techniques required. Multiple fixed measurement locations may be acquired at once or a single hydrophone can be used on a boat and location recorded into the data files with a GPS receiver. Data may be analyzed to verify compliance with fish protection limits or to verify compliance with RMS limits for the protection of marine mammals. All project reports to date have been accepted by NHDOT and MaineDOT and this research has allowed UNH to take a leading role in this emerging field of construction engineering and environmental compliance. The results of the sound surveys completed to date have helped provide guidance to regional infrastructure owners and contractors to maintain noise limit compliance while not unduly impacting the project schedules. In Eastport, the results of UNH’s research allowed reduction of mammal exclusion zones and reduced project delay while maintaining the necessary level of protection required in the project specifications.

This research has been successful in developing a regional capability to monitor underwater sound on foundation projects with flexibility and accuracy and to analyze the data efficiently. All completed and accepted project reports to date are included in Appendix C “Completed Project Reports”.

CHAPTER VI

Future Research

4.1 – NHDOT Guidance on Foundation Selection

NHDOT has approached UNH about providing guidance on the planning and design of future projects where hydroacoustic limits may be applied. In March of 2015, UNH submitted a proposal to the NHDOT RAC program for funding to produce a guidance document that would provide infrastructure planners, designers, and contractors with data-driven information on how to select foundations for permanent and temporary structures to avoid or minimize the cost and risk of delay associated with underwater noise limits. The 2009/2012 CalTRANS/NOAA guidance document on sound monitoring includes only a cursory treatment of sound mitigation measures for conventional pile driving work.

The proposed research includes a survey of existing pile driving sound data with the intention to track down more detailed information on the pile types, subsurface conditions, hammer specifications, and driving criteria associated with the sound levels reported to NOAA. The current compendium of pile driving data made available by NOAA only relates pile overall diameter, or size, and the maximum sound levels recorded on the project. UNH's observations to date have indicated that driving criteria and hammer characteristics may be related to sound generation beyond a simple relationship between pile size and/or hammer size.

In addition to developing a more detailed understanding of pile driving noise generation, the manual will include guidance on how to avoid exceeding both the peak noise limits and the duration limits by advancing the pile as quickly as possible to the load-bearing layer before proving its capacity with impact driving. These methods may include vibratory driving, pre-drilling, jetting, or other processes.

This document will also include a data-driven treatment of sound mitigation methods based on existing projects with the intention to provide contractors and engineers with general parameters for the design of bubble curtains, shielding, or other noise mitigation methods.

Finally, this document will include a treatment of the costs associated with noise monitoring, noise mitigation, and the selection of alternative foundation methods. While noise monitoring and mitigation add cost, abandoning driven pile systems for exclusively drilled or alternative foundations may not prove cost-effective on all types of projects. There does not currently exist any data-driven guidance for planners or designers on this issue. Data will be pulled from public infrastructure projects across the United States with costs adjusted for regional differences in labor or material prices.

The funding for this research was awarded in April of 2016.

4.1 – MaineDOT Development of Specifications and Training

MaineDOT approached UNH about improving the state’s noise monitoring specifications and closing the gaps in parameters and procedures that was causing ambiguity, inconsistency, and contract claims on some projects.

Additionally, UNH has proposed the development of training materials and curriculum to familiarize DOT personnel and contractors with underwater acoustics, noise monitoring equipment and procedures, and the calculations to produce accurate results from raw sound pressure data.

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Appendix A – Example of Data Record

Typical .LVM data header for a recording from the Cutt’s Cove Trestle.

```
Date   2015/03/05

Time   10:38:47.786027350058116888 1

***End_of_Header***


Channels     3

Samples      5000   5000   5000

Date   2015/03/05   2015/03/05   2015/03/05

Time   10:38:47.7860273500581168881 10:38:47.7860356749177807322

10:38:47.7860439995446139327

Y_Unit_Label         Volts   Volts   Volts

X_DimensionTime   Time   Time

X0      0.0000000000000000E+0  0.0000000000000000E+0

0.0000000000000000E+0

Delta_X        2.500000E-5 2.500000E-5 2.500000E-5

***End_of_Header***

X_Value        Voltage (Filtered)     Voltage_0 (Filtered) Voltage_1 (Filtered)

Comment

0.000000      -1.105589      1348.640243 108.573399

2.500000E-5 -2838.338998          -1168.711726          227.988688

5.000000E-5 -5656.519090          -6848.339076          143.615650

7.500000E-5 -2387.225857          -4897.244494          91.310374
```

1.000000E-4	-241.013885	-2208.751346	100.764346
0.000125	-1019.212783	-1903.731121	58.378222
0.000150	-415.603676	-492.707813	65.515565
0.000175	-768.001502	-1108.985681	51.765053
0.000200	-815.038176	-827.941816	37.428826
0.000225	-654.597295	-724.897111	36.056778
0.000250	-883.404189	-1002.837837	19.275695
0.000275	-718.018944	-701.264422	16.297741
0.000300	-815.311074	-929.693550	4.114549
0.000325	-784.338285	-797.185028	-5.437628
0.000350	-777.955426	-833.008327	-13.139563
0.000375	-810.744768	-856.234573	-23.054046
0.000400	-780.597188	-802.534553	-30.922425
0.000425	-810.327256	-850.763208	-40.951478
0.000450	-794.101589	-813.502788	-49.556500
0.000475	-807.112136	-834.630681	-57.347968
0.000500	-816.628249	-837.195706	-66.152729
0.000525	-813.782184	-832.629998	-75.025857

Appendix B – MATLAB Data Processing Scripts

For processing and plotting data on projects with Fish Protection Limits

```
clearvars

disp('Processing...');

%This version currently has to be manually run per bent (only three loops)
%Input assumed to be time and SPL data


%Import data line by line....file size not an issue.

for i = 1:3

    %Create suffix vector...note all strings must be same length.
    %Pad short names with spaces
    suffix = ['_north '; '_center'; '_south '];
    cellsuffix = cellstr(suffix);

    %k is offset, if needed.

   %k = i + 5;

    %index = num2str(k);

    %Grab indexed suffix
    suffixstr = char(cellsuffix(i));
    filename = strcat('P16', suffixstr, '.lvm');

    %import file, tab delineated, start at line 24, column 0
    data = dlmread(filename, '\t', 24, 0);

    status = strcat('Loaded file: ', i);
    disp(status);

    %display long format numbers (for GPS readings)
    format long

%GPS readings acquired at 1kHz...repopulate blank rows to match
%20kHz sound data
GPSraw = data(:, 3:4);

rows = size(GPSraw);
endrow = rows(1,1);

disp('Repopulating zero GPS entries with previous reading...');


for i = 1:endrow
```

```
    if GPSraw(i, 1) ~= 0;
        lat = GPSraw(i,1);
        lon = GPSraw(i,2);
    else
        GPSraw(i,1) = lat;
        GPSraw(i,2) = lon;
    end
end

%Replace incomplete lat/long vectors with filled vectors
data(:, 3:4) = GPSraw;

disp('Done.  Repopulating time vector...');

%Rebuild time vector at absolute zero for convenience.
% delta t = 0.0000390625 from LVM header

t = 0;

for i = 1:endrow
    t = t + .0000390625;
    newtime(i, 1) = t;
end

data(:, 1) = newtime;
disp('Done.  Saving');

%Save mat file with full GPS and zero-start time
%This data is untrimmed

savedata = data;

handle = '_TimeAbs';

name = strcat('C6', suffixstr);

matfilename = strcat(name, handle);

save(matfilename, 'savedata');

spldata = data;

%Plot SPL data for review
disp('Successful.  Plotting SPL...');

time = spldata(:, 1);
t = data(endrow, 1)
SPLvect = spldata(:, 2);

figure(1);
plot(time, SPLvect);
axis([0 t 100 200]);
xlabel('Time (sec)');
ylabel('dB (re 1uPa)');
```

```
plottitle = name;
title(plottitle);
grid on;
figfile = strcat(name, '_SPL_plot');
savefig(figfile);

%Prompt user to trim the end of the file to time = ?
trimstart = input('Clip All After: ');

%trimstart = str2num(trimstart);

index = 1;

%find index of desired trim time in seconds
while spldata(index, 1) < trimstart
    index = index +1;
end
index = index-1;

%Trim data
indexdata = spldata(1:index, :);

disp('Successful.  Plotting SPL...');

%re-define "endrow" to be size of trimmed file
newsize = size(indexdata);
endrow = newsize(1,1);

%Plot trimmed SPL data and save figure file and trimmed SPL data
time = indexdata(:, 1);
t = indexdata(endrow, 1);
SPLvect = indexdata(:, 2);

figure(1);
plot(time, SPLvect);
axis([0 t 100 200]);
xlabel('Time (sec)');
ylabel('dB (re 1uPa)');
plottitle = name;
title(plottitle);
grid on;
figfile = strcat(name, '_SPL_plot');
savefig(figfile);

disp('Saving fig file...');

matfilename = strcat(figfile);

save(matfilename, 'indexdata');

%Compute cSEL

disp('Computing cSEL');
```

```
%load SPL data

seldata = indexdata;

%prompt for starting time and ending time for cSEL calculation

startsec = input('Start seconds?');
endsec = input('End seconds?');

startrow = startsec*(1/.0000390625);
endrow = endsec*(1/.0000390625);

%clip SPL data of interest

cseltime = seldata(startrow:endrow, 1);
cselSPL = seldata(startrow:endrow, 2);

seldata = [cseltime cselSPL];

%Convert SPL vector to pressure data vector
soundpressuredata = 1E-6*power(10,(cselSPL/20));

%Square pressure data vector
spsquared = power(soundpressuredata,2);

time = cseltime;

%find index+1 as line 0 will already be written as 0 when SELacc is
%initiallized
index = endrow-startrow+1;
SELacc = 0;

%compute vector of accumulating cSEL and accumulating cSEL in dB
for i = 1:index
    SELacc = SELacc+spsquared(i,1)*.0000390625;
    SELvector(i,1) = SELacc;
    SELvectordB(i,1) = 10*log10(SELacc/power(1E-6,2));
end

%Display final cSEL in dB
t = time(end);
SELdB = SELvectordB(end, 1)

%create, plot, and save cSEL data in dB as mat file and figure file
SELplot = [time, SELvectordB];

figure(2);
plot(time, SELvectordB);
axis([0 t 100 195]);
xlabel('Time (sec)');
ylabel('dB (re 1uPa^2 x sec)');
plottitle = name;
title(plottitle);
grid on;
```

```
figfile = strcat(name, '_SEL_plot');
savefig(figfile);

disp('Saving file...');

matfilename = strcat(figfile);

save(matfilename, 'seldata');

disp('Done.');

clearvars

end


disp('Done.');
```

For processing and plotting data on projects with limits on the RMS 90% Energy Window intensity for impact hammer strikes.

```
%This script loads a file of SPL and GPS data and computes the 90% Energy
%Window RMS SPL assuming no return to ambient conditions between strikes

%Prompt for file name

clearvars;
hold off;

filename = input('Load Filename: ');

data = load(filename);

data = data.savedata;

disp('Loaded. Converting SPL to pressure.')

%convert spl to pressure

orgdb = data(:,2);

spl = data(:,2);
splb = spl/20;
pressure = 0.000001*power(10, splb);

pressuredata = data;

pressuredata(:,2) = pressure;
```

```
%determine peaks and locations

disp('Done. Finding peaks and locations with MinPeakHeight = 500Pa')

x = pressuredata(:,1);
pressure = pressuredata(:,2);

[peaks, locs] = findpeaks(pressure, x, 'MinPeakDistance', .5,
'MinPeakHeight', 500);

%plot(locs, peaks, 'or')

hold off
plot(pressuredata(:,1), pressure)

xlabel('Time (sec)');
ylabel('Sound Pressure (Pa)');
grid on;


%loop for index of locs

disp('Done.  Processing')

indexmax = size(locs);

for i = 1:80

    location = locs(i);

    startint = location - 0.1;
    endint = startint + (locs(i+1) - location);


    dataindexstart = (startint-pressuredata(1,1))*25600;
    dataindexend = (endint-pressuredata(1,1))*25600;

    selint = dataindexend - dataindexstart;

    dataindexstart = floor(dataindexstart);
    dataindexend = floor(dataindexend);

    dataint = pressuredata(dataindexstart:dataindexend, 1:2);

    SELintacc = 0;
    SELint = [0,0];

    for j = 1:selint

        pressuresquared = power((dataint(j, 2)), 2);

        SELint(j, 2) = pressuresquared*0.00003906325 + SELintacc;
```

```
        SELintacc = SELintacc + pressuresquared*0.00003906325;

        SELint(j, 1) = dataint(j,1);
    end

    fiveeng = 0.05*SELintacc;
    ninetyfiveeng = 0.95*SELintacc;

    [c indexint] = min(abs(SELint(:,2)-fiveeng));
    fiveint = indexint;

    [c indexint] = min(abs(SELint(:,2)-ninetyfiveeng));
    ninetyfiveint = indexint;

    rmsint = dataint(fiveint:ninetyfiveint, 2);

    RMS90(i,2) = rms(rmsint);
    RMS90(i,1) = locs(i);

    RMS90dB(i,2) = 20*log10((RMS90(i,2)/0.000001));
    RMS90dB(i,1) = locs(i);
end

data(:,2) = orgdb;

A = size(data);
endrms = A(1,1);
t = data(endrms,1);
time = data(:, 1);

plotname = input('RMS Plot Full Title: ');
averagerms90 = mean(RMS90(:,2));
averagerms90 = 20*log10(averagerms90/0.000001)
averagerms90 = floor(averagerms90);
avgrms90db = num2str(averagerms90);
maxlabel = strcat({'Mean RMS 90% SPL:'}, {' '}, avgrms90db, {'dB'});

figure(2);

plot(data(:,1), data(:,2));
hold on
plot(RMS90dB(:,1), RMS90dB(:,2), 'or');
axis([0 t 100 210]);
xlabel('Time (sec)');
ylabel('dB (re 1uPa)');
title(plotname);
legend('RMS SPL', 'RMS 90% Energy Window', 'Location', 'southwest');
dim = [0.55, 0.15, 0.33, 0.06];
annotation('textbox', dim, 'String', maxlabel, 'BackgroundColor', 'w');
grid on;
figfile = strcat(plotname, '_plot');
savefig(figfile);
```

```
figure(3);

SELintdB = 10*log10((SELint(:,2)*1000000000000));
SELint(:,2) = SELintdB;
plot(SELint(:,1), SELint(:,2));
hold on

x = [SELint(fiveint,1), SELint(fiveint,1)];
y = [0, 200];
line(x, y, 'color', 'r', 'Linewidth', 2);

xb = [SELint(ninetyfiveint,1), SELint(ninetyfiveint,1)];
y = [0, 200];
line(xb, y, 'color', 'r', 'Linewidth', 2);

figure(4);

y = [-1000, 10000];
line(x, y, 'color', 'r', 'Linewidth', 2);
line(xb, y, 'color', 'r', 'Linewidth', 2);
hold on

x1 = SELint(fiveint,1);
[d t1] = min(abs(pressuredata(:,1)-startint));

x2 = SELint(ninetyfiveint,1);
[e t2] = min(abs(pressuredata(:,1)-endint));

plot(pressuredata(t1:t2, 1), pressuredata(t1:t2, 2));
```

Appendix C – Project Data Results

Department Of Civil Engineering

Underwater SPL During Foundation Drilling For The Portsmouth-Kittery Memorial Bridge Replacement

8/6/2012

Dr. Charlie Goodspeed
James Browne, EIT

Contents

Summary

The University Of New Hampshire, in cooperation with the New Hampshire Department of Transportation and Archer-Western Contractors, performed monitoring of underwater sound pressure levels (SPL) during foundation drilling operations on the Portsmouth-Kittery Memorial Bridge.

Introduction

In recent years, sound pressure produced by underwater construction operations have become a major area of regulatory activity by federal and state agencies in an effort to protect endangered fish species. Construction projects in rivers and bays have come under increasingly strict schedule and SPL guidelines that influence infrastructure budgets and construction time.

To date, most in-situ measurements of underwater construction SPL have been conducted during impact pile driving operations. Several studies have been done on large diameter drilled shaft installation in open ocean conditions for wind turbine foundations, but little information currently exists on standard foundation drilling operations in relatively shallow, inter-coastal waters.

The replacement of the Portsmouth – Kittery Memorial Bridge which carries US Route 1 over the Piscataqua River between Portsmouth, NH and Kittery, ME presented an opportunity to observe underwater SPL during installation of two different types of drilled-in foundations. The proposed design called for 36” diameter drilled shafts to support the approach spans and 9” diameter micropiles to reinforce the four existing granite piers that support the main lift span towers and back spans.

Equipment

UNH performed the SPL measurements using a Reson TC-4013 calibrated hydrophone amplified by a Reson VP2000 voltage preamplifier and band-pass filter. For all measurements, signals over 10kHz were filtered out and an initial low-cut filter of 1Hz was chosen to admit low-frequency pulses from the drilling activity. In the field, however, the decision was made to increase the low-cut to 10Hz to filter out long-period variations observed from wave action. The amplifier provided 40dB of voltage gain which was compensated for in the final plots.

The amplified signals were acquired by a National Instruments 24-bit USB-9334 Multifunction DAQ at a sample rate of 20kHz to reduce the size of the data files while allowing spectral acquisition of signals up to 10kHz. It was anticipated that sounds above this frequency would only minimally contribute to the total power spectrum distribution.

The acquired signals were displayed and recorded by a National Instruments LabVIEW application built for this purpose. The results were post-processed and plotted in Matlab.

Field Measurements

UNH conducted the field measurements on August 6th, 2012 beginning at 10am. The weather was clear and calm with an incoming tide. Low tide was at 9:30am. No major ship traffic passed through the channel during the measurements.

Micropiles

Micropile installation was in progress on Pier 4 using a Soilmec PSM-1350 hydraulic rotary drill rig. During the measurement period, drilling crews were completing installation of a 9-5/8" diameter casing to a depth of 44' below the top of pier and transitioned to installing the 9" diameter micropile at the same depth. The drill tool was a pneumatic down-hole-hammer (DHH) with spoil removal by the returning hammer exhaust air.

Figure 1- PSM-1350 On Pier Four

Figure 2 - Soilmec R-930 On North Trestle

Drilled Shafts

Drilled shaft installation was ongoing with a Soilmec R-930 rotary drill rig using a toothed auger bit at a depth of approximately 5' below the top of rock. During all measurements where drilling was in progress, drilling speed was slow.

The shaft in progress was located on the western end of the second most northerly pier in a tidal zone. The drilling location was dry at the beginning of the measurement period and was under several feet of water by the final test. The shaft diameter was 36" and was being installed within a 6' diameter steel casing.

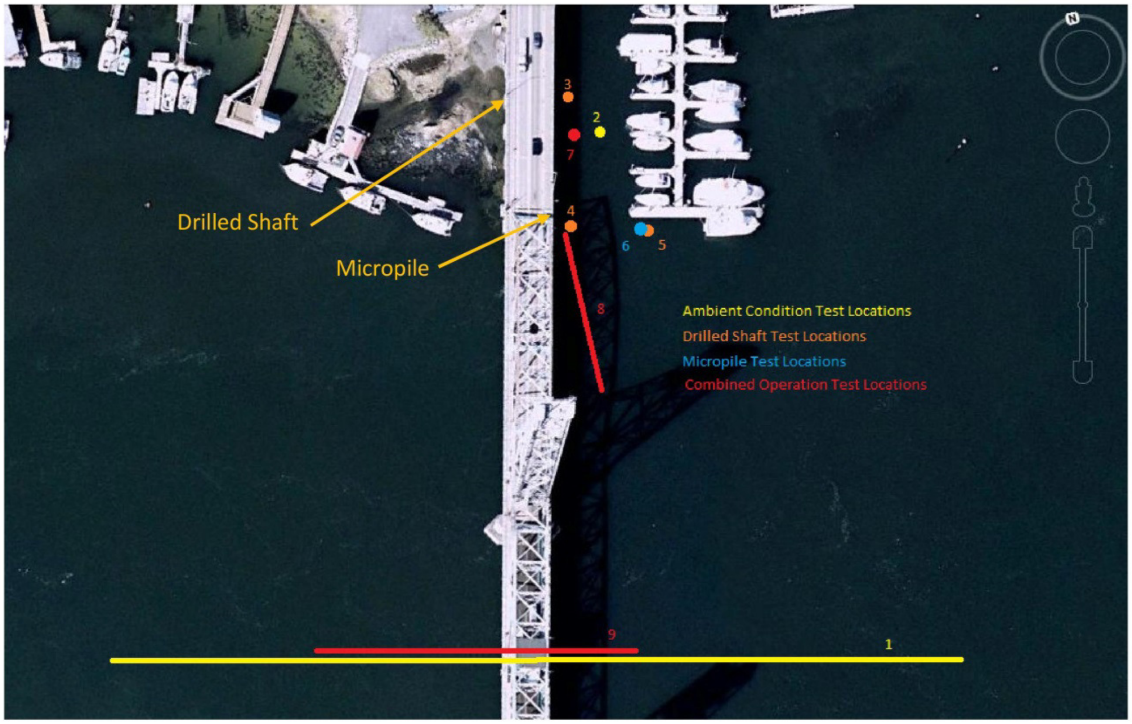
A summary of the measurement runs is given below:

Table 1 - Measurement Summary

No.	Time	Location	Distance From Source (feet)	Depth (feet)	Micro pile	Drilled Shaft	Boat Engine	Ambient Sound (dBa)	Max Submerged SPL (dbA)
1	10:40am	400' W to 400' E	450	20	No	No	No		20
2	12:41pm	Near Trestle	100	5	No	No	No		15
3	12:34pm	Near Trestle	75	5	No	Yes	Yes	84	95
4	10:53am	20' Off Pier 4	150	5	No	Yes	No		100
5	10:47am	Fixed at Marina	200	5	No	Yes	No		55
6	1:12pm	Fixed At Marina	90	10	Yes	No	No	75	240
7	10:34am	Between DS and MP	100	5	Yes	Yes	No		93
8	12:48pm	At Pier 4	30	10	Yes	Yes	No		105
9	1:06pm	100' E to 200' W	450	10	Yes	Yes	No		130

A map showing the measurement locations is given below.

Figure 3 - Map of Measurement Locations

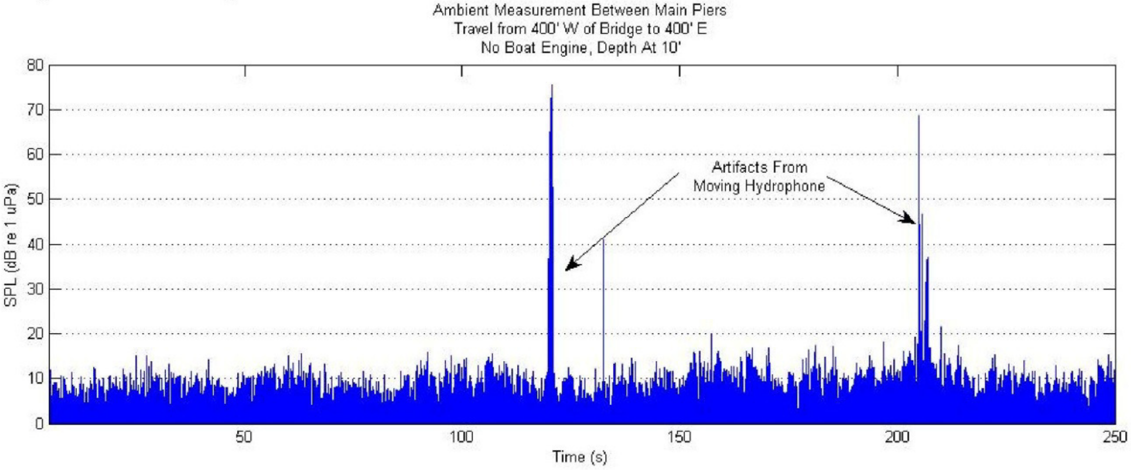


Summary of Results

Ambient Conditions

Several measurements were conducted on the ambient (no drilling work) conditions on site. Measurement run 5 showed the ambient conditions in the main channel with no local boat traffic:

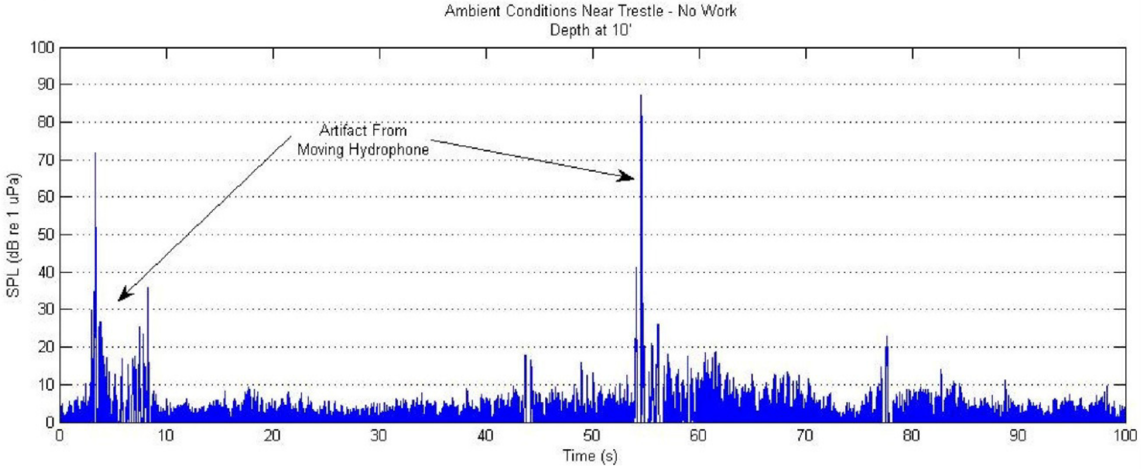
Figure 4 – Test 1 - Navigation Channel Ambient SPL



The average ambient SPL in the main navigation channel is ~10dBa.

Ambient measurements were also made near the north work trestle with no drilling activity indicating an average ambient SPL of ~ 5dBa:

Figure 5 – Test 2 - Drilling Area Ambient SPL

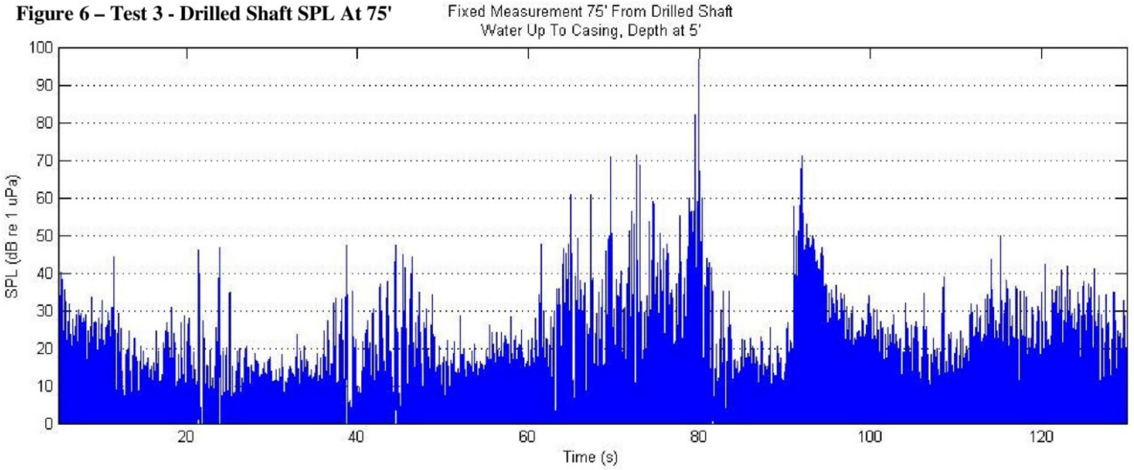


Drilled Shaft Boring

Several measurements were made of the underwater SPL while the SR-930 was boring the 36" drilled shaft. During all measurements, the drilling work was occurring in bedrock at slow rotational speeds. The drill tool was a toothed auger bit.

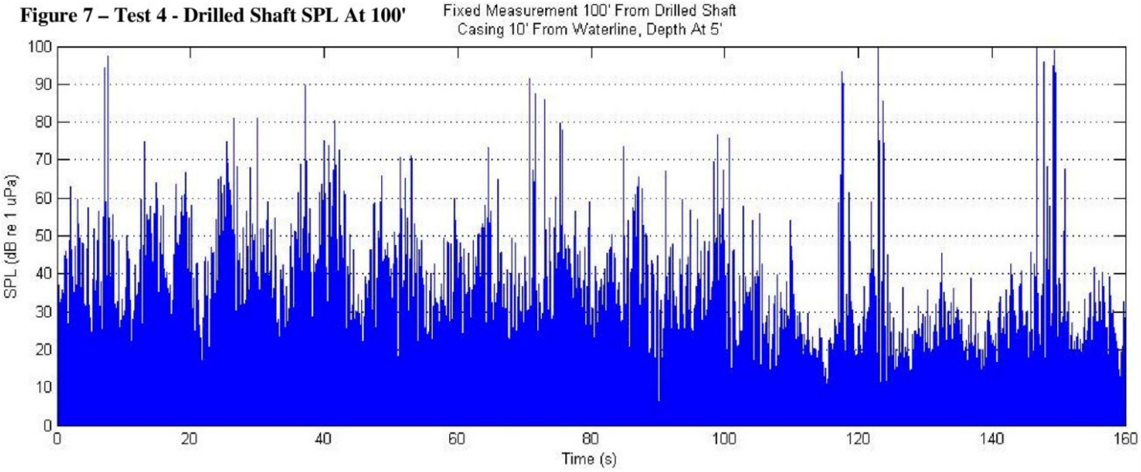
The following recording was conducted at a distance of approximately 75' from the shaft casing. The tide had just reached the casing, meaning the majority of the sonic energy in the water was being transmitted through the river bottom. The average SPL was ~25 dBa and the maximum peak was ~95 dBa.

Figure 6 – Test 3 - Drilled Shaft SPL At 75'



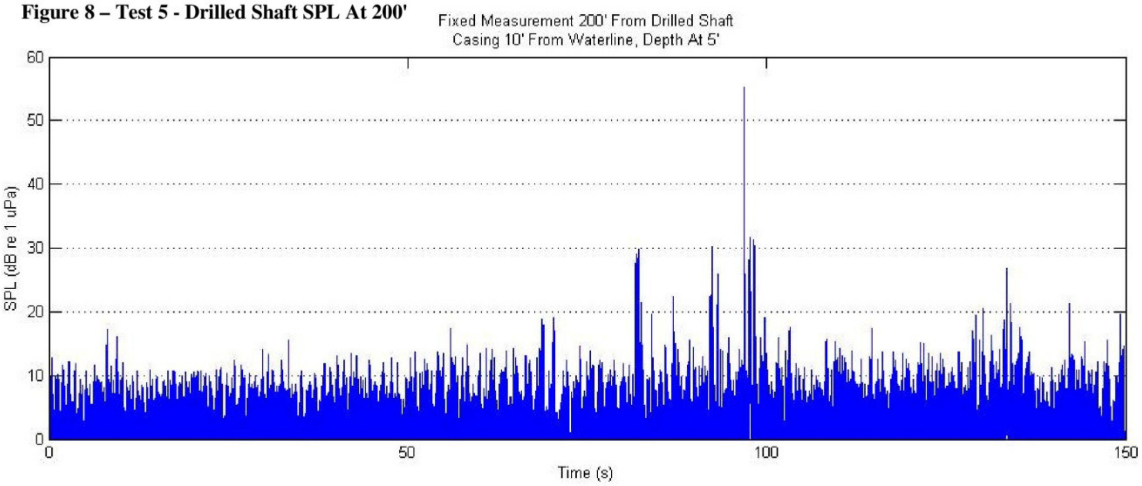
The following recording was made at a distance of 100' from the shaft location. The average SPL is ~40 dBa and the maximum observed SPL was ~100 dBa.

Figure 7 – Test 4 - Drilled Shaft SPL At 100'



The following recording was made at a distance of 200' from the drilled shaft location during drilling. At this distance, the observed SPL is not substantially higher than the observed ambient conditions.

Figure 8 – Test 5 - Drilled Shaft SPL At 200'

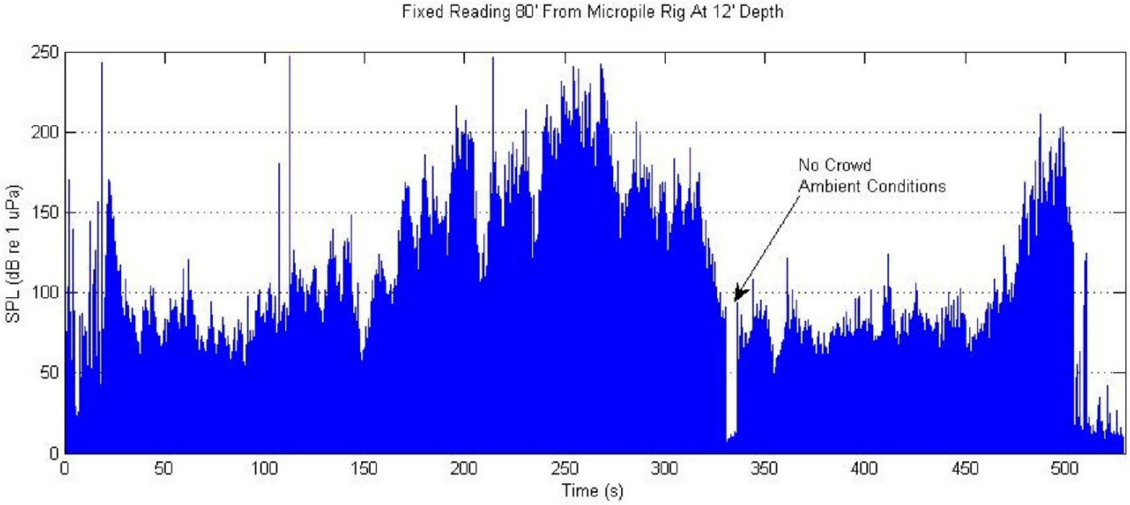


The drilled shaft recordings show significant variability in the underwater SPL; however, the observed levels did not exceed 100 dBa and were typically much lower. The observed open-air SPL was approximately 84 dBa measured with a Galaxy Audio CM-130. It should be noted that 0 dB ref. in air is 20 uPa while 0 dB ref in water is taken as 1 uPa. This means that for a given dBa value the value in air represents 20x more energy.

Micropile Boring

Due to work overlap, it was difficult to get isolated measurements of the micropile drilling operation. However, one 8 minute recording was made at a distance of 80' after the drilling crew had transitioned to drilling the 9" diameter micropile at a depth of 44' below the top of pier. The recording shows SPL variation from 60 dBa to peaks at nearly 240 dBa. The principle component of the sound seemed to come from the down-hole-hammer strikes rather than the rotary drilling action. A brief lull is shown when the drill crew let off on the crowd (down-pressure) and SPL returned to ambient. The observed in-air SPL was ~75 dBa.

Figure 9 – Test 6 - Micropile SPL At 80'

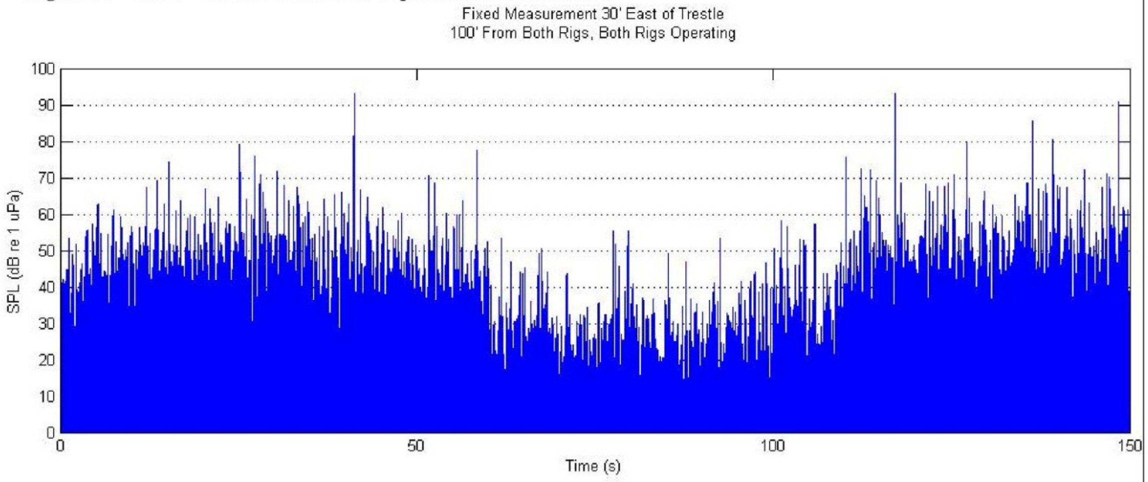


Combined Operation

Several observations were made of the underwater SPL while both rigs were operating. The majority of the sonic energy peaks seemed to be produced by the down-hole-hammer strikes of the micropile rig.

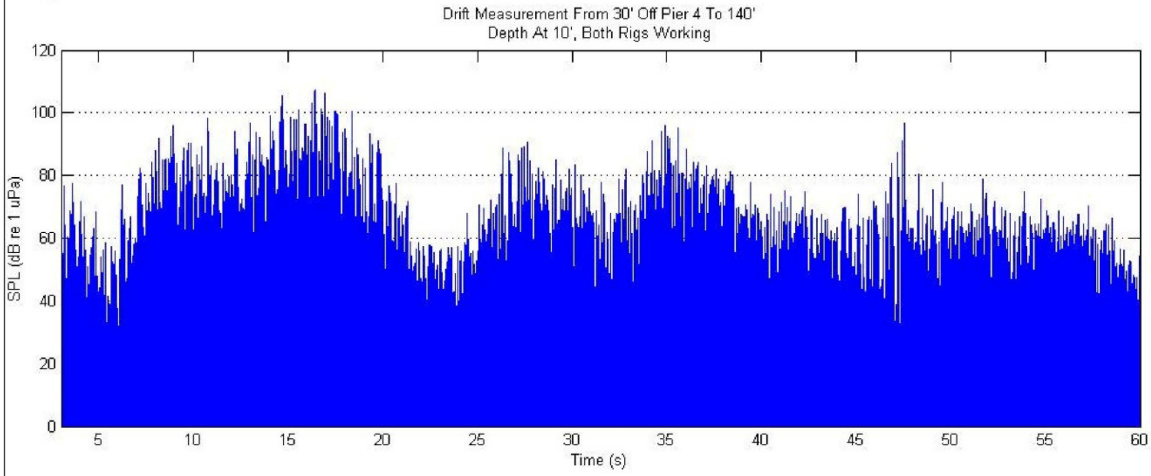
The following recording shows the combined SPL measured near the work trestle and approximately 100' from both rigs. The average SPL is ~45 dBa and the maximum observed SPL was ~93 dBa.

Figure 10 – Test 7 - Combined SPL 100' Equidistant From Sources



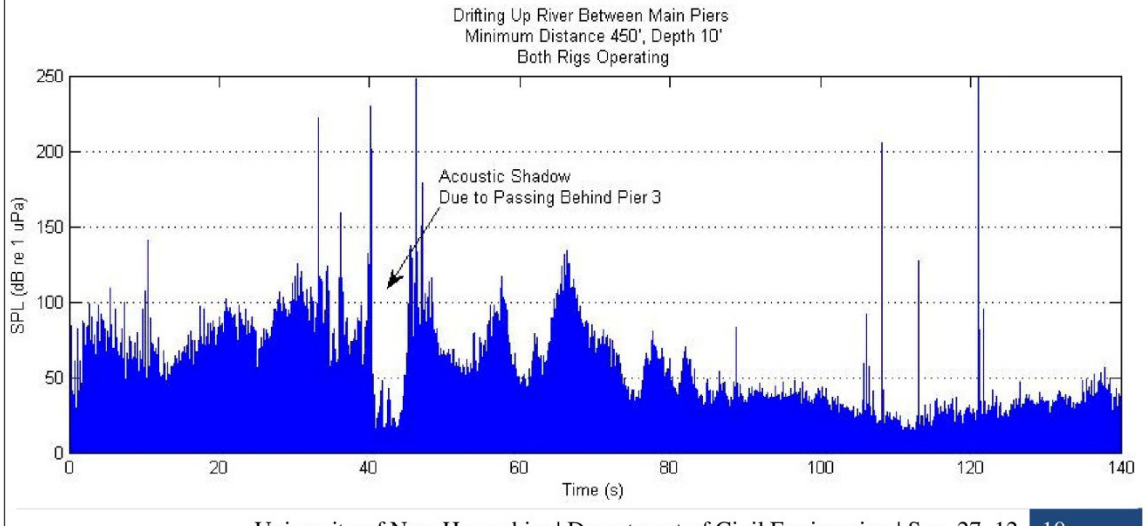
The following recording shows combined operation SPL taken along a line starting 30' from the micropile rig out to a distance of 140'. The peak SPL near the pier exceeded 100 dBa but dropped off to ~50 dBa at 140'.

Figure 11 – Test 8 - Combined SPL From 30' to 140'



Finally, the most interesting measurement was taken during a drift test where tidal currents carried the observation boat upstream past the bridge site. The recording began approximately 100' East of the bridge centerline and ended approximately 200' West of the centerline. The acoustic shadow produced by Pier 3 is clearly seen on the recording. The minimum distance to the micropile rig was approximately 450'. The variability of the SPL produced by this rig is also readily apparent. The maximum SPL approached 200 dBa during transient spikes but did not exceed 130 dBa during extended peaks. The average SPL was approximately 80 dBa but tapered off as the distance from the source increased.

Figure 12 – Test 9 - Combined SPL Through Navigation Channel



Conclusion

Unlike pile driving, which produces discrete blows of relatively constant energy, drilling in rock produces sound with considerable intensity variation. Sources of this variation include drilling speed, rig crowd, the nature of the rock encountered, the drill tool in use, and the nature of the overburden at a given depth. While surrounding soil layers may serve to somewhat moderate the strikes of a pile hammer, they have a profound effect on noise from drilling, which is primarily produced at the bottom of the bore.

This study gives a snapshot of underwater SPL that is valid only for the specific locations, equipment, and drilling conditions observed. However, conclusions can be drawn from the data that apply to a broad array of conditions.

The substantially lower SPL produced by the drilled shaft boring versus the micropile boring was unexpected. Despite the fact that the micropile rig was boring a much smaller hole at a much greater depth, the strikes from its pneumatic down-hole-hammer produced sound energy that eclipsed that which was produced by the larger SR-930. In air, the SR-930 sounded much louder than the PSM-1350 (as confirmed by the Galaxy CM-130); however, careful listening revealed that the majority of the noise was produced by the rattling of the machine's boom. The sound being projected from the bit into the water was relatively small. This suggests that percussive drilling tools may be considered similar to impact pile driving with respect to SPL while drilled shaft installation does not appear to present a risk of exceeding NOAA's 155 dBa limit for sound mitigation based on this study

It should be noted that this study represents a fairly worst-case scenario for these types of drilling. The Piscataqua River bottom is mostly hard bedrock with very shallow layers of extremely dense glacial till. This provides ideal conditions for sound to be transmitted through the bedrock and out into the water body. If the river bottom was comprised largely of sand or mud, the observed SPL would have been much lower and it is unlikely either rig would have exceeded NOAA's current standards.

Department Of Civil Engineering

Sarah Mildred Long Bridge Emergency Repairs
Temporary Substructure Pile Driving

Underwater SPL Observations

5/24/2013

Dr. Charlie Goodspeed
James Browne, EIT

Contents

Summary

The University Of New Hampshire, in cooperation with the New Hampshire Department of Transportation and Cianbro Corporation, performed monitoring of underwater sound pressure levels (SPL) during emergency repairs to the Sarah Mildred Long Bridge. Temporary substructure installation required driving eight 30" diameter closed-end steel pipe piles to refusal with vibratory and impact pile hammers. During both types of driving, underwater SPL averaged 170dB with peaks near 185dB.

Introduction

In recent years, sound pressure produced by underwater construction operations have become a major area of regulatory activity by federal and state agencies in an effort to protect endangered fish species. Construction projects in rivers and bays have come under increasingly strict schedule and SPL guidelines that influence infrastructure budgets and construction time.

On April 4th, 2013 at roughly 1:30pm, a 473 foot tanker drifted from its moorings at the NH State Pier and collided with the Sarah Mildred Long Bridge that carries Route 1 Bypass over the Piscataqua River from Portsmouth, NH, to Kittery, Maine. The stern of the ship damaged several critical structural members, including the lower chord, on the southernmost 224' truss span. After NHDOT engineers and engineers from Cianbro Corporation inspected the damage, it was determined that temporary pile bents would be required to support the truss while repairs were made.

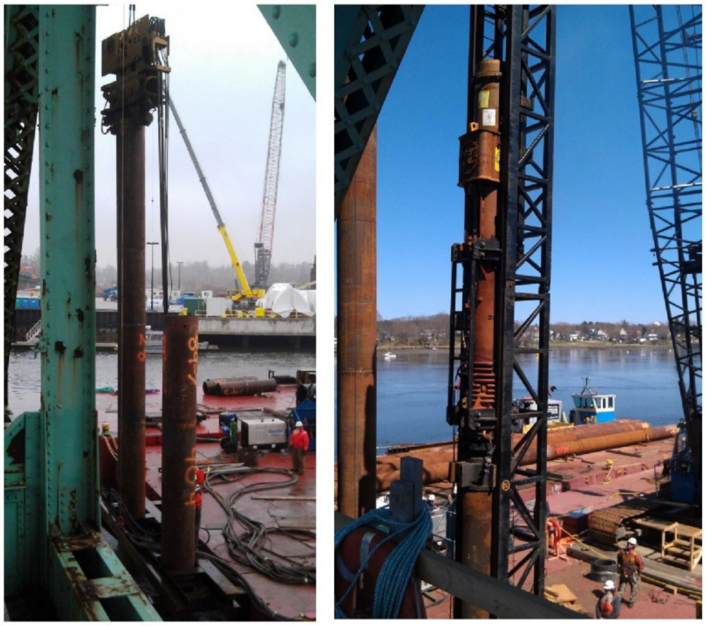
Figure 1 - Overview Of Collision Site

Figure 2 – Vertical Member Damage (left) and Lower Chord Damage (right)

Cianbro's bent design called for 8ea 30" diameter pipe piles to be installed in four pairs at truss panel points L4 and L6. The piles were designed to be driven to rock at a depth of roughly 70-80' below mean high water to a minimum capacity of 125 tons.

Pile Driving Equipment and Operations

Figure 3 - APE 200 Vibratory Hammer (left) and D62-42 Diesel Hammer (right)



Cianbro selected to begin driving the piles with an APE Model 200 vibratory pile hammer. This hammer produces a peak driving force of 181 tons at a frequency range of 0-28.3Hz. Cianbro crews operated the hammer at peak output during most of the driving cycles.

The piles were driven to refusal with an APE Model D62-42 diesel pile hammer. This hammer delivers a maximum energy of 179,000ft-lbs at maximum stroke with a 6.2 metric ton ram.

All piles were driving through a template erected off the crane barge. Two piles per day were driven from April 20th to April 23rd. All driving occurred during the afternoon outgoing tide due to the crew repositioning the crane barge at slack tide during the late morning.

Figure 4 - Setting 30" Pipe Piles in Template

The outgoing tidal current flows at a roughly 60 degree angle to the bridge alignment and varied during observation from 0fps to just over 3.0fps. Typical currents during the driving cycles varied between 1.5fps and 2.5fps. Current speed measurements were made using a Marsh-McBirney Flo-Mate 2000 velocity meter.

Data Acquisition

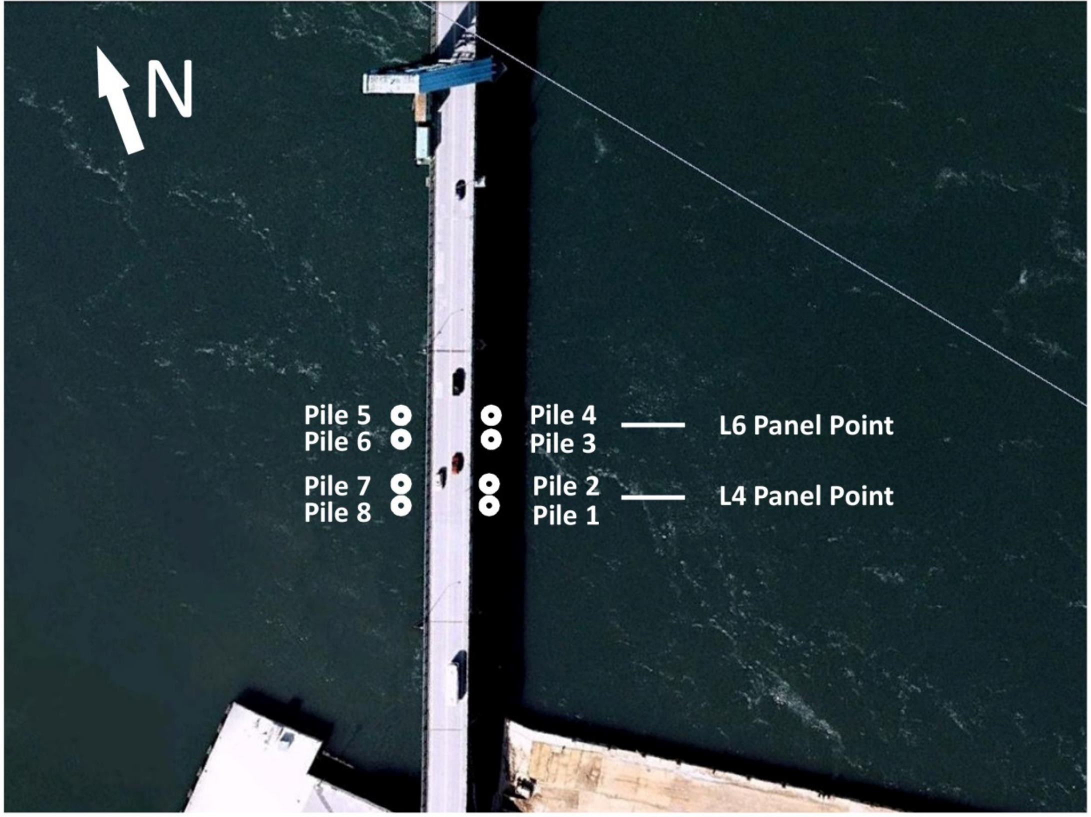
UNH performed the SPL measurements using three Reson TC-4013 omnidirectional hydrophones located at roughly 10m, 20m, and 40m from the piles being driven. The hydrophones were deployed from the railroad tracks on the lower deck of the bridge. Several methods were considered to keep the hydrophones from being carried downstream by the current including placing fixed anchors on the channel bottom. To maintain navigational safety, it was decided to lower steel conduit from the railroad catwalk just prior to the start of driving and deploy the hydrophones through the conduit to prevent excessive drift. The hydrophones were allowed to drop 5-6' below the end of the conduit to minimize exposure to vortices. This provided a final depth of 5' to 10' below the water's surface depending on the elevation of the tide, which varies up to 10' in the vicinity of the bridge. For this reason, all measurements are considered to be near-surface measurements.

Figure 5 - Conduit Secured to Catwalk

The hydrophones were deployed at various locations along the bridge to maintain the roughly 10m, 20m, and 40m distances requested by NHDOT from each pile being driven. A map of the pile locations is given in Figure 6.

The signals were amplified by

Figure 6 - Pile Locations



two Reson VP2000 voltage preamplifiers and one Reson VP1000 voltage preamplifier with all set to provide a band-pass filter of 10Hz to 10KHz. It was found that signals below 10Hz contained significant oscillation from swells while signals above 10kHz did not contain significant energy from the pile driving work.

The signals were acquired simultaneously by a National Instruments 24-bit USB-9334 Multifunction DAQ at a sample rate of 10KHz. The acquired data was displayed and recorded by a National Instruments LabVIEW application built for this purpose. The results were post-processed and plotted in Matlab.

Data Analysis

Hydrophones produce a voltage signal that varies linearly with the applied sound pressure. This voltage signal is amplified before being acquired by the DAQ device to provide increased resolution. After being converted from an analog signal to a digital signal and stored by LabVIEW, the signals must be processed to remove the amplification and convert the voltage values first to instantaneous sound pressure in Pascals and finally into Sound Pressure Level in dB.

Sound pressure is converted to Sound Pressure Level (SPL) by comparing the measured sound pressure with a reference pressure and expressing the difference as a logarithmic ratio. This provides convenience during analysis and comparison of acoustic measurements as sound pressures in the environment can vary over many orders of magnitude. The SI unit for this ratio is the Bel and it represents a tenfold increase in intensity. Therefore, an increase from 1Pa to 10Pa is expressed as 1 Bel.

For most applications, the Decibel (dB), or 0.1 Bel, is used to provide convenience. Therefore, each order of magnitude increase in intensity is expressed as 10dB. Each doubling of intensity is approximately 3dB as 10^(0.3) = 1.99 or roughly 2. Therefore a SPL measurement of 166 dB would be roughly twice the sound pressure of a measurement of 163 dB.

Sound pressure is converted to SPL by comparing the measured pressure with a standard reference pressure via:

$$SPL = 20\log_{10}\left(\frac{P}{P_{ref}}\right)$$

In air, the reference pressure of 20 uPa, commonly taken as the threshold of human hearing, is set as 0 dB and is comparable to the sound of a mosquito flying 10 feet away. In the study of underwater acoustics, it was found that 20 uPa was too large of a reference value and commonly produced negative dB values when working in the extreme quiet of deep water. As a result, the standard reference pressure was changed to 1 uPa for hydroacoustic measurements. All dB measurements in this report are provided with respect to this reference pressure.

The hydrophones used on this project have a receiving sensitivity of -213 dB re 1uV/Pa or 25.2 microvolts per Pascal. This produces signals in the microvolt range for most common measurements. To provide more resolution in the acquired data, the Reson preamplifiers were used amplify the input signals in 10dB increments. Most channels were acquired with a gain of 30dB; however, all data sets were individually processed with the gain used for each run. To avoid reporting amplified SPL values, these gain adjustments were removed from the signals in the post-processing phase.

After gain correction, the voltage values were converted to sound pressure in Pascals using the hydrophones' receiving sensitivity. Finally, the values were converted to SPL using the standard hydroacoustic reference pressure.

From all data sets, the ambient SPL in the Piscataqua River varied from 100 – 140dB and appeared to vary with tidal conditions and other non-pile driving sources of sound. This range is consistent with other research on ambient SPL in estuarine environments.

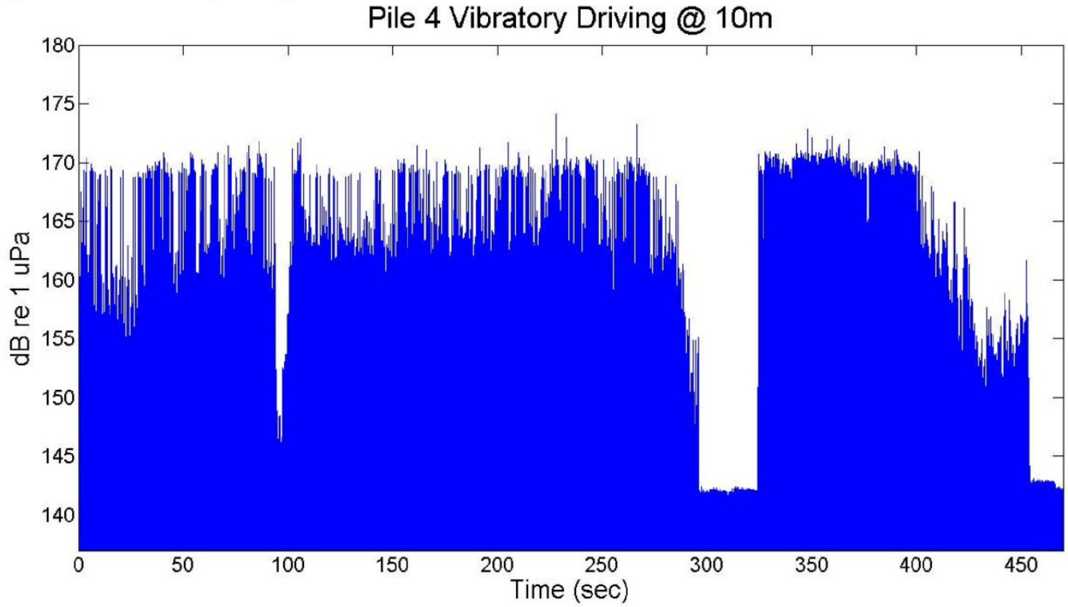
Summary of Results

Vibratory Driving

Peak SPL from the vibratory driving varied from 150dB to 180dB at a distance of 10m. The propagated sound in the water varied due to a number of factors including the operating power of the hammer, the depth of the pile, and the resistance of the soil layers encountered. It was observed that during periods of hard driving, there was a noticeable increase in the vibration felt in the bridge structure, and this corresponded to the highest SPL underwater. The typical driving time varied between 6 and just over 20 minutes.

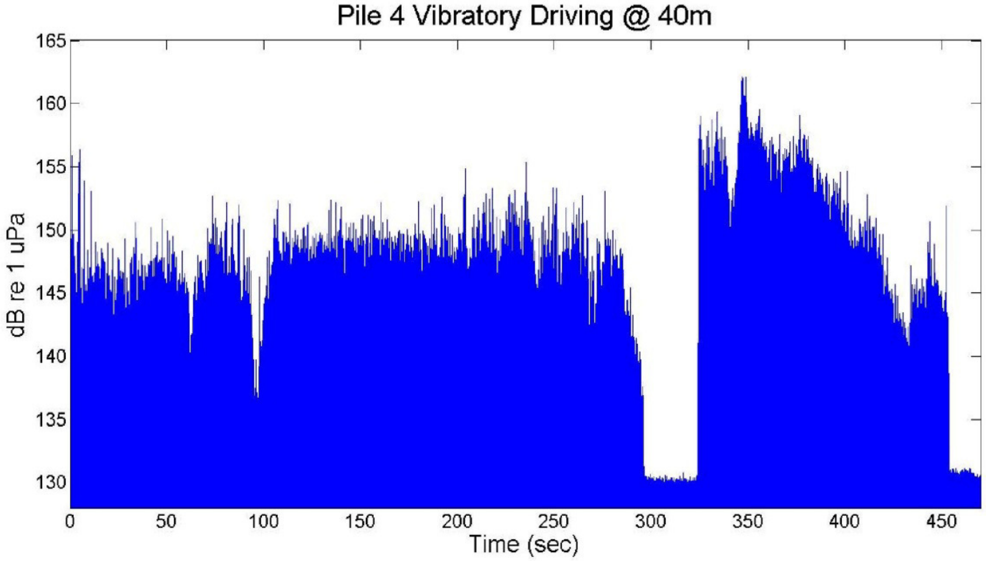
A plot of the driving cycle at Pile 4 is given below and includes periods when the hammer was shut off:

Figure 7 - Pile 4 Vibratory Driving At 10m



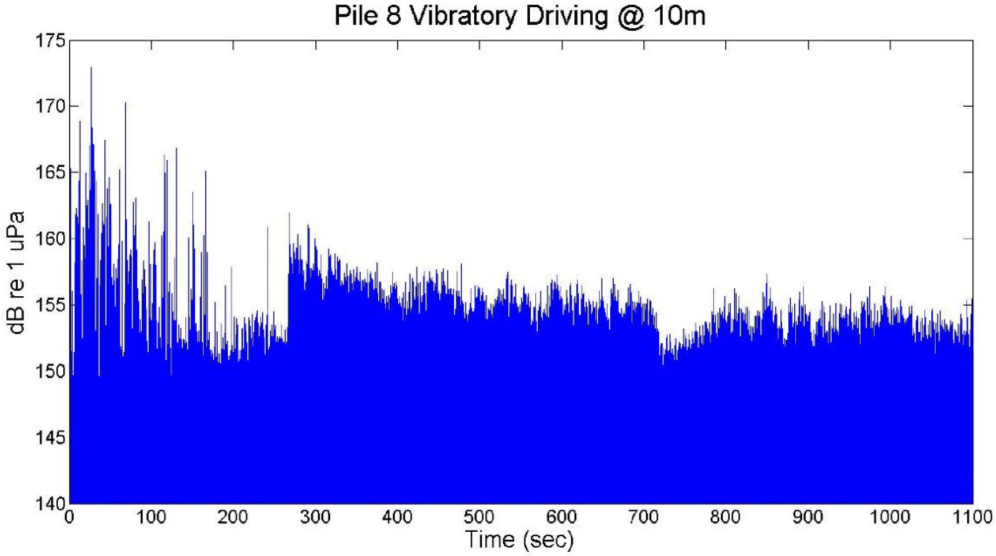
The same pile at a distance of 40m showing attenuation:

Figure 8 - Pile 4 Vibratory Driving at 40m



For comparison, the following shows the vibratory driving at Pile 8 and illustrates the variation in SPL commonly seen with this type of hammer despite similar piles and soil profiles.

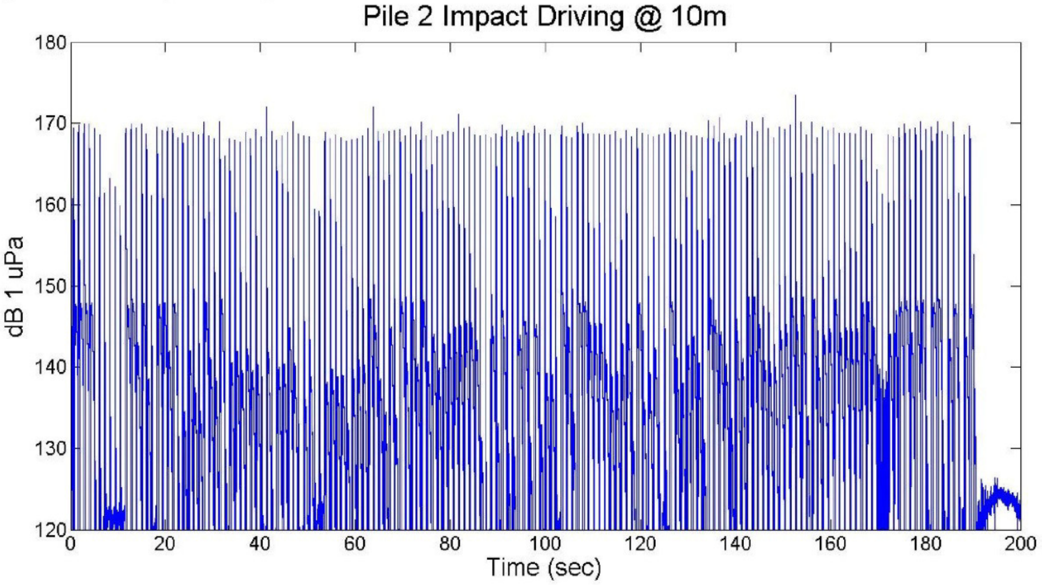
Figure 9 - Pile 8 Vibratory Driving at 10m



Impact Driving

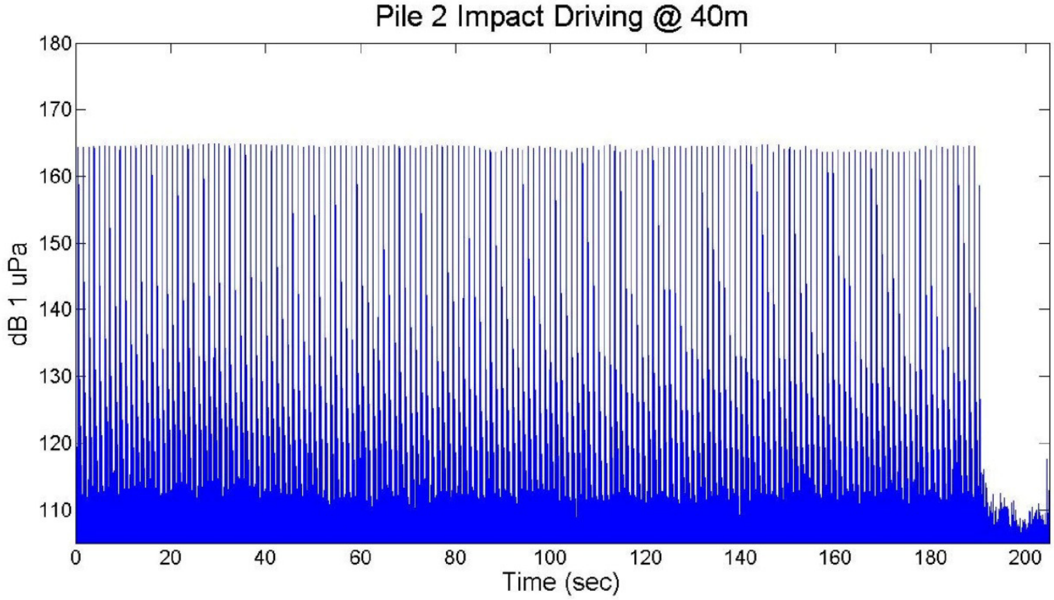
Peak SPL from impact driving remained fairly constant at roughly 160-180 dB and did not appear to vary with the depth of the pile. The average for most of the piles was 170dB. Typical driving times were between 6 and 20 minutes. A plot of a typical driving cycle is given below:

Figure 10 - Pile 2 Impact Driving at 10m



The same driving cycle at 40m shows attenuation:

Figure 11 - Pile 2 Impact Driving At 40m



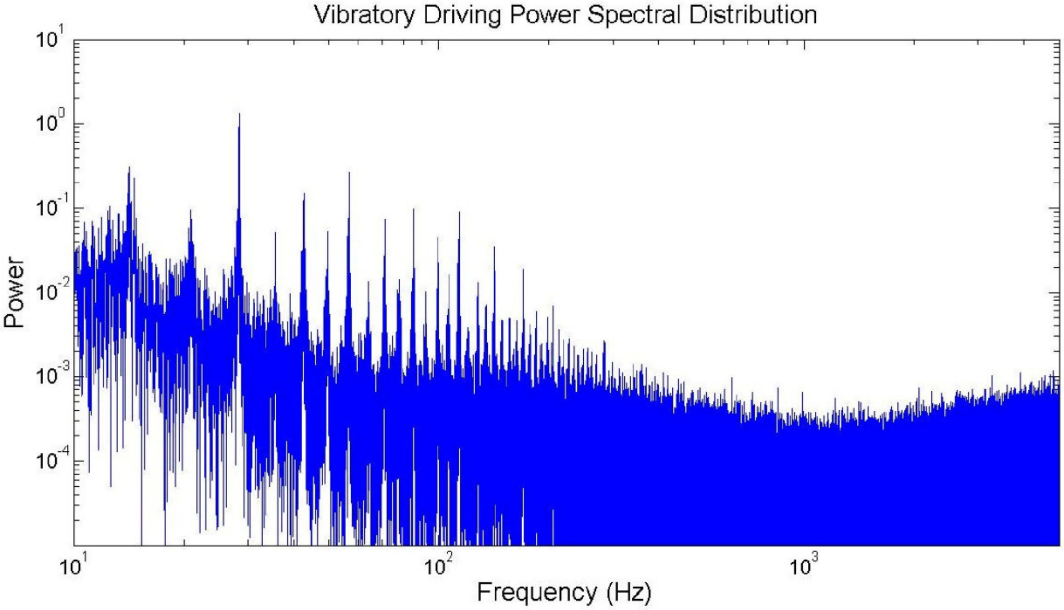
Spectral Analysis

Growing research shows that the ability of fish and other aquatic organisms to detect and respond to dangerous sound levels often depends on the frequency characteristics of the signal. Therefore, it is useful to analyze the power spectral distribution of both pile driving methods and identify primary tones.

To conduct this analysis, a Fast Fourier Transform was performed on subsets of the vibratory and impact driving data and the results plotted against the frequency range of 10Hz-5kHz. The resulting power spectral distribution shows the relative distribution of the total sonic energy over the period being analyzed.

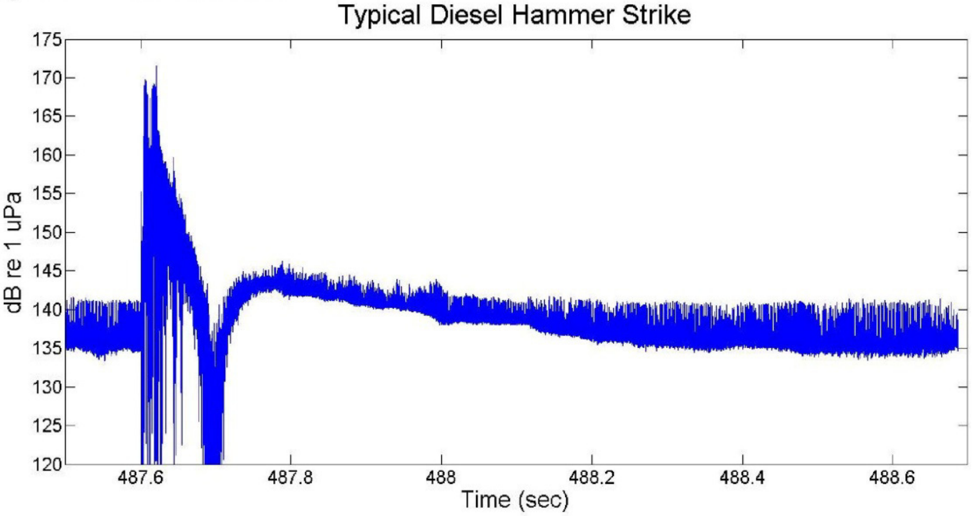
The plot for a typical period of vibratory driving shows a pronounced primary tone of roughly 15Hz with clear harmonics over the next several octaves.

Figure 12 - Vibratory Driving Power Spectral Distribution



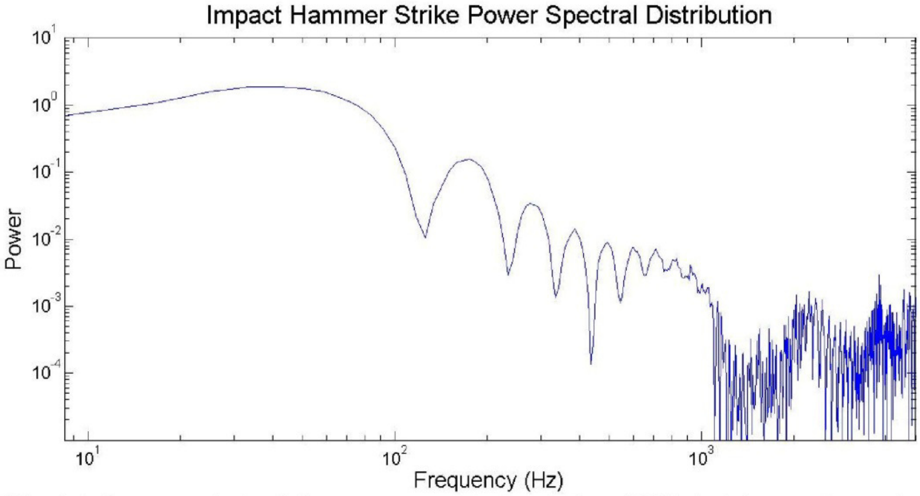
To analyze the impact hammer strikes, a single blow was isolated. A plot of the strike in dB shows the initial impact followed by a negative shockwave and a brief return to ambient conditions.

Figure 13 - Diesel Hammer Strike



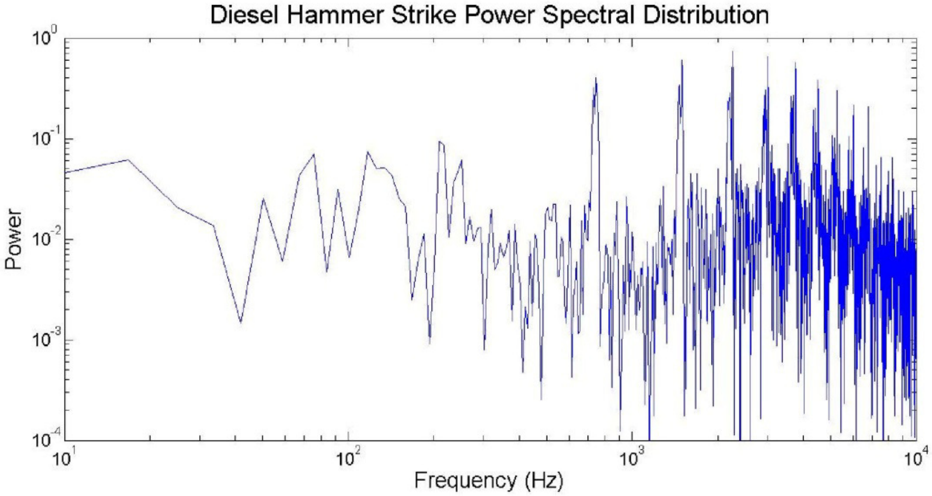
A plot of the power spectral distribution of this interval shows the following spectra:

Figure 14 - Impact Hammer Strike Spectra



This plot shows a substantial energy concentration below 100Hz but does not reveal any pronounced tones from the initial impact. This is consistent with the energy spectrum of a shockwave. However, some peaks are noticed between 1kHz and 10kHz and indicate harmonics from the pile "ringing". To better understand the spectral distribution over a series of hammer strikes a second FFT analysis was performed:

Figure 15 - Long-Term Power Spectra of Impact Driving



This analysis shows substantial harmonic tones above 1kHz that indicate pronounced pile ring. This high frequency noise associated with impact driving is more likely to elicit a startle response in small fish than the low frequency energy of vibratory driving.

Attenuation

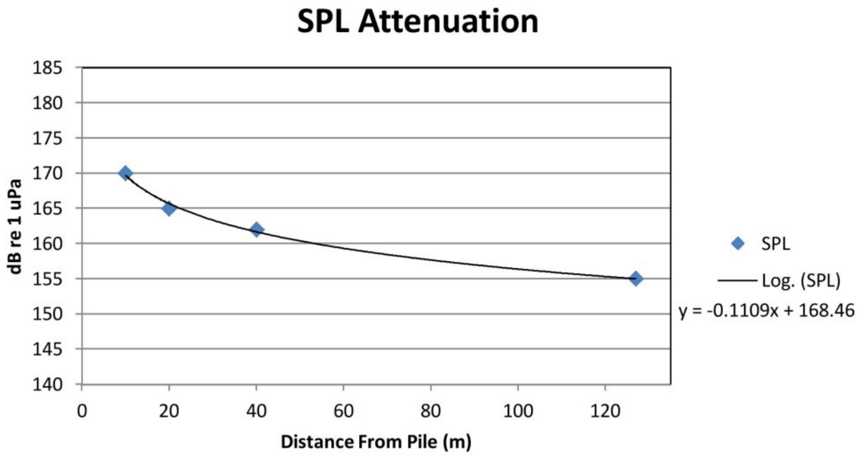
The final area of analysis was a study of attenuation over distance. Theoretically, sound intensity decreases with the square of the distance from the source. This means that for every doubling of distance, the signal will drop roughly 6dB. On this project, the 40m measurements are four times farther from the source than the 10m measurements and should see a theoretical drop of 12dB.

By comparing peak values in each data set, it was found that peak SPL attenuation was closer to 9dB/40m for vibratory driving and 7dB/40m for impact driving.

Theoretical attenuation does not take the propagation characteristics of the environment into account. Factors such as water depth, nearby solid objects (such as piers or barges), and the proximity of the hydrophone to the surface will all tend to increase the measured SPL by limiting the dispersion of sound energy into the larger body of water. Shallow environments will also tend to produce a "waveguide" effect where sound energy is concentrated between the channel bottom and water surface and transmitted with increased efficiency.

Three data points representing average values for impact driving at 10m, 20m, and 40m were used to create a logarithmic regression curve in Excel to estimate the distance at which the typical 170dB SPL drops below the NOAA regulatory threshold of 155dB. The result of this analysis shows this threshold is reached at a distance of 126m (415ft).

Figure 16 - Attenuation Regression Analysis

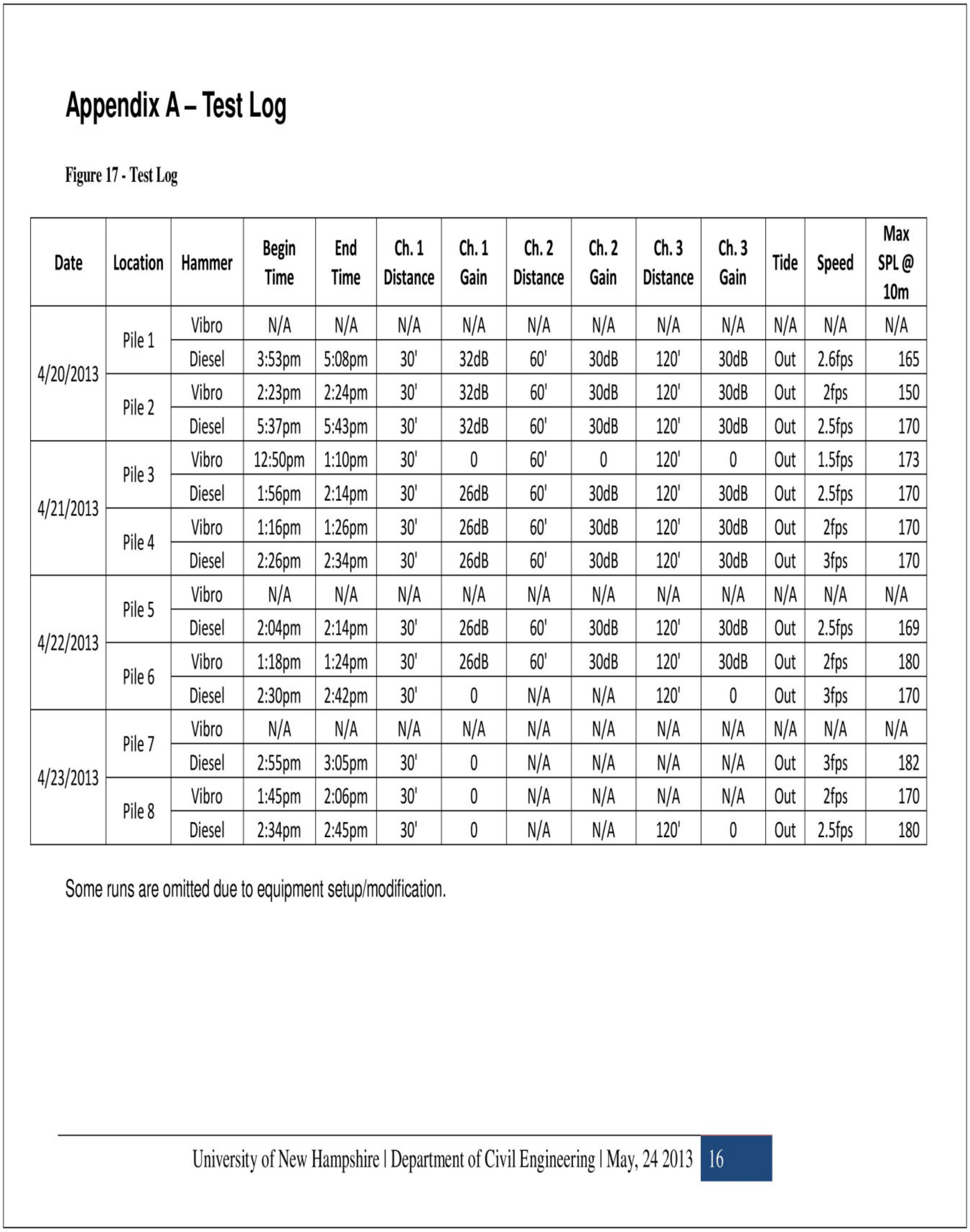


Conclusion

These SPL results show close correlation with similar studies on vibratory and impact pile driving. The results show no unusually high sound pressures despite the installation of large diameter piles and the use of larger than average equipment. The shallow overburden in the Piscataqua River allowed the contractor to maintain shorter driving cycles than have been observed in other studies. The turbulent environment around the Sarah Long Bridge may also produce a mild mitigating effect on sound propagation.

The likelihood of marine life mortality due to sound exposure was low and no evidence of fish kills, such as increased seagull activity, was noticed during the project.

While the current velocity did not seem to affect the peak SPL during pile driving, the ambient conditions before and after driving varied significantly due to turbulence around the bridge structure and construction vessels. A detailed analysis of ambient SPL conditions in the estuary would be helpful to determine how pile driving operations compare with normal ship traffic in the area. During the measurement periods, only one large ship passed through the navigation channel but did not appear to be under power and produced no noticeable change in the measurements.



Appendix A – Test Log

Figure 17 - Test Log

Date	Location	Hammer	Begin Time	End Time	Ch. 1 Distance	Ch. 1 Gain	Ch. 2 Distance	Ch. 2 Gain	Ch. 3 Distance	Ch. 3 Gain	Tide	Speed	Max SPL @ 10m
4/20/2013	Pile 1	Vibro	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		Diesel	3:53pm	5:08pm	30'	32dB	60'	30dB	120'	30dB	Out	2.6fps	165
	Pile 2	Vibro	2:23pm	2:24pm	30'	32dB	60'	30dB	120'	30dB	Out	2fps	150
		Diesel	5:37pm	5:43pm	30'	32dB	60'	30dB	120'	30dB	Out	2.5fps	170
4/21/2013	Pile 3	Vibro	12:50pm	1:10pm	30'	0	60'	0	120'	0	Out	1.5fps	173
		Diesel	1:56pm	2:14pm	30'	26dB	60'	30dB	120'	30dB	Out	2.5fps	170
	Pile 4	Vibro	1:16pm	1:26pm	30'	26dB	60'	30dB	120'	30dB	Out	2fps	170
		Diesel	2:26pm	2:34pm	30'	26dB	60'	30dB	120'	30dB	Out	3fps	170
4/22/2013	Pile 5	Vibro	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		Diesel	2:04pm	2:14pm	30'	26dB	60'	30dB	120'	30dB	Out	2.5fps	169
	Pile 6	Vibro	1:18pm	1:24pm	30'	26dB	60'	30dB	120'	30dB	Out	2fps	180
		Diesel	2:30pm	2:42pm	30'	0	N/A	N/A	120'	0	Out	3fps	170
4/23/2013	Pile 7	Vibro	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		Diesel	2:55pm	3:05pm	30'	0	N/A	N/A	N/A	N/A	Out	3fps	182
	Pile 8	Vibro	1:45pm	2:06pm	30'	0	N/A	N/A	N/A	N/A	Out	2fps	170
		Diesel	2:34pm	2:45pm	30'	0	N/A	N/A	120'	0	Out	2.5fps	180

Some runs are omitted due to equipment setup/modification.

UNIVERSITY of NEW HAMPSHIRE
Department Of Civil Engineering

Sarah Mildred Long Bridge Replacement
Underwater SPL Observations

Temporary Crane Trestle Pile Driving

James Browne, EIT

Cutt's Cove Trestle

5/25/2016

Contents

Summary

This report shows the hydroacoustic monitoring results from all piles driven to support the “Cutt’s Cove” temporary crane trestle on the Sarah Mildred Long Bridge Replacement Project in Portsmouth, NH. The Sarah Long Bridge carries US Route 1 Bypass over the Piscataqua River from Portsmouth, NH to Kittery, Maine. The results of these tests show compliance with the project limitations on underwater sound produced by pile driving.

Trestle Description

The Cutt’s Cove trestle is the southernmost trestle on the project and spans the Cutt’s Cove inlet to North Mill Pond between Market St. and the Newington spur rail line. This trestle allows heavy equipment access to Pier PV2 and vehicular bridge segment erection from Market St. to PV3 and is designed to accommodate equipment up to a 300 ton capacity crawler crane. A general plan of the trestle is given below.

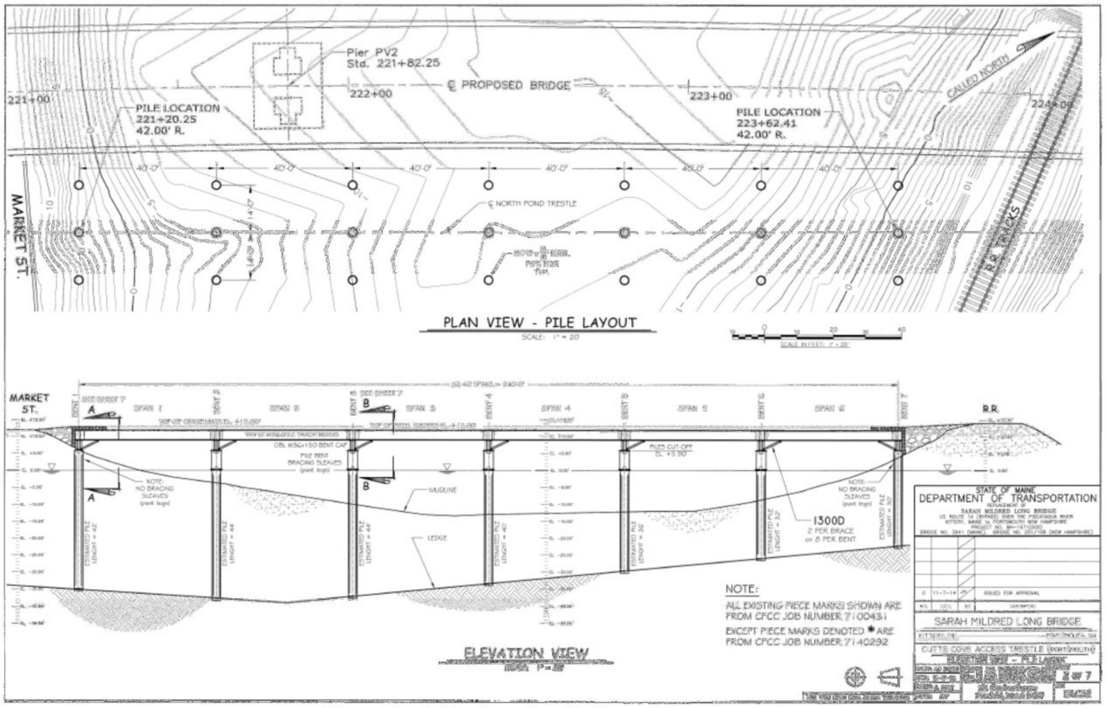


Figure 1 - Cutt's Cove Trestle General Arrangement

The trestle consists of seven three-pile bents supporting six forty-foot spans from project STA 221+ 20.25 42.00' R to STA 223 + 62.41 42.00' R. The piles are all 30" dia. X 5/8" ASTM A252 GR 60 pipe piles driven to an ultimate capacity of at least 1,240 kips.

Figure 2 - Cutt's Cove Trestle Nearing Completion as Seen From Market St.

Requirements

Underwater noise monitoring is required on this project during any impact pile driving work in the Piscataqua River, Cutt's Cove, or Mill Pond area. This monitoring must verify that the underwater sound pressure generated does not exceed 206dB peak re 1µPa and that the accumulated sound energy does not exceed 187dB cSEL re 1µPa^2•sec as required by NOAA National Marine Fisheries Service.

Results

Piles were driven between January 29th, 2015 and March 19th, 2015 starting with Bent No. 7 next to the railroad and concluding with Bent No. 1 next to Market St. The first two piles on Bent No. 7 were not included in the hydroacoustic monitoring as these piles were out of the water when driven at low tide.

The results are given in the following table and computed by the methods shown in Appendix D "Development of Representative Strike Data". All piles fell below the hydroacoustic limits on this project with peak SPL likely not above 195dB and a maximum cSEL of 185.8dB on the center pile of Bent No. 1.

Date	Bent	Pile	Size	No. Blows	SPL Peak (dB)	cSEL - 10m (dB)	cSEL - 20m (dB)	cSEL - 40m (dB)
Jan 29 2015	No. 7	North	30"ø x 5/8"	74	< 206	178.9	173.9	163.9
Feb 2 2015	No. 6	Center	30"ø x 5/8"	120	< 206	181.0	176.0	166.0
Feb 2 2015	No. 6	South	30"ø x 5/8"	139	< 206	181.6	176.6	166.6
Feb 2, 2015	No. 6	North	30"ø x 5/8"	145	<206	181.8	176.8	166.8
Feb 19 2015	No. 5	North	30"ø x 5/8"	61	< 206	178.1	173.1	163.1
Feb 19 2015	No. 5	Center	30"ø x 5/8"	87	< 206	179.6	174.6	164.6
Feb 19 2015	No. 5	South	30"ø x 5/8"	113	< 206	180.7	175.7	165.7
Feb 27 2015	No. 4	North	30"ø x 5/8"	44	< 206	176.6	171.6	161.6
Feb 27 2015	No. 4	Center	30"ø x 5/8"	80	< 206	179.2	174.2	164.2
Feb 27 2015	No. 4	South	30"ø x 5/8"	78	< 206	179.1	174.1	164.1
Mar 5 2015	No. 3	North	30"ø x 5/8"	61	< 206	178.1	173.1	163.1
Mar 5 2015	No. 3	Center	30"ø x 5/8"	47	< 206	176.9	171.9	161.9
Mar 5 2015	No. 3	South	30"ø x 5/8"	45	< 206	176.7	171.7	161.7
Mar 11 2015	No. 2	North	30"ø x 5/8"	41	< 206	176.3	171.3	161.3
Mar 11 2015	No. 2	Center	30"ø x 5/8"	81	< 206	179.3	174.3	164.3
Mar 11 2015	No. 2	South	30"ø x 5/8"	115	< 206	180.8	175.8	165.8
Mar 19 2015	No. 1	North	30"ø x 5/8"	127	< 206	181.2	176.2	166.2
Mar 19 2015	No. 1	Center	30"ø x 5/8"	359	< 206	185.8	180.8	170.8
Mar 19 2015	No. 1	South	30"ø x 5/8"	358	< 206	185.7	180.7	170.7

Figure 3 - Pile Driving Sound Data Summary

Conclusion

The results of these tests were compared with values included in the NOAA GARFO Acoustics Tool compendium of pile driving data for steel pipe piles with a diameter of 30 inches. Data from two historical projects are included in the database showing average peak sound pressures ranging from 194dB to 210dB. The maximum peak SPL observed on this project of 194dB correlates with data for "cushioned impact driving" on a project in San Rafael, CA where a wooden driving cushion was used.

The piles driven on this project included 1/2" and 5/8" wall piles and are significantly lighter sections than the 1" wall piles included in the compendium database. Additionally, the B64 hammer used on this project was operated at a low stroke of no more than 7 feet out of its maximum of 13 feet. Most pile driving on this project was terminated at a maximum stroke of roughly 6.5-7.0 feet at a low fuel setting. This criteria is unusual, as most hammers are sized so that the pile reaches capacity near the maximum stroke of the hammer at the highest fuel setting. This allows the use of the smallest hammer possible which reduces equipment cost and weight. The hammer stroke was limited on this project to avoiding damage to the tops of the lighter pile sections. This "low stroke" driving criteria appears to have the additional benefit of producing relatively moderate sound for the size pile and hammer being used.

UNH recommends that this data be categorized as having been produced during “low stroke” impact driving. “Low stroke” driving using a hammer with a heavy ram and a low ram stroke to provide high strike energy at low ram strike velocity is a known method in the pile driving industry to avoid producing tension cracks in concrete piles. Steel piles tend to be driven by hammers with lighter rams operated at high stroke as steel piles can withstand the higher tensile stresses this type of driving produces.

This project appears to demonstrate that using a heavy hammer at a low stroke or fuel setting on steel piles may be a method to reduce underwater sound from impact pile driving. With a low stroke, the driving energy is delivered more slowly as the ram is traveling at a lower velocity when the pile is struck. This is the same physical mechanism that reduces peak sound when using a driving cushion as the elastic response of the cushion spreads out the kinetic energy delivery over a longer time interval reducing peak amplitude. Further research into low stroke driving as a method of noise reduction is encouraged.

Appendix A - Pile Driving Operations and Equipment

Trestle Arrangement

The proposed Sarah Long Bridge requires the installation of 45EA 10' diameter drilled shafts in the Piscataqua River supporting nine approach piers and the two main lift towers. The area's swift tidal currents, among the fastest on the East Coast, prohibit working from barges and require the installation of temporary trestles to access all pier and tower locations. The design loads vary by location and include 230 ton capacity crawler cranes (Manitowoc 4100 Series 2) with drilling equipment and up to 300 ton capacity crawler cranes (Manitowoc 2250) to erect portions of the segmental approach bridges. These temporary trestles are supported by driven pile bents supporting 40' spans and consist of three to five 30" diameter closed-end pipe piles driven to capacities up to 1,240 kips.

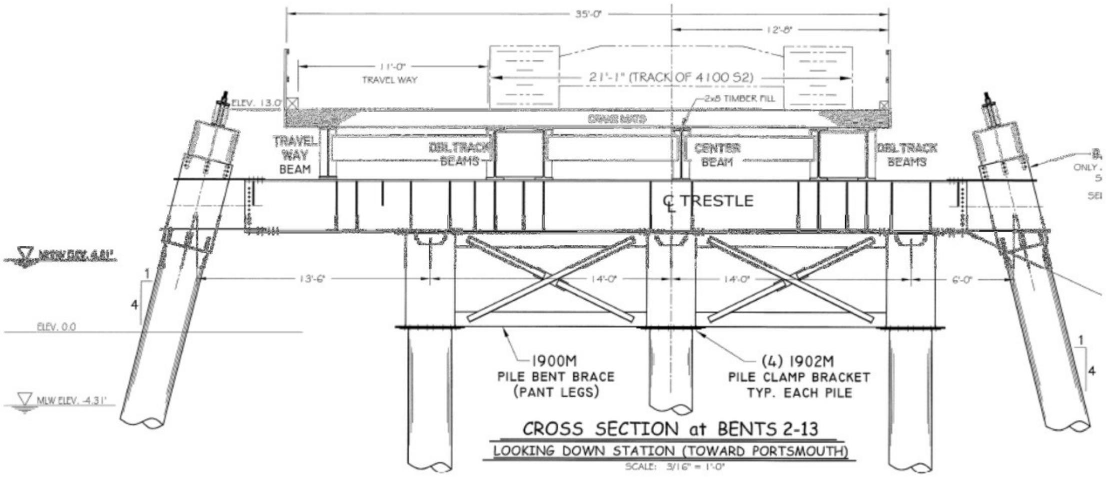


Figure 4 - Typical SML Temporary Crane Trestle Bent Elevation

The general trestle plan consists of a three pile bent that is occasionally braced with two battered piles to resist lateral loads imposed by tidal currents. The pile cap is a two-part design consisting of a set of braced 6' long by 32" diameter sleeves around the main piles and a double cap beam bolted to flanges on the sleeves. Together, the cap beam and sleeves provide a semi-moment connection and contributes to the lateral stability of the trestle system. The cap beams overhang one side of the trestle and provide a passing lane around cranes and drilling equipment located on the main trestle deck. Trestle spans consist of double or triple W36 beams located under each track of the design crane with additional beams under the intended travel ways and passing lanes.

Pier locations will be accessed via finger trestles that extend from the main trestle alignment. The Kittery and Portsmouth side trestles will extend to the main lift tower locations and will terminate in platforms of similar arrangement to allow drilling of the 32 drilled shafts supporting the towers.

After installation of all drilled shafts, the tower platforms and finger trestles will be removed to allow construction of the piers. The main trestles will remain for the duration of substructure construction and will be removed prior to completion of the proposed bridge.

Pile Driving Equipment

Figure 5 - APE Model 200 Vibratory Hammer

All piles are initially driven with an APE Model 200 vibratory pile hammer. This hammer produces a peak driving force of 181 tons at a frequency range of 0-28.3Hz. Cianbro crews operated the hammer at peak output during most of the driving cycles.

This vibratory hammer generates dynamic energy with a set of rotating excentric weights driven by by an external diesel-hydraulic power pack. These excentric weights are timed to produce no net lateral acceleration and additive vertical acceleration. A damper assembly isolates the crane from the vibratory unit and allows very high dynamic driving forces to be developed with a relatively light weight machine. Vibratory hammers are useful in advancing piles in short periods of time, but cannot be used to estimate capacity on load-bearing piles.

Piles are driven to design capacity with a Bermingham B64 diesel impact hammer. This hammer delivers a maximum energy of 162,260ft-lbs at maximum stroke with a 14,110lb ram. All pile hammers were handled by Manitowoc Model 4100 Series 2 crawler cranes.

This impact hammer is driven by the internal combustion of diesel fuel injected below the ram just prior to striking the anvil. The hammer is started by raising the ram using on-board hydraulic cylinders and is dropped, initiating combustion through very high compression. Successive blows continue until the fuel supply is shut off. The stroke of the ram can be computed from the period of the strikes allowing the energy delivered by the hammer to be accurately known. With *in situ* PDA test data, this allows the capacity of any pile to be reliably approximated by reaching a consistent blow count per inch at a consistent fuel setting.

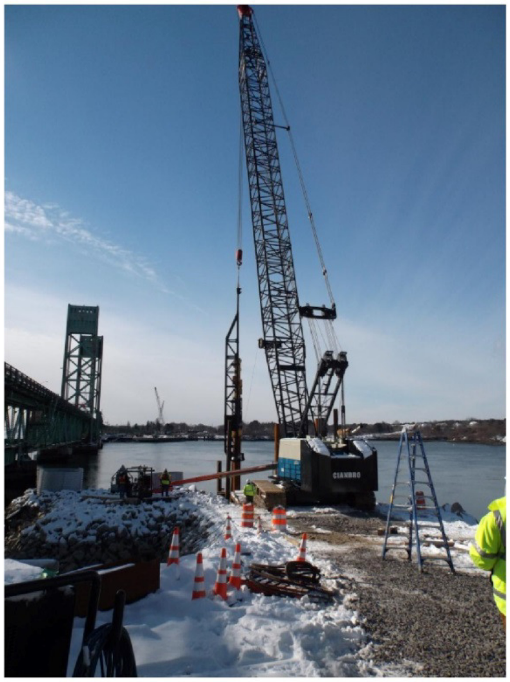


Figure 6 - Bermingham B64 Diesel Hammer

Appendix B - Instrumentation

Hydrophones

Sound pressure data was acquired with a Reson TC4013 piezoelectric hydrophone.

In shallow water, the hydrophones are deployed at mid depth to avoid inconsistent data near the water surface and river bottom. In deep water, the hydrophones were deployed at a depth of 10 – 20 feet. Near shore, hydrophones were deployed from floating booms at distances of 10m, 20m, and 40m or as can be safely accessed. The TC-4013 is fully omnidirectional in the horizontal and vertical plane through the entire audio spectrum (up to 20kHz) preventing the need to orient the hydrophone in any particular direction.

The TC-4013 has a receiving sensitivity of -212dBV re 1µPa or 25.2µV/Pa and has a linear frequency response from 1Hz through 300kHz.

Signals from the TC-4013 were amplified by a Reson VP-1000 voltage preamplifier. The amplifier gain was set at 20dB, per a calibration test, and had a high-pass filter set at 20Hz.

A GRAS 42AC pistonphone calibration unit was used to check the accuracy of the hydrophone data acquisition system. A pistonphone uses a series of precision cam-driven pistons to produce a displacement of air in a confined space of known volume. This produces a sound signal of known intensity. Due to the slight variations of seating depth and force in inserting the hydrophone into the pistonphone coupling adapter, manufacturers advise that a pistonphone reading should only be considered accurate to within 2-3dB. The 42AC produces 165dB at 250Hz. The hydrophone system used on this project was within 2dB during all calibration checks. The calibration recording performed just after monitoring of the Portsmouth No. 16 bent is given below.

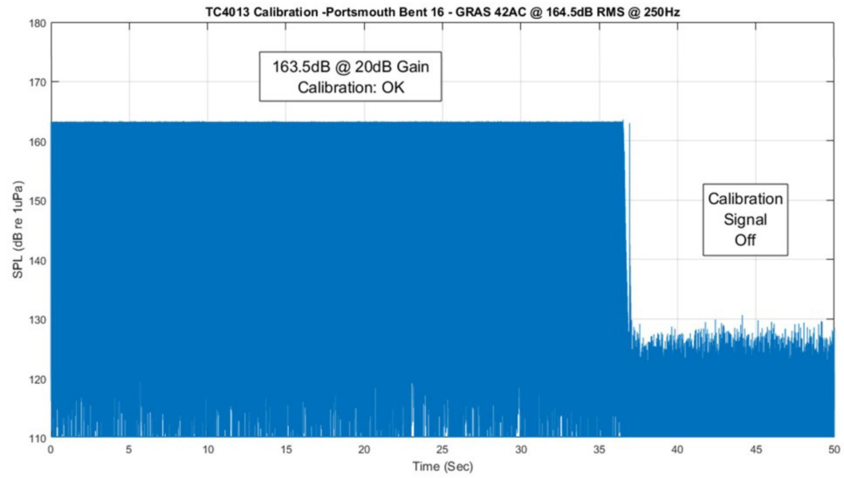


Figure 7 - Reson TC-4013 Calibration Test At Portsmouth Bent No. 16

Data Acquisition Device

Hydrophone data was acquired with a National Instruments USB-9234 Multifunction DAQ device. This DAQ device is capable of simultaneous acquisition of up to 4 channels simultaneously at 51.2KHz. Data was acquired on this project at a rate of 20,000 samples per second allowing the acquisition of sound data up to 10kHz.

The USB-9234 is considered a low-impedance (line level) input device and presents a substantial load to high impedance sensors, such as piezoelectric hydrophones. To ensure accurate operation, the VP-1000 amplifier provided voltage gain that compensates for the high input load of the USB-9234. Using an external calibration signal from the GRAS 42AC Pistonphone, it was found that a voltage gain of 20dB provided adequate coupling of the high impedance hydrophone sensor to the low impedance DAQ device to produce accurate results within 2dB. See Figure 7.

LabVIEW Application

UNH utilized a custom National Instruments LabVIEW application to record and display the hydrophone data. LabVIEW is an industry-standard real-time test and measurement development environment that allows software-based instruments to be built to meet the requirements of each project.

The LabVIEW application provided the following functionality:

- Receive the voltage data from the hydrophones and convert to sound pressure.
- Provide a means to input calibration values
- Convert sound pressure to SPL re 1µPa and display in real time.
- Provide the ability to record data as desired.
- Display the maximum peak SPL and RMS SPL observed during each measurement run

Appendix C - Hydroacoustic Calculations and Metrics

Hydrophones produce a voltage signal that varies linearly with the applied sound pressure. After being converted from an analog signal to a digital signal and stored by LabVIEW, the signals must be processed to convert the voltage values first to instantaneous sound pressure in Pascals and then to SPL relative to a reference pressure.

Sound energy is typically reported as a metric called Sound Pressure Level (SPL). SPL is reported in decibels (dB), which is 1/10th of the Bel, an SI unit of energy or power. The Bel is defined as a logarithmic ratio between a measured energy or power level and a reference energy or power level:

$$L_P = \frac{1}{2}\ln\left(\frac{P}{P_0}\right)\ \mathrm{Np} = 10\log_{10}\left(\frac{P}{P_0}\right)\ \mathrm{dB}.$$

A measurement reported in decibels of a power level that equals the reference value is 0dB. Measurements below the reference value will produce negative decibel values. Any energy or power measurement reported in decibels is considered a "power quantity" measurement and a tenfold increase in decibels represents a tenfold increase in the measurement energy. Therefore, 10dB is a tenfold increase in sonic energy and every 3dB increase in sonic energy is a doubling of that energy.

Sound energy generally cannot be measured directly; instead, sound pressure is measured with hydrophones and relates to sound energy by the square of the pressure signal amplitude. Therefore, to compute SPL from pressure measurements, the measurement value and the reference value are squared in the original decibel equation. When reduced, this yields the following familiar equation for SPL in decibels computed from pressure amplitude.

$$L_F = \ln\left(\frac{F}{F_0}\right)\ \mathrm{Np} = 10\log_{10}\left(\frac{F^2}{F_0^2}\right)\ \mathrm{dB} = 20\log_{10}\left(\frac{F}{F_0}\right)\ \mathrm{dB}.$$

Decibel values computed from signal amplitude data such as voltage or pressure are known as "field quantity" measurements. SPL computed from sound pressure is a field quantity; therefore, every 20dB increase in SPL is a tenfold increase in sound pressure and every 6dB is a doubling of sound pressure. The squaring of the measured and reference pressures produces the factor of two difference between power and field quantities expressed in dB.

In air, the reference pressure of 20 uPa, commonly taken as the threshold of human hearing, is set as 0 dB and is comparable to the sound of a mosquito flying 10 feet away. In the study of underwater acoustics, it was found that 20 uPa was too large of a reference value and commonly produced negative dB values when working in the extreme quiet of deep water. For convenience, the standard reference pressure was reduced to 1 uPa for hydroacoustic measurements. All dB measurements in this report are provided with respect to this reference pressure.

The hazards of sound exposure relate to duration and accumulated energy as well as peak intensity. A common metric for time-domain sound exposure is Sound Exposure Level (SEL) that is the double integral of the sound pressure over the time period of the event. For underwater measurements it is reported in dB re $1\mu Pa^2$•sec. SEL is typically calculated over one second for short duration sounds (such as a gunshot or single hammer strike), but for long-term sounds (such as a continuous series of pile hammer strikes), the cumulative SEL (cSEL) is calculated over the entire duration of the event.

cSEL can also be computed for a continues series of similar events or pile strikes by taking the SEL of a single strike (ssSEL) and projecting across the total number of strikes by the following equation:

$$cSEL = 10 * \log(\#\, strikes) + ssSEL$$

The data sets for each pile were imported into Matlab for processing and plotting. Matlab is ideal for performing automated and customized batch calculations on very large data sets. Each data set was reviewed for integrity and trimmed to eliminate extraneous data before and after the driving cycle. SPL data from Labview was converted back to sound pressure and stored separately to compute cSEL. cSEL was computed by squaring each pressure value and multiplying it by the delta-t of 50 microseconds (20,000 samples per second).

Appendix D - Development of Representative Strike Data

Following the first set of readings performed on Kittery Bent No. 1, the hydroacoustic monitoring system began showing inconsistent and greatly increased readings for peak sound pressure. Various parameters were checked and evaluated before attention was focused on the hydrophones themselves. Several sensors failed in service and serial-number tracking seemed to indicate that continued use at the closest range (10m) was related to eventual loss of sensitivity and noise (failure). The manufacturer was not able to provide calibration data for high intensity, low frequency sound exposure or comparative results from previous use in pile driving applications. The inconsistent voltage excursions followed by sensor failure are consistent with the symptoms of a piezoelectric device being driven outside of its linear pressure range, but the specific issue has not yet been resolved with the manufacturer.

The industry-standard Reson equipment used on previous projects by UNH was rented and included a pistonphone for on-site calibration. Recordings were made on the Portsmouth trestle No. 16 bent of three piles being driven and the following results were obtained (shown along with the results from Kittery Bent No. 1). These tests show close correlation with a peak SPL of 194dB and an average single-strike SEL of 160.2dB +/- roughly 2.5dB.

Date	Bent	Pile	Size	No. Blows	Peak SPL (dB)	cSEL (dB)	ssSEL (dB)	Mean ssSEL (dB)
Jan. 26, 2015	Kittery No. 1	Center	30" Dia. X 5/8"	110	189.0	181.1	160.7	160.2
Jan. 26, 2015	Kittery No. 1	North	30" Dia. X 5/8"	45	191.4	176.7	160.2	
Jan. 26, 2015	Kittery No. 1	South	30" Dia. X 5/8"	42	182.3	173.5	157.3	
July 29 2015	Portsmouth No. 16	Center	30" Dia. X 1/2"	163	194.0	182.4	160.3	
July 29 2016	Portsmouth No. 16	North	30" Dia. X 1/2"	151	191.0	184.2	162.4	
July 29 2017	Portsmouth No. 16	South	30" Dia. X 1/2"	122	191.0	181.4	160.5	

Figure 8 - Representative Strike Test Data

A typical SPL recording from the Portsmouth No. 16 tests is shown below followed by the plot of cSEL. The recording shows the period during which the hammer was tripped manually using hydraulic assist followed by the hammer firing under its own power. During manual tripping, the hammer would fire once or twice before stalling. This behavior was typical of nearly all piles as the Bermingham B64 was operated at the low end of its stroke range and would not fire until the piles had reached substantial resistance. Pre-driving with the vibratory hammer was discontinued after some time.

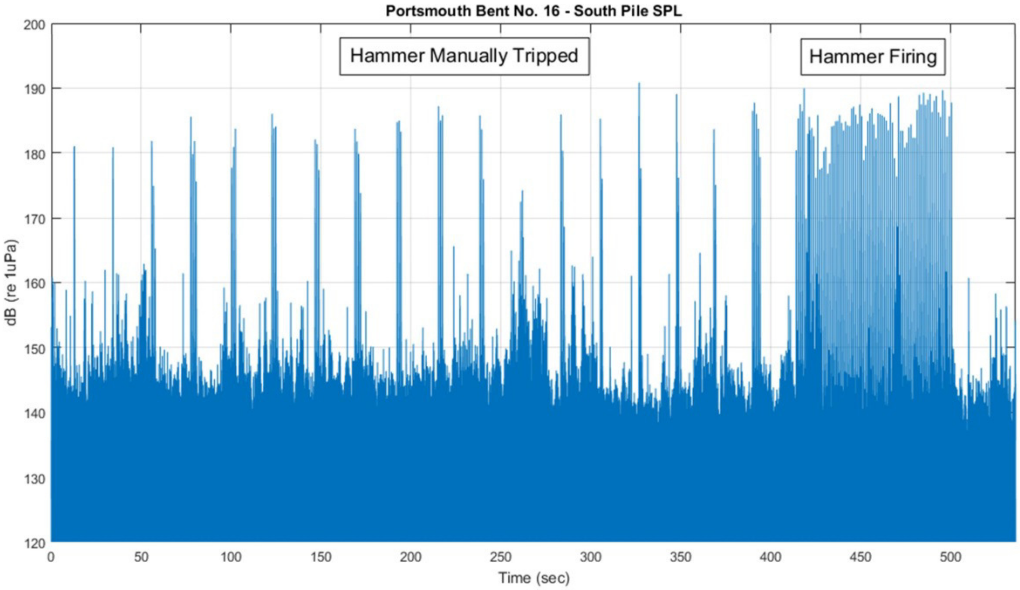


Figure 9 - Portsmouth Bent No. 16 - South Pile SPL

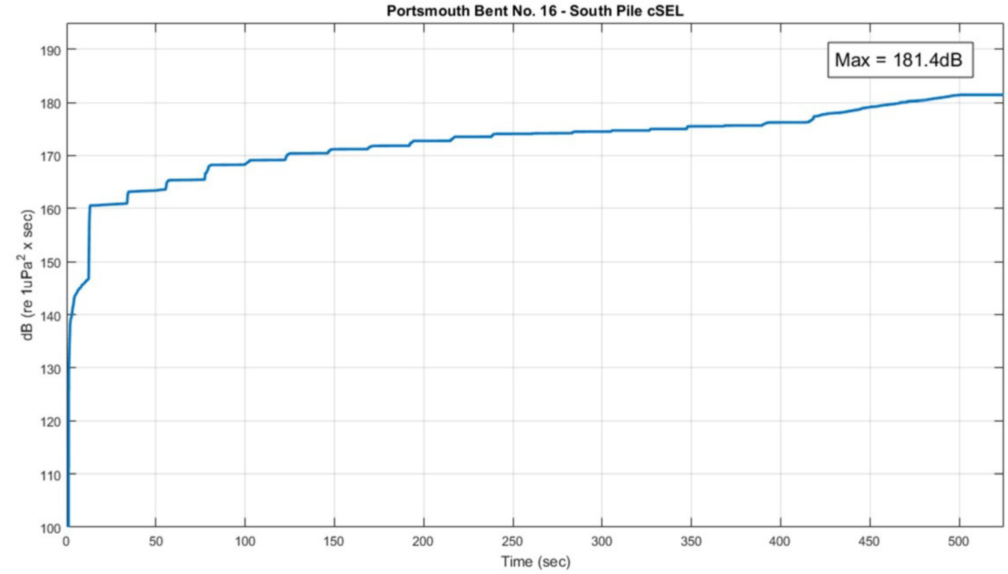


Figure 10 - Portsmouth Bent No. 16 South Pile cSEL

All piles driven on this project were of similar type and driven with similar criteria to those observed in these six tests. The calibration test performed on Portsmouth Bent No. 16 is given in Appendix B and shows that these tests are accurate. The results from Kittery Bent No. 1 also show close correlation and these two tests effectively book-end the pile driving work on this project. This strongly suggests the ssSEL per blow on all piles was likely very close to 160dB.

UNH recommends that the ssSEL of 160.2dB be used in conjunction with the original test data, which provides a record of the number of blows each pile received, to compute the cSEL for those piles.

As only one hydrophone was used at the 10m location to develop this maximum ssSEL, the attenuation to project the cSEL and peak SPL at the 20m and 40m ranges must be computed separately. For a solution, the recently distributed NOAA GARFO hydroacoustic tool shows a recommended attenuation of 5dB per 10m as observed on several projects driving 30" pipe piles in shallow, confined water bodies, similar to Cutt's Cove. This information was based on a survey of pile driving data as compiled by CALTRANS in 2009 and amended by ICF Jones & Stokes and Illingworth and Rodkin, Inc in 2012.

This attenuation of 5dB per 10m was used to project the cSEL at the 20m and 40m ranges in Cutt's Cove.

University of New Hampshire

Department Of Civil Engineering

Eastport Breakwater And Pier Replacement

Pile Driving Hydroacoustic Isopleth Report
H&M 3400 Vibratory Hammer

James Browne, EIT

5/3/2016

Contents

Summary

The main pier and breakwater serving commercial and government vessels in the town of Eastport, ME partially collapsed on December 12, 2014 due to failure of a sheet pile earth retaining wall. The existing breakwater is a 'L' shaped facility consisting of retained earth fill with a pile supported concrete deck on the outboard side. Originally constructed in 1962, this facility is a vital transportation resource for the region, and CPM Constructors of Freeport, ME is currently replacing the existing structure. This work requires the driving of sheet pile and pipe piles with impact and vibratory hammers.

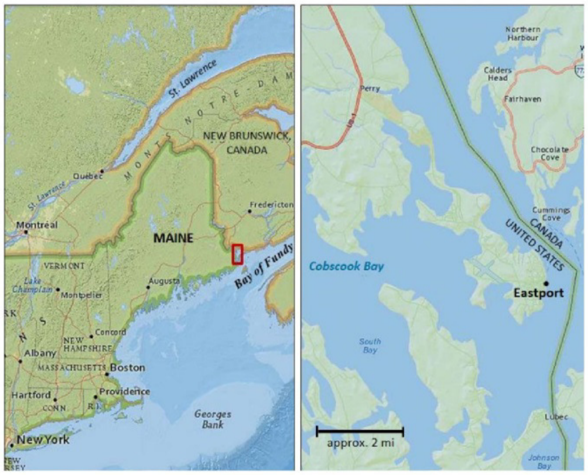


Figure 1 - Project Location

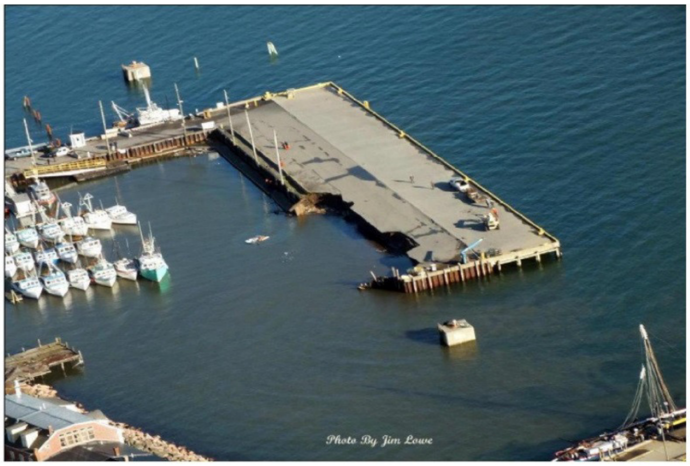


Figure 2 - Existing Breakwater After Collapse

Eastport is the easternmost point of the continental United States and located on Cobscook Bay near the mouth of the St. Croix River, a marine region with significant natural resources. NOAA National Marine Fisheries identified potential underwater sound hazards to pinnapeds (seals) and cetaceans (porpoises, dolphins, and whales) that may result from pile driving activity on this project. In addition to underwater sound monitoring during pile driving work, NOAA identified levels of ensonification for various construction tasks that may result in harm or harassment to marine life. Based on published data, NOAA developed zones of anticipated sound pressures for impact pile driving, vibratory pile driving, underwater sawing, and down-hole hammer drilling equipment. CPM is required to monitor these zones for the intrusion of various wildlife and must stop work until the zone is clear.

To reduce the schedule impact of wildlife intrusion, NOAA allows these zones to be reduced in size based on actual hydroacoustic data on the specific equipment in use. Based on measurements at various distances, isopleths are developed showing regions of uniform maximum sound pressure.

The University of New Hampshire was approached to develop these isopleth maps with broad-spectrum hydrophone data acquisition equipment.

This report presents data acquired July 23-24 on the use of an H&M Model 3400 vibratory hammer driving PZC-18 and PZC-26 sheet piles for the proposed breakwater.

Requirements

NOAA permit requirements set the following limits on RMS SPL for marine mammal protection on this project. The RMS SPL for impact hammer strikes is to be computed using the 90% energy window analysis, where the RMS SPL is calculated using the portion of the signal that contains 90% of the total energy of each strike. The limits on this RMS SPL are set forth in Table 1 of Section 105 of the project Special Provisions.

Table 1. Guidelines for Level A and Level B Marine Mammal Harassment

Type	Level A (possibly resulting in injury)	Level B (possibly resulting in behavioral modification)
Vibratory Hammer and Underwater Saw (continuous)	180 dB RMS	120 dB RMS
Impact Hammer/ Down Hole Hammer (impulse)	180 dB RMS for Cetaceans 190 dB RMS for Pinnipeds	160 dB RMS
Airborne construction noise	Not established	90 dB RMS (Harbor Seals) 100 dB RMS (Other Pinnipeds)

Based on existing sound data, NOAA indicated the following preliminary zones where marine mammal monitoring and exclusion were required during the indicated construction activities.

Table 2. Initial harassment zones

	Exclusion Zone (m)	Zone of Influence (m)
Impact Pile Driving	30	1,000
Vibratory Pile Driving	30	1,000
Downhole Pile Driving	333	1,000
Underwater Sawing	30	1,000

UNH's work on this project involves the measurement of the *in-situ* SPL produced by these work activities using the contractor's specific equipment and methods. Based on the results in this report, the proposed zones may be modified.

Pile Driving Equipment And Operations

UNH performed field measurements while CPM was installing the sheet pile wall which will eventually form the north wall of the proposed breakwater access roadway. This wall is constructed of both PZC-18 and PZC-26 epoxy coated sheet piles with the lighter sections used on the portion of wall closest to shore and the heavier sections used on the taller portions of the wall in deeper water.

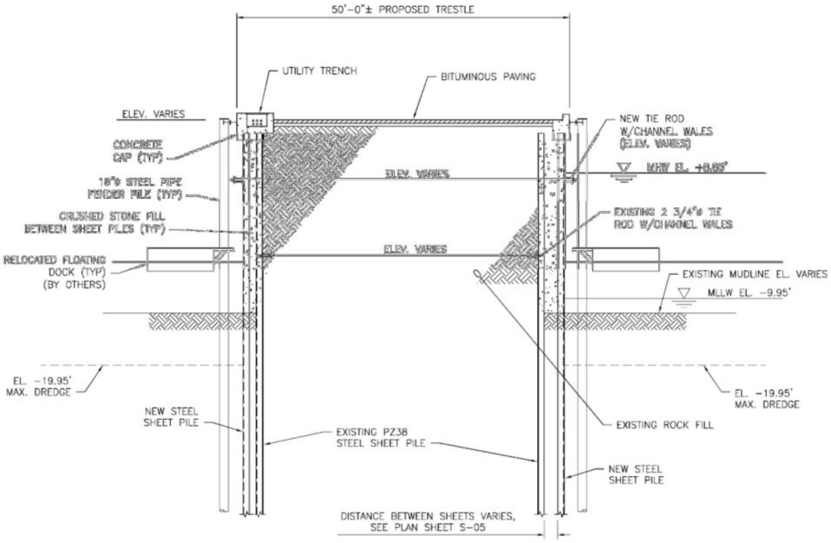


Figure 3 - Proposed Approach Roadway Section

The sheets observed being driven by UNH varied in length from 50 – 65 feet and were driven to an elevation requirement rather than a toe depth requirement, which is typical. Drains installed on alternating pairs of sheets were to be kept at the same elevation. Although not required to be driven to bedrock, the sheets were observed to be driven to near-refusal in most cases. A pair of interlocking sheets was installed during each driving cycle.

CPM had two vibratory hammers available for driving these piles including an American Piledriving Equipment (APE) Model 100 Vibrator/Extractor and an H&M Model 3400 vibratory hammer. Measurements taken for the Model 3400 are the subject of this report.

The Model 3400 has a maximum driving force of 180,700lb and a maximum driving frequency of 20.8Hz and was operated at full output on all observed sheets It is powered by a 450 horsepower diesel hydraulic power pack and was handled on this project by an American Model HC-110 crawler crane.

Figure 4 - Handling 65 foot Sheet Piles

The proposed sheet pile wall is installed several feet beyond the existing uncoated sheets with the void between intended to be filled with un-compacted crushed stone. To maintain the alignment of the wall, CPM is using H-pile supported beams as a driving template. Strips of lumber are attached to the contact faces of the template beams to protect the sheet's epoxy coating.

Figure 5 - H&M 3400 Hammer and Power Pack

Due to the length of the sheets used on this project and their inherent flexibility, the rocky subsurface conditions and presence of large boulders would tend to deflect each pair during driving and distort the alignment of the wall. CPM was required to drive, pull, and re-drive most of the piles several times to work each pair as plumb as possible. This contributed to longer than average driving cycles.

Figure 6 - Typical Pile Driving Operation

UNH observed the driving of both PZC-18 and PZC -26 sheets and the resulting isopleths for both are shown.

Hydrophone Data Acquisition And Analysis

All measurements were made from a small boat at various locations throughout Eastport harbor. The outboard motor was shut off during all recordings.

UNH performed the SPL measurements using a Reson TC-4013 omnidirectional hydrophone located at a depth of 15 – 25 feet. The hydrophone used on this project has a receiving sensitivity of -212 dB re 1uV/Pa or 28.2 microvolts per Pascal. This hydrophone has a linear frequency response from 5Hz – 100kHz. The signal was amplified by a Reson VP1000 voltage preamplifier set to provide a high-pass filter at 20Hz.

The voltage signal was converted to digital information by a National Instruments 24-bit USB-9334 Multifunction DAQ at a sample rate of 20KHz. The acquired data was displayed and recorded by a National Instruments LabVIEW application built specifically for this project. GPS data was acquired simultaneous with the sound data via a Garmin GPS 18x receiver at a rate of 1Hz and the position data was recorded directly into the sound data file to preserve synchronization.

A GRAS 42AC pistonphone calibration unit was used to periodically check the accuracy of the hydrophone data acquisition system. A pistonphone uses a series of precision cam-driven pistons to produce a displacement of air in a confined space. This produces a sound signal of known intensity. Due to the slight variations of seating depth and force in inserting the hydrophone into the pistonphone coupling adapter, manufacturers advise that a pistonphone reading should only be considered accurate to within 2-3dB. The 42AC produces 164dB at 250Hz. The hydrophone system used on this project was always within 2dB during all calibration checks.

Hydrophones produce a voltage signal that varies linearly with the applied sound pressure. After being converted from an analog signal to a digital signal and stored by LabVIEW, the signals must be processed to convert the voltage values first to instantaneous sound pressure in Pascals and then to SPL relative to a reference pressure.

Sound energy is typically reported as metric called Sound Pressure Level (SPL). SPL has the units of decibels which is 1/10th of the SI Bel. A Bel is defined as a logarithmic ratio between a measured energy or power level and reference:

$$L_P = \frac{1}{2}\ln\left(\frac{P}{P_0}\right)\ \mathrm{Np} = 10\log_{10}\left(\frac{P}{P_0}\right)\ \mathrm{dB}.$$

A measurement reported in decibels that equals the reference value is 0dB. Measurements below the reference value will produce negative decibel values. Any energy or power measurement reported in decibels is considered a “power quantity” measurement and a tenfold increase in decibels represents an order of magnitude increase in the measurement energy. Therefore, 10dB is a tenfold increase in sonic energy and every 3dB increase in sonic energy is a doubling of that energy.

Sound energy generally cannot be measured directly; instead, sound pressure is measured with hydrophones and relates to sound energy by the square of the pressure signal amplitude. Because SPL is calculated from sound pressure measurements, the measurement value and the reference value are squared in the original decibel equation. When reduced, this yields the following familiar equation for SPL in decibels computed from pressure amplitude.

$$L_F = \ln\left(\frac{F}{F_0}\right)\ \mathrm{Np} = 10\log_{10}\left(\frac{F^2}{F_0^2}\right)\ \mathrm{dB} = 20\log_{10}\left(\frac{F}{F_0}\right)\ \mathrm{dB}.$$

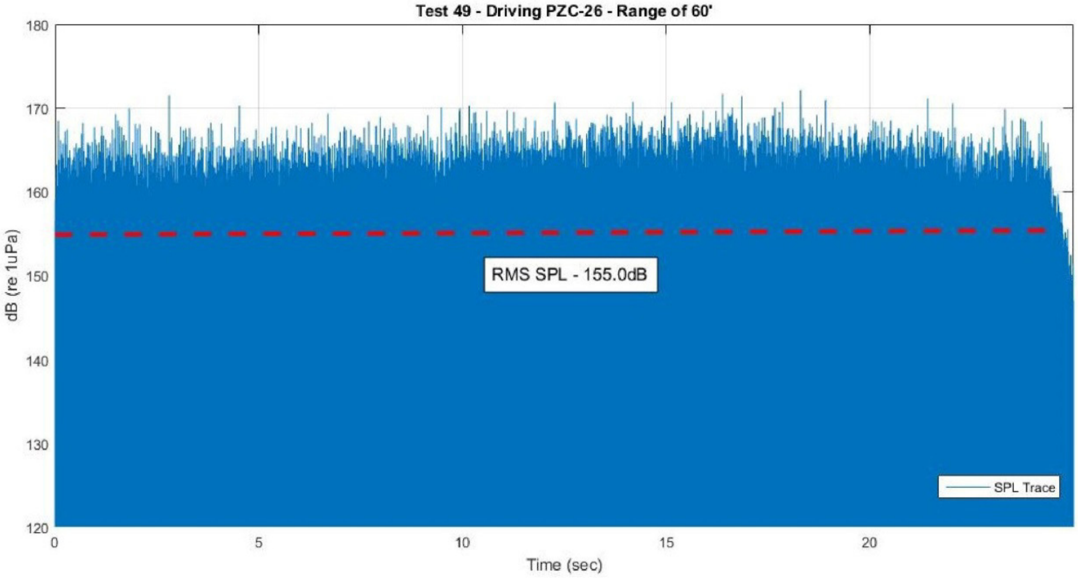
Decibel values computed from signal amplitude data such as voltage or pressure are known as “field quantity” measurements. SPL computed from sound pressure is a field quantity; therefore, every 20dB increase in SPL is a tenfold increase in sound pressure and every 6dB is a doubling of sound pressure. The squaring of the measured and reference pressures produces the factor of two difference between power and field quantities expressed in dB.

In air, the reference pressure of 20 uPa, commonly taken as the threshold of human hearing, is set as 0 dB and is comparable to the sound of a mosquito flying 10 feet away. In the study of underwater acoustics, it was found that 20 uPa was too large of a reference value and commonly produced negative dB values when working in the extreme quiet of deep water. As a result, the standard reference pressure was changed to 1 uPa for hydroacoustic measurements. All dB measurements in this report are provided with respect to this reference pressure.

For broadband noise measurements, SPL is computed from the RMS sound pressure signal. For sinusoidal signals, the RMS energy of a signal is equal to the amplitude of the pressure signal divided by root 2. In the area of noise monitoring and compliance testing, all SPL values should be assumed to be RMS SPL.

For marine mammal protection, focus is placed on the long term RMS sound pressure that a marine mammal might be exposed to. This is a slightly different approach than that used to protect fish from injury due to sonic overpressure (barotrauma) or physical harm from accumulated sonic energy. The primary concern for the protection of mammals is preventing hearing loss or shifts in hearing sensitivity. The data files acquired on this project were processed to produce the RMS sound pressure for the entire recording during the portion of the recording where the hammer was active. During some recordings, the boat carrying the hydrophone drifted a considerable distance, and for these recordings, the RMS sound pressure is reported at two separate data points located at the average latitude and longitude of the first and second half of the recording. Tables showing the test results summaries are given in Appendix A.

The following plot shows the relationship between the SPL trace and the RMS sound pressure level of the test duration for a typical recording on this project.

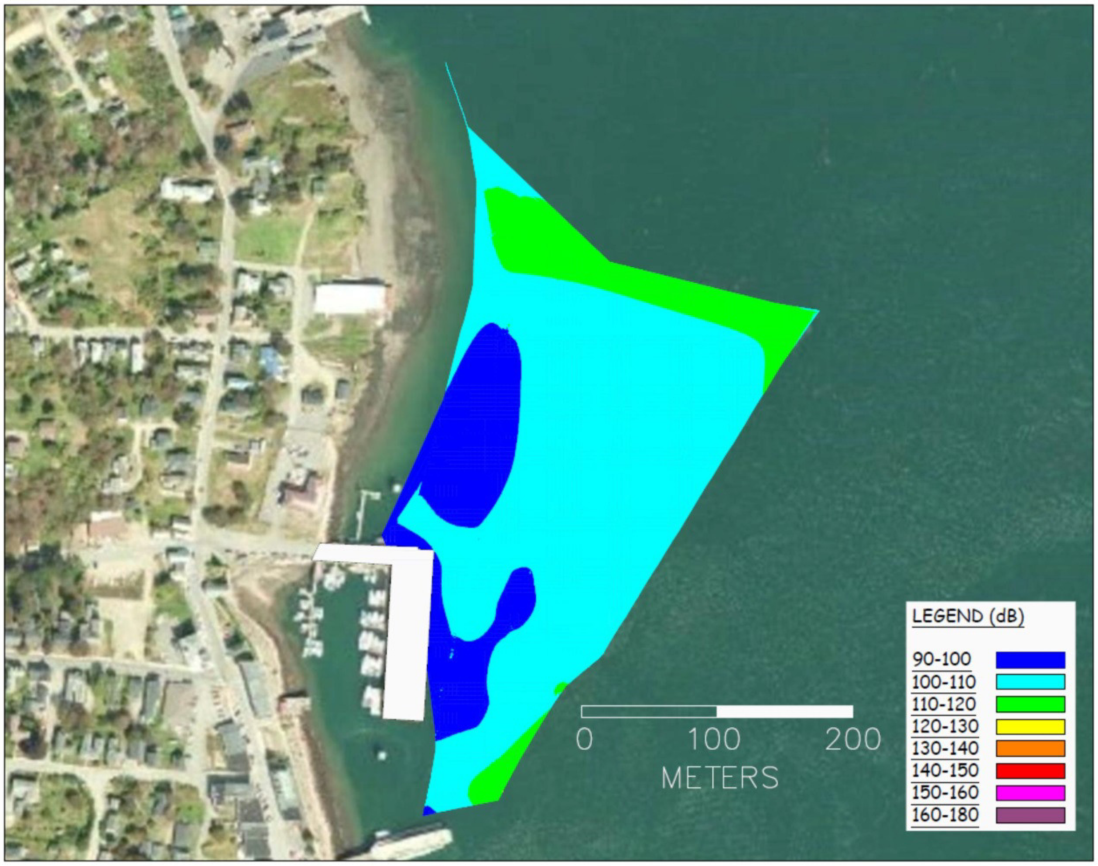


An ambient sound survey was conducted with no driving and no nearby boat traffic. The data showed very quiet conditions near shore, with increasing background sound into the navigation channel. It was assumed that the pile driving data would need to be adjusted with changes in ambient sound as caused by tidal currents or passing boats. However, it was not found that the ambient sound varied much with the tidal flow and no pile driving recordings were made with a boat close enough to influence the results. Furthermore, the background ranges of 115-130dB represent sound pressures around 10Pa. The driving levels were observed up to 170dB peak, in the range of 300Pa. Adjusting several hundred Pascal data by less than 10Pa would change the SPL in dB by a few tenths of a dB, which has no meaningful effect. As a result, no ambient adjustment was performed.

Ambient Conditions Survey

The results of the ambient conditions survey are shown below. Sound pressure is displayed in dB RMS.

Figure 7 - Ambient Conditions RMS



Isopleth Locations For Driving PZC-18 Sheet Piles

A total of 16 recordings at various locations around the project site were conducted during the driving of PZC-18 sheet piles with the H&M 3400 hammer. A map of the measurement locations is given below and a summary of the test results is given in Appendix A.

Figure 8 - PZC-18 Test Locations

The RMS results of these measurements were plotted based on range from the pile being driven and a regression analysis was performed on the sound pressure data. The results of this regression analysis were used to predict the Level A and Level B isopleth locations.

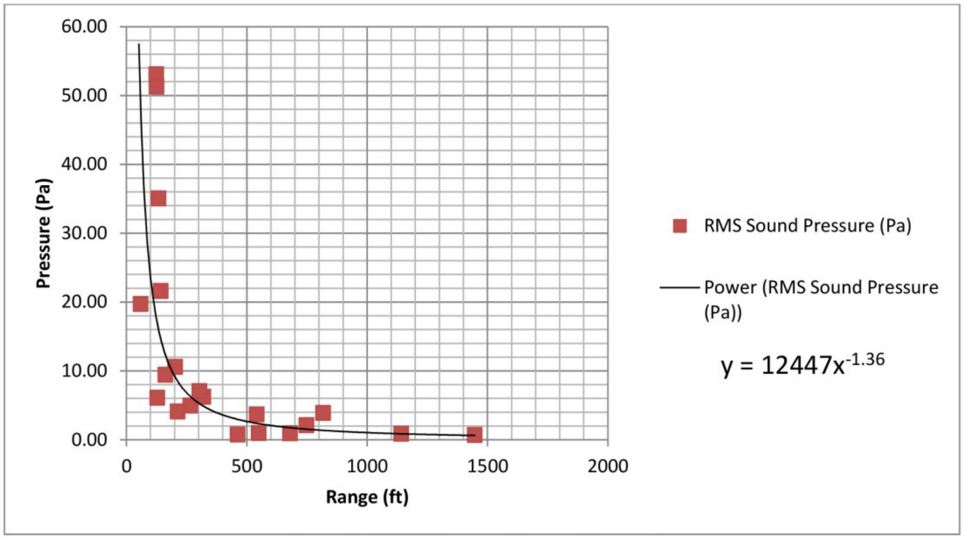


Figure 9 - PZC 18 Sound Pressure Regression

Based on the regression results, the Level A exclusion zone for all marine mammals where RMS sound pressure likely exceeds 180dB (1,000 Pa) RMS is 10ft (3m). Detailed information at this close range was not available due to the safety issues associated with approaching directly beneath the hammer while driving.

The Level B zone of influence (ZOI) where RMS sound pressure likely exceeds 120dB (1.0 Pa) is 1,025ft (310m).

Isopleth Locations For Driving PZC-26 Sheet Piles

A total of 16 recordings at various locations around the project site were conducted during the driving of PZC-26 sheet piles with the H&M 3400 hammer. A map of the measurement locations is given below and a summary of the test results is given in Appendix A.

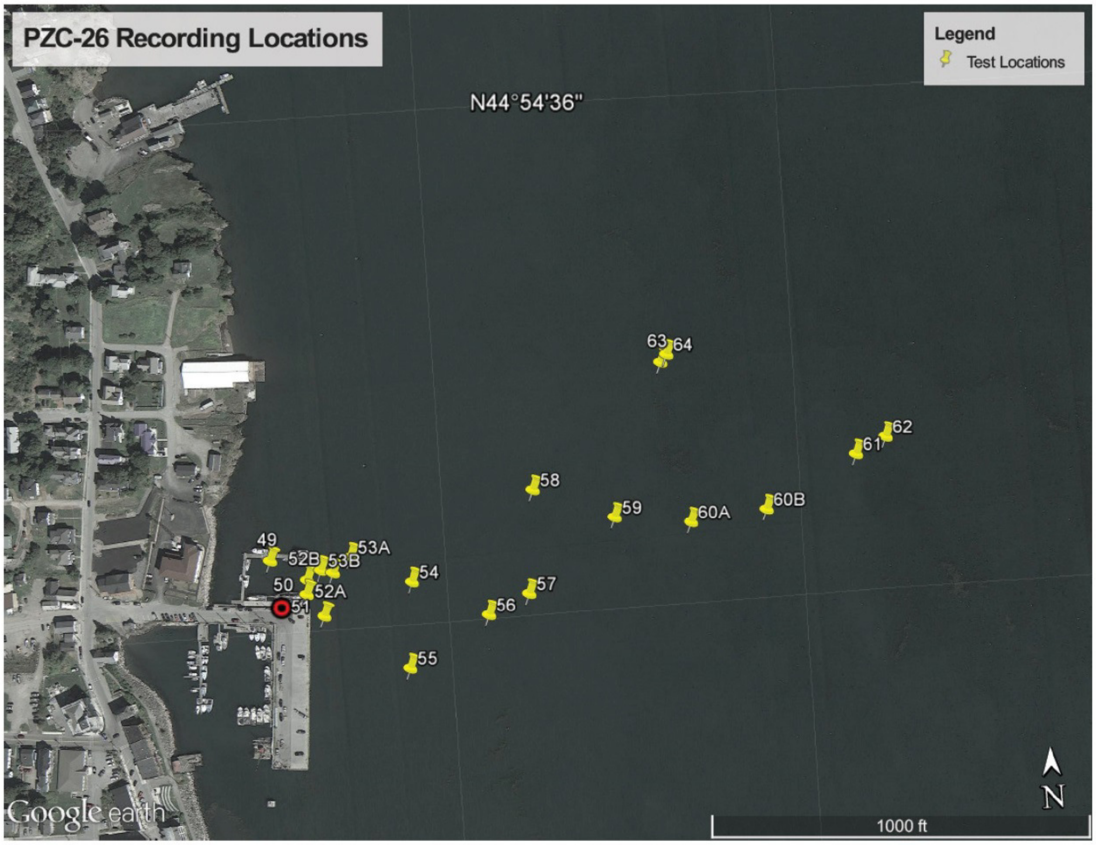


Figure 10 - PZC-26 Test Locations

The results of these measurements were plotted based on range from the pile being driven and a regression analysis was performed on the sound pressure data. The results of this regression analysis were used to predict the Level A and Level B isopleth locations.

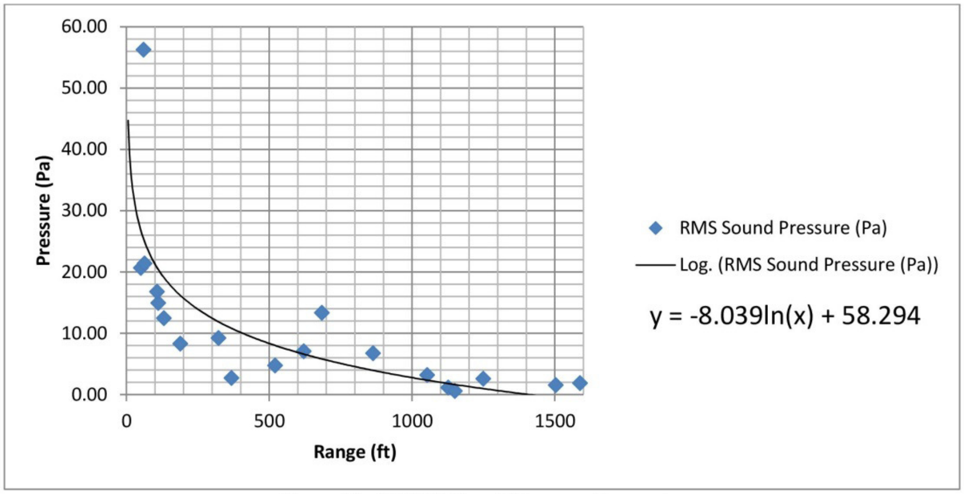


Figure 11 - PZC-26 Sound Pressure Regression

Based on the regression results, the Level A exclusion zone for all marine mammals where RMS sound pressure likely exceeds 180dB (1,000 Pa) RMS is 10ft (3m). Detailed information at this close range was not available due to the safety issues associated with approaching directly beneath the hammer while driving.

The Level B zone of influence (ZOI) where RMS sound pressure likely exceeds 120dB (1.0 Pa) is 1,245ft (380m).

Appendix A – Data Tables

			Pile Location (approx)		44.9066495531	-66.9837155940	0.783768891	-1.169086382			
Test No.	**RMS Interval (sec)**	**Pile**	**SPL (dB)**	**Pressure (Pa)**	**Laitude (deg)**	**Longitude (deg)**	**Laitude (rad)**	**Longitude (rad)**	**a**	**b**	**Range (ft)**
33	entire test	PZC-18	119.6	0.95	44.906343252	-66.981120955	0.78376354478	-1.16904109733	2.64323E-10	3.2516E-05	680
34	entire test	PZC-18	145.9	19.72	44.906721650	-66.983510544	0.78377014907	-1.16908280354	2.00204E-12	2.82987E-06	59
35	entire test	PZC-18	146.7	21.63	44.907039325	-66.983654650	0.78377569354	-1.16908531867	1.17114E-11	6.84439E-06	143
36A	70	PZC-18	133.9	4.95	44.907280526	-66.983200474	0.78377990329	-1.16907739180	4.04556E-11	1.27209E-05	266
36B	70	PZC-18	135.9	6.24	44.907377055	-66.983023742	0.78378158804	-1.16907430724	5.85905E-11	1.53089E-05	320
37	entire test	PZC-18	131.3	3.67	44.907881950	-66.982550005	0.78379040013	-1.16906603897	1.67562E-10	2.58892E-05	541
38A	30	PZC-18	126.5	2.11	44.908478693	-66.982406336	0.78380081525	-1.16906353147	3.20274E-10	3.57924E-05	748
38B	30	PZC-18	131.8	3.89	44.908655234	-66.982306620	0.78380389648	-1.16906179110	3.82185E-10	3.90991E-05	817
39A	100	PZC-18	118.8	0.87	44.909464085	-66.981780533	0.78381801359	-1.16905260915	7.463E-10	5.4637E-05	1142
39B	100	PZC-18	116.7	0.68	44.910290543	-66.981495126	0.78383243800	-1.16904762785	1.1979E-09	6.92214E-05	1447
40A	125	PZC-18	117.6	0.76	44.906547542	-66.981932884	0.78376711031	-1.16905526818	1.22198E-10	2.21087E-05	462
40B	125	PZC-18	119.7	0.97	44.906708664	-66.981590596	0.78376992243	-1.16904929412	1.72768E-10	2.62883E-05	550
41	entire test	PZC-18	137.0	7.08	44.906574807	-66.982545575	0.78376758617	-1.16906596165	5.2721E-11	1.45218E-05	304
42	entire test	PZC-18	140.5	10.59	44.906676481	-66.982931775	0.78376936073	-1.16907270211	2.3525E-11	9.70052E-06	203
43	entire test	PZC-18	139.5	9.44	44.906631295	-66.983089397	0.78376857208	-1.16907545313	1.5005E-11	7.74725E-06	162
44	entire test	PZC-18	132.3	4.12	44.906853997	-66.982941678	0.78377245896	-1.16907287495	2.60635E-11	1.02105E-05	213
45	entire test	PZC-18	135.7	6.10	44.906781315	-66.983252353	0.78377119042	-1.16907829725	9.51982E-12	6.17084E-06	129
46	entire test	PZC-18	150.9	35.08	44.906781315	-66.983233096	0.78377119042	-1.16907796115	1.02155E-11	6.39235E-06	134
47	200 sec to end	PZC-18	154.5	53.09	44.906687344	-66.983236210	0.78376955031	-1.16907801551	8.88775E-12	5.96247E-06	125
48	entire test	PZC-18	154.2	51.29	44.906689988	-66.983233858	0.78376959646	-1.16907797445	8.98987E-12	5.99662E-06	125

Figure 12 - PZC-18 Driving Data

Column "a" and "b" show a two-step computation of the distance between the geodetic coordinates of the pile location and measurement location via the Haversine formula:

$$a = \sin\left(\frac{\text{lat2} - \text{lat1}}{2}\right)^2 + \cos(\text{lat1}) * \cos(\text{lat2}) * \sin\left(\frac{\text{lon2} - \text{lon1}}{2}\right)^2$$

$$b = 2 * \arctan\left(\frac{\sqrt{a}}{\sqrt{1-a}}\right)$$

$$Range = b\ x\ mean\ earth\ radius\ (20,902,000ft)$$

			Pile Location (approx)		44.906586387	-66.983238972	0.783767788	-1.169078064			
Test No.	RMS Interval (sec)	Pile	SPL (dB)	Pressure (Pa)	Laitude (deg)	Longitude (deg)	Laitude (rad)	Longitude (rad)	a	b	Range (ft)
49	entire test	PZC-26	155.0	56.23	44.906826963	-66.983380741	0.78377198712	-1.16908053804	5.17534E-12	4.54987E-06	60
50	entire test	PZC-26	146.3	20.65	44.906577339	-66.983042049	0.78376763037	-1.16907462676	1.48762E-12	2.43936E-06	51
51	entire test	PZC-26	143.5	14.96	44.906417989	-66.982878858	0.78376484918	-1.16907177855	7.11361E-12	5.33427E-06	112
52A	75	PZC-26	141.9	12.45	44.906717384	-66.982765171	0.78377007462	-1.16906979432	9.88254E-12	6.2873E-06	131
52B	75	PZC-26	146.6	21.38	44.906677061	-66.983027861	0.78376937084	-1.16907437914	2.32866E-12	3.05199E-06	64
53A	75	PZC-26	138.4	8.32	44.906816254	-66.982582986	0.78377180022	-1.16906661459	2.04626E-11	9.04712E-06	189
53B	75	PZC-26	144.5	16.79	44.906738898	-66.982883950	0.78377045010	-1.16907186741	6.58622E-12	5.13273E-06	107
54	entire test	PZC-26	139.3	9.23	44.906617022	-66.981990380	0.78376832296	-1.16905627167	5.96266E-11	1.54437E-05	323
55	entire test	PZC-26	128.7	2.72	44.906014054	-66.982063857	0.78375779919	-1.16905755408	7.76981E-11	1.76293E-05	369
56	entire test	PZC-26	133.5	4.73	44.906348056	-66.981253038	0.78376362863	-1.16904340263	1.5499E-10	2.4899E-05	520
57	entire test	PZC-26	137.0	7.08	44.906479139	-66.980838312	0.78376591645	-1.16903616429	2.21037E-10	2.97346E-05	622
58	entire test	PZC-26	142.5	13.34	44.907203534	-66.980736433	0.78377855954	-1.16903438617	2.68246E-10	3.27564E-05	685
59	entire test	PZC-26	136.6	6.76	44.906972613	-66.979941283	0.78377452920	-1.16902050818	4.26787E-10	4.13177E-05	864
60A	60	PZC-26	130.1	3.20	44.906902370	-66.979186339	0.78377330323	-1.16900733191	6.35013E-10	5.03989E-05	1054
60B	60	PZC-26	128.3	2.60	44.906957602	-66.978431671	0.78377426720	-1.16899416048	8.93327E-10	5.97771E-05	1250
61	entire test	PZC-26	123.8	1.55	44.907301595	-66.977508917	0.78378027102	-1.16897805538	1.29322E-09	7.19228E-05	1503
62	entire test	PZC-26	125.4	1.86	44.907410227	-66.977201281	0.78378216700	-1.16897268613	1.44425E-09	7.60065E-05	1589
63	entire test	PZC-26	121.2	1.15	44.908035688	-66.979387930	0.78379308335	-1.16901085034	7.26492E-10	5.3907E-05	1127
64	entire test	PZC-26	115.5	0.60	44.908088689	-66.979324396	0.78379400840	-1.16900974148	7.57252E-10	5.50364E-05	1150

Figure 13 – PZC-26 Driving Data

Column "a" and "b" show a two-step computation of the distance between the geodetic coordinates of the pile location and measurement location via the Haversine formula:

$$a = \sin\left(\frac{\text{lat2} - \text{lat1}}{2}\right)^2 + \cos(\text{lat1}) * \cos(\text{lat2}) * \sin\left(\frac{\text{lon2} - \text{lon1}}{2}\right)^2$$

$$b = 2 * \arctan\left(\frac{\sqrt{a}}{\sqrt{1-a}}\right)$$

$$Range = b\ x\ mean\ earth\ radius\ (20,902,000ft)$$

University of New Hampshire
Department Of Civil Engineering

Eastport Breakwater and Pier Replacement Project

Pipe Pile and Spin-Fin Pile Driving Hydroacoustic Isopleth Report
PileCo D30-32 Diesel Hammer

James Browne, EIT

4/4/2016

Contents

Summary

The main pier and breakwater serving commercial and government vessels in the town of Eastport, ME partially collapsed on December 12, 2014 due to failure of a sheet pile earth retaining wall. The existing breakwater is an 'L' shaped facility consisting of retained earth fill with a pile supported concrete deck on the outboard side. Originally constructed in 1962, this facility is a vital transportation resource for the region, and CPM Constructors of Freeport, ME is currently replacing the existing structure. This work requires the driving of sheet pile and pipe piles with impact and vibratory hammers.

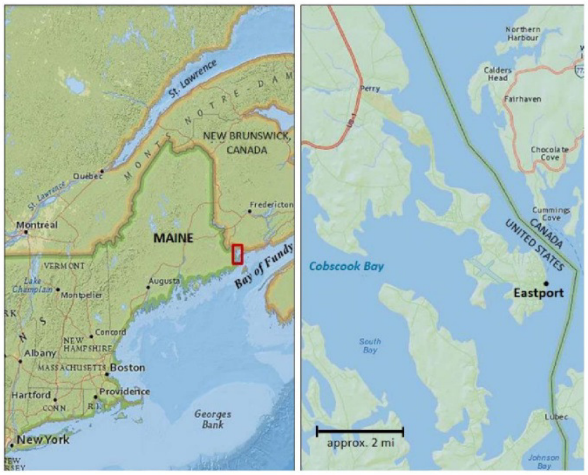


Figure 1 - Project Location

Eastport is the easternmost point of the continental United States and located on Cobscook Bay near the mouth of the St. Croix River, a marine region with significant natural resources. NOAA National Marine Fisheries identified potential underwater sound hazards to pinnipeds (seals) and cetaceans (porpoises, dolphins, and whales) that may result from pile driving activity on this project. In addition to underwater sound monitoring during pile driving work, NOAA identified levels of ensonification for various construction tasks that may result in harm or harassment to marine life. Based on published data, NOAA developed zones of anticipated sound pressures for impact pile driving, vibratory pile driving, underwater sawing, and down-hole hammer drilling equipment. CPM is required to monitor these zones for the intrusion of various wildlife and must stop work until the zone is clear.

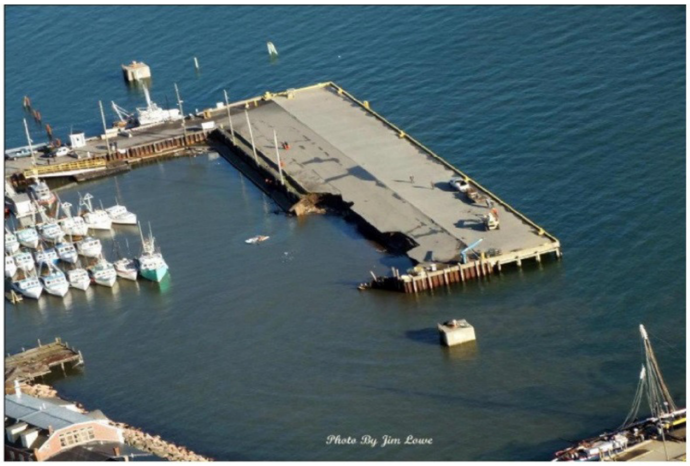


Figure 2 - Existing Breakwater After Collapse

To reduce the schedule impact of wildlife intrusion, NOAA allows these zones to be reduced in size based on actual hydroacoustic data on the specific equipment in use. Based on measurements at various distances, isopleths are developed showing regions of uniform maximum sound pressure.

The University of New Hampshire was approached to develop these isopleth maps with broad-spectrum hydrophone data acquisition equipment.

This report presents data acquired November 16th-17th, 2015 and December 14th-16th, 2015 on the use of a Pileco D30-32 diesel impact hammer driving vertical 20” diameter pipe piles and battered 20” diameter Spin-Fin piles.

Requirements

NOAA permit requirements set the following limits on RMS SPL for marine mammal protection on this project. The RMS SPL for impact hammer strikes is to be computed using the 90% energy window analysis, where the RMS SPL is calculated using the portion of the signal that contains 90% of the total energy of each strike. The limits on this RMS SPL are set forth in Table 1 of Section 105 of the project Special Provisions.

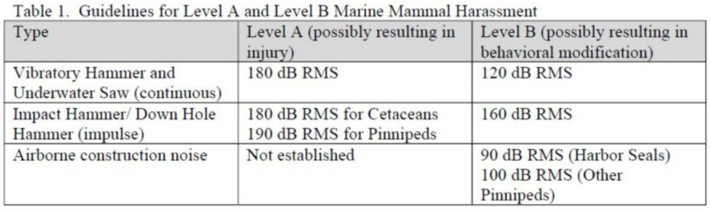


Table 1. Guidelines for Level A and Level B Marine Mammal Harassment

Type	Level A (possibly resulting in injury)	Level B (possibly resulting in behavioral modification)
Vibratory Hammer and Underwater Saw (continuous)	180 dB RMS	120 dB RMS
Impact Hammer/ Down Hole Hammer (impulse)	180 dB RMS for Cetaceans 190 dB RMS for Pinnipeds	160 dB RMS
Airborne construction noise	Not established	90 dB RMS (Harbor Seals) 100 dB RMS (Other Pinnipeds)

Based on existing sound data, NOAA indicated the following preliminary zones where marine mammal monitoring and exclusion were required during the indicated construction activities.

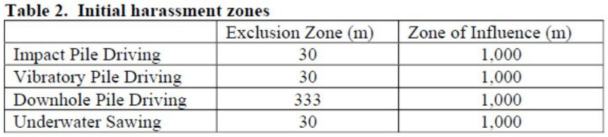


Table 2. Initial harassment zones

	Exclusion Zone (m)	Zone of Influence (m)
Impact Pile Driving	30	1,000
Vibratory Pile Driving	30	1,000
Downhole Pile Driving	333	1,000
Underwater Sawing	30	1,000

UNH’s work on this project involves the measurement of the *in-situ* SPL produced by these work activities using the contractor’s specific equipment and methods. Based on the results in this report, the proposed zones may be modified.

Pile Driving Operations and Equipment

UNH performed field measurements while CPM was driving pipe piles on the first and second bents (Bent 1 and Bent 2) of a new section of elevated pier that will expand the existing pier and breakwater further east.

This section of pier consists of precast concrete deck panels and precast pile caps supported on 29’ centers by bents of four PP20x0.625 ASTM A252 Grade 3 Modified pipe piles. These vertical piles are driven to ultimate capacities ranging from 278 kips (Row E) to 612 kips (Row G). Berthing load resistance and east/west stability are provided by pairs of PP20x0.625 Spin-Fin piles at each bent on a 1:4 batter. These piles are driven to a minimum ultimate compression capacity of 439 kips.

The depth of water in the area around Bent 1 and Bent 2 is approximately 50’ with a tidal change of roughly 20’. Top of bedrock, where all piles reached capacity, is located at an approximate depth of 100’ below MSL. All pipe piles observed were driven open-ended and PDA dynamic load tests were conducted on all piles monitored in this report.

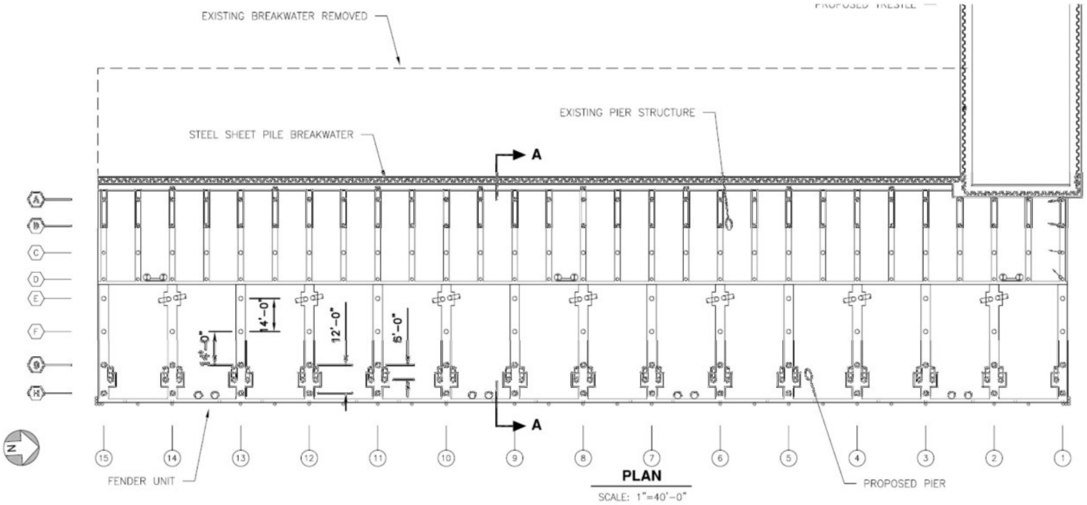


Figure 3 - Proposed Pier Plan

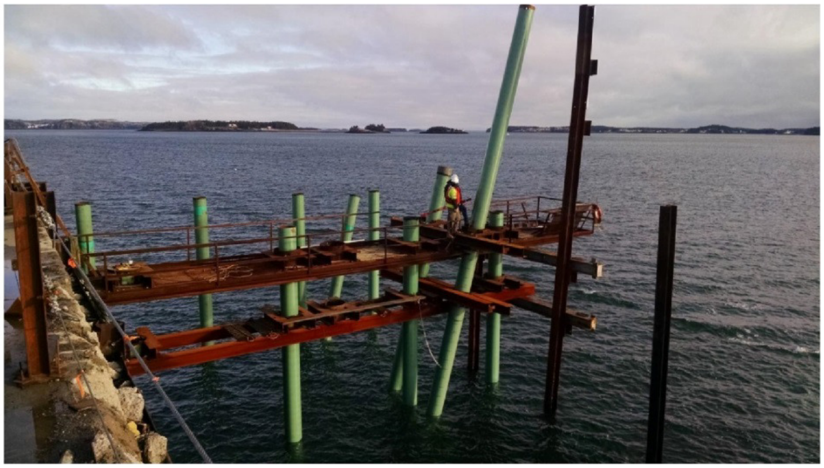


Figure 4 - Bent 2 Template Showing Pile Arrangement and Battered Spin-Fin Piles

All pipe piles were driven with a Pileco D30-32 diesel impact pile hammer. This hammer has a ram weight of 6,615 lbs and delivers a maximum energy per strike of 69,923 ft-lbs at a maximum stroke of 10.5 ft at the maximum of four fuel settings. The hammer was operated on the 3rd fuel setting for all piles except row E piles where it is set to fuel setting 2. This hammer was handled by an American model HC-110 crawler crane.

Piles were initially driven 15'-25' with a vibratory hammer. Impact driving started with a hammer stroke of roughly 6' increasing 9'-10 'at the end of driving. Piles on Row E are driven to a blow count of 3 blows per inch and all other vertical piles are driven to 9 blows per inch. The battered Spin-Fin piles are driven to 7 blows per inch.

Figure 5 – Pileco D30-32 Hammer In Use on Bent 1

Hydrophone Data Acquisition And Analysis

All measurements were made from a small boat at various locations throughout Eastport harbor. The outboard motor was shut off during all recordings.

UNH performed the SPL measurements using a Reson TC-4013 omnidirectional hydrophone located at a depth of 15 – 25 feet. The hydrophone used on this project has a receiving sensitivity of -212 dB re 1uV/Pa or 28.2 microvolts per Pascal. This hydrophone has a linear frequency response from 5Hz – 100kHz. The signal was amplified by a Reson VP1000 voltage preamplifier set to provide a high-pass filter at 20Hz.

The voltage signal was converted to digital information by a National Instruments 24-bit USB-9334 Multifunction DAQ at a sample rate of 20KHz. The acquired data was displayed and recorded by a National Instruments LabVIEW application built specifically for this project. GPS data was acquired simultaneous with the sound data via a Garmin GPS 18x receiver at a rate of 1Hz and the position data was recorded directly into the sound data file to preserve synchronization.

A GRAS 42AC pistonphone calibration unit was used to periodically check the accuracy of the hydrophone data acquisition system. A pistonphone uses a series of precision cam-driven pistons to produce a displacement of air in a confined space. This produces a sound signal of known intensity. Due to the slight variations of seating depth and force in inserting the hydrophone into the pistonphone coupling adapter, manufacturers advise that a pistonphone reading should only be considered accurate to within 2-3dB. The 42AC produces 164dB at 250Hz. The hydrophone system used on this project was always within 2dB during all calibration checks.

Hydrophones produce a voltage signal that varies linearly with the applied sound pressure. After being converted from an analog signal to a digital signal and stored by LabVIEW, the signals must be processed to convert the voltage values first to instantaneous sound pressure in Pascals and then to SPL relative to a reference pressure.

Sound energy is typically reported as metric called Sound Pressure Level (SPL). SPL has the units of decibels which is 1/10th of the SI Bel. A Bel is defined as a logarithmic ratio between a measured energy or power level and reference:

$$L_P = \frac{1}{2}\ln\left(\frac{P}{P_0}\right)\ \mathrm{Np} = 10\log_{10}\left(\frac{P}{P_0}\right)\ \mathrm{dB}.$$

A measurement reported in decibels that equals the reference value is 0dB. Measurements below the reference value will produce negative decibel values. Any energy or power measurement reported in decibels is considered a “power quantity” measurement and a tenfold increase in decibels represents an order of magnitude increase in the measurement energy. Therefore, 10dB is a tenfold increase in sonic energy and every 3dB increase in sonic energy is a doubling of that energy.

Sound energy generally cannot be measured directly; instead, sound pressure is measured with hydrophones and relates to sound energy by the square of the pressure signal amplitude. Because SPL is calculated from sound pressure measurements, the measurement value and the reference value are squared in the original decibel equation. When reduced, this yields the following familiar equation for SPL in decibels computed from pressure amplitude.

$$L_F = \ln\left(\frac{F}{F_0}\right)\ \mathrm{Np} = 10\log_{10}\left(\frac{F^2}{F_0^2}\right)\ \mathrm{dB} = 20\log_{10}\left(\frac{F}{F_0}\right)\ \mathrm{dB}.$$

Decibel values computed from signal amplitude data such as voltage or pressure are known as “field quantity” measurements. SPL computed from sound pressure is a field quantity; therefore, every 20dB increase in SPL is a tenfold increase in sound pressure and every 6dB is a doubling of sound pressure. The squaring of the measured and reference pressures produces the factor of two difference between power and field quantities expressed in dB.

In air, the reference pressure of 20 uPa, commonly taken as the threshold of human hearing, is set as 0 dB and is comparable to the sound of a mosquito flying 10 feet away. In the study of underwater acoustics, it was found that 20 uPa was too large of a reference value and commonly produced negative dB values when working in the extreme quiet of deep water. As a result, the standard reference pressure was changed to 1 uPa for hydroacoustic measurements. All dB measurements in this report are provided with respect to this reference pressure.

For broadband noise measurements, SPL is computed from the RMS sound pressure signal. For sinusoidal signals, the RMS energy of a signal is equal to the amplitude of the pressure signal divided by root 2. In the area of noise monitoring and compliance testing, all SPL values should be assumed to be RMS SPL.

For marine mammal protection, focus is placed on the RMS sound pressure that a marine mammal might be exposed to. This is a different approach than that used to protect fish from injury due to sonic overpressure (barotrauma) or physical harm from accumulated sonic energy. The primary concern for the protection of mammals is preventing hearing loss or shifts in hearing sensitivity.

For impact hammer strikes, the RMS sound pressure is computed for the portion of the strike between the time when 5% of the total final energy has been created and the time when 95% of the energy has been created. This is the central 90% of the total energy of the strike. The following three plots show the relationship between the pressure trace from a typical pile strike, the 90% energy window relative to the original pressure trace, and the 90% energy window relative to the strike accumulated energy.

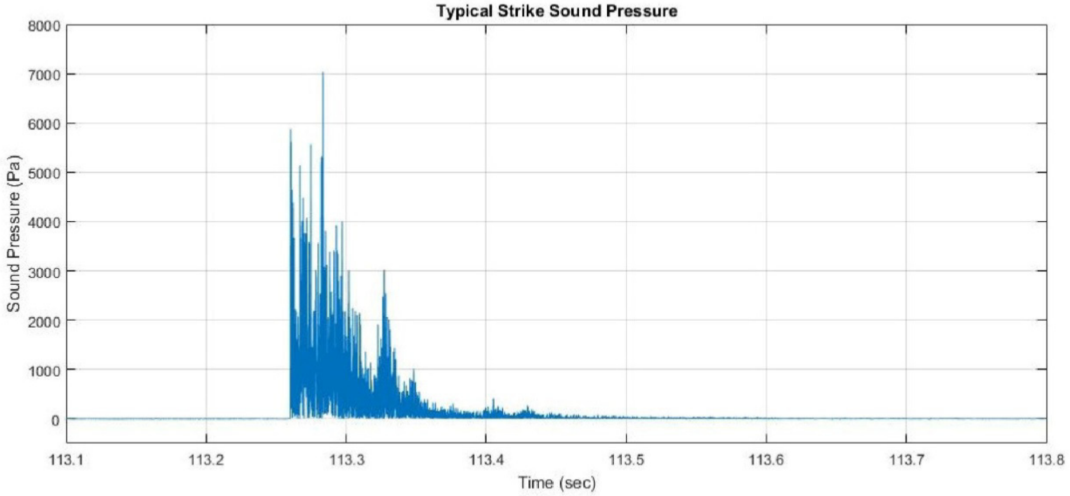


Figure 6 - Pressure Trace of Typical Strike

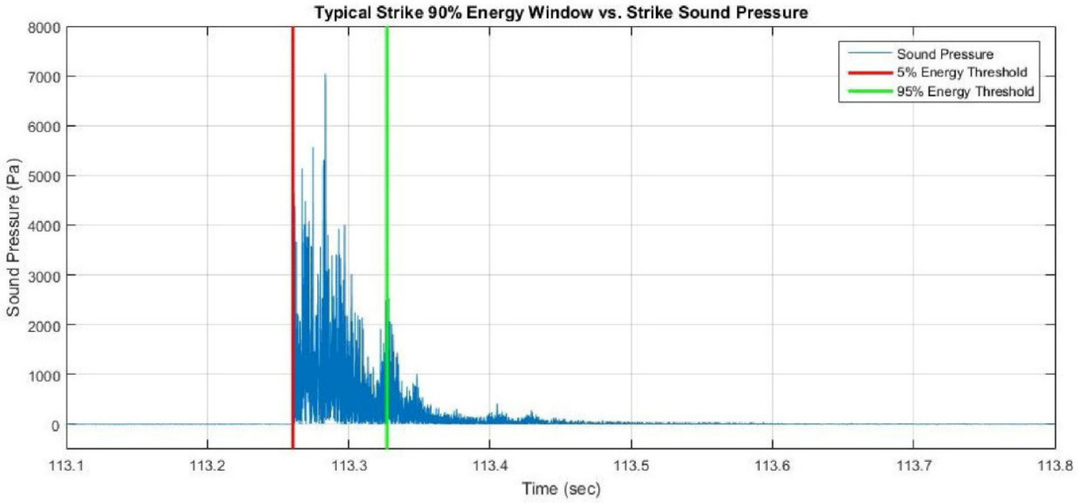


Figure 7 - Relationship Between 90% Energy Window and Pressure Trace

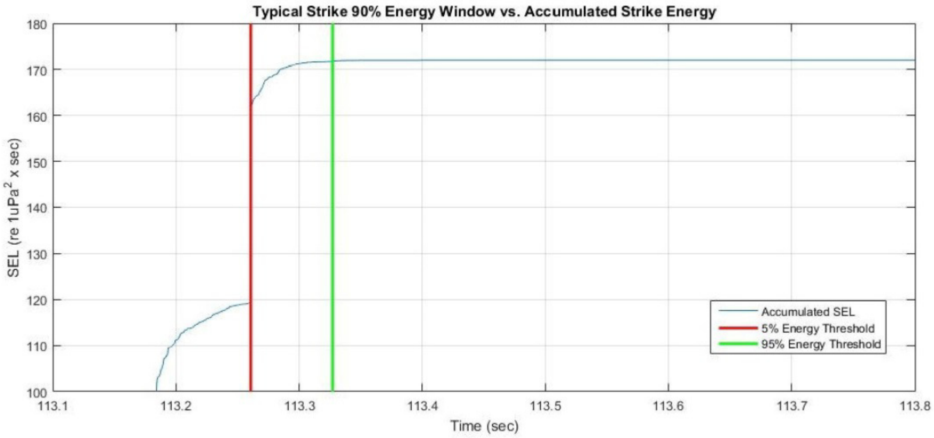


Figure 8 - Relationship Between 90% Energy Window and Accumulated Strike Energy

Results

The following plots show the RMS SPL trace for all piles observed by UNH and the 90% energy window RMS SPL computed for each strike. The mean 90% energy window RMS SPL is shown on each plot. Each test was performed with the hydrophone located in a quasi-static position. A map of the measurement locations is shown below.

Figure 9 - Map of Measurement Locations

The following shows a plot of the typical highest observed ambient SPL in the vicinity of the pier. Ambient SPL tends to vary between 110dB close to shore at slack tide to roughly 140dB in open water when the tide is at its maximum velocity.

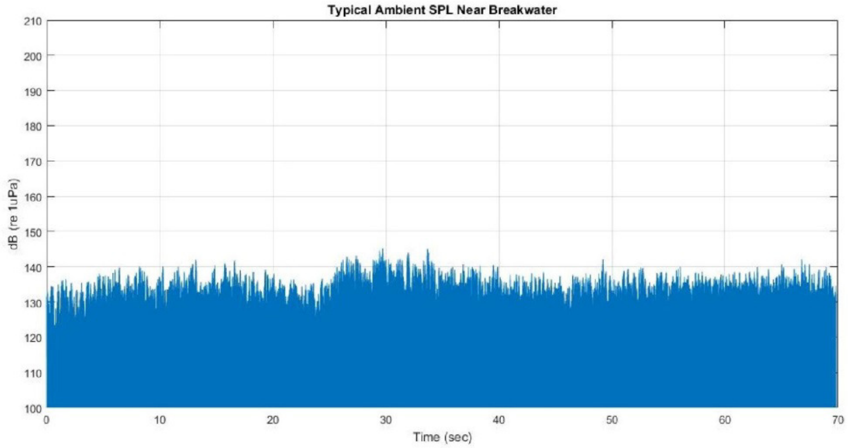


Figure 10 - Typical Ambient Conditions

The first pile driving recording on Bent 1, Pile E was done with the hydrophone located at 33' (10m) from the pile and shows the entire driving cycle.

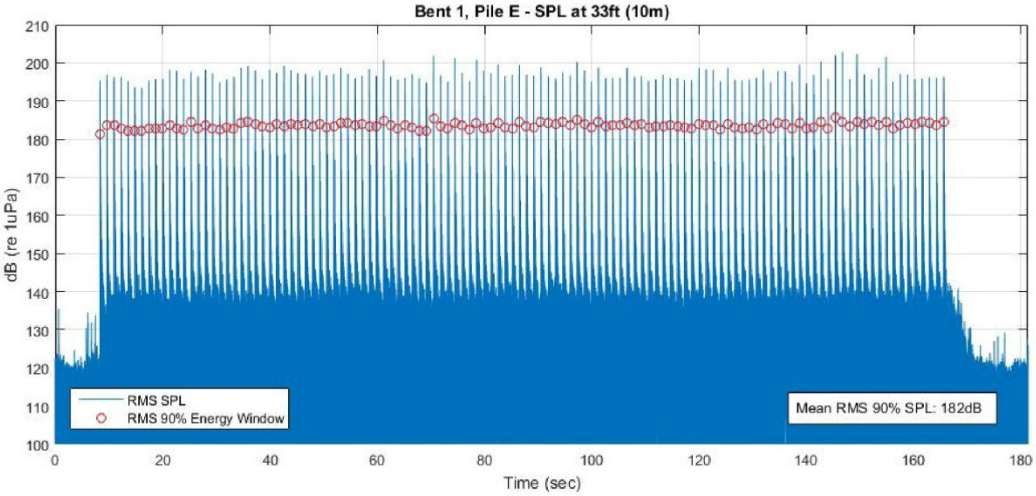


Figure 11 - Pile 1E SPL and RMS 90% Energy Window

The following plot shows two periods of driving on Bent 1, Pile F at a mean distance of 300' (90m) from the pile.

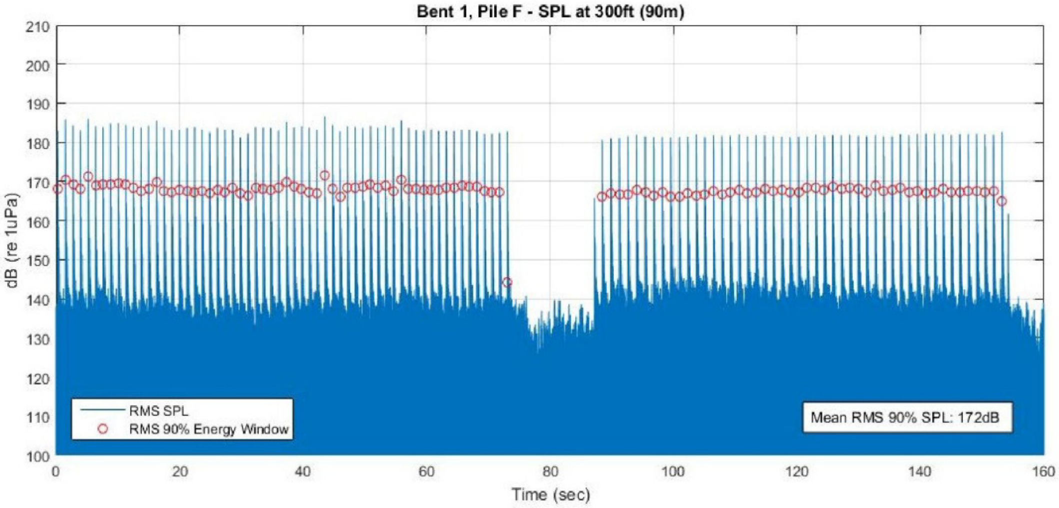


Figure 12 - Pile 1F SPL and RMS 90% Energy Window

The following plot shows a re-strike on Pile G at 10m (33') from the pile.

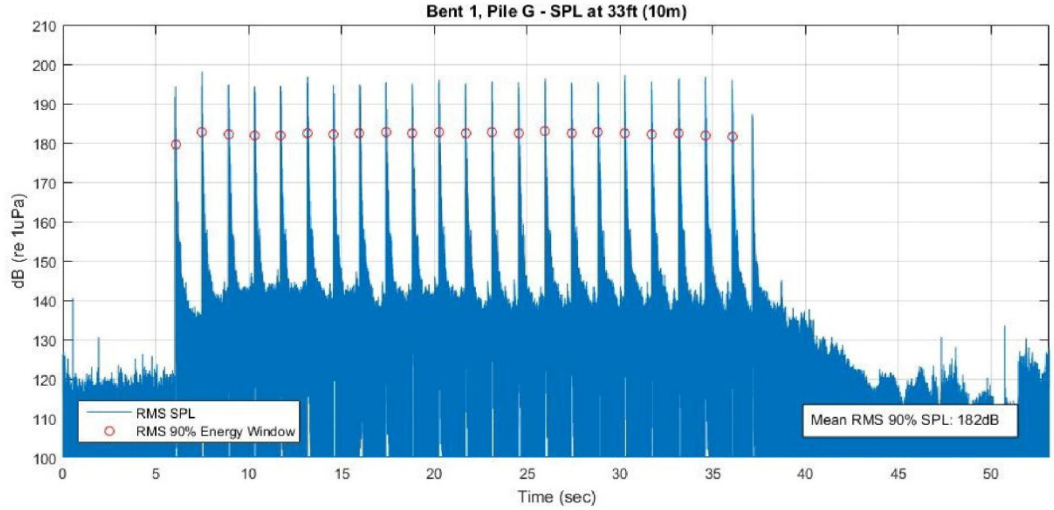


Figure 13 - Pile 1G SPL and RMS 90% Energy Window

The following plots show recordings of the driving of Pile H at various distances.

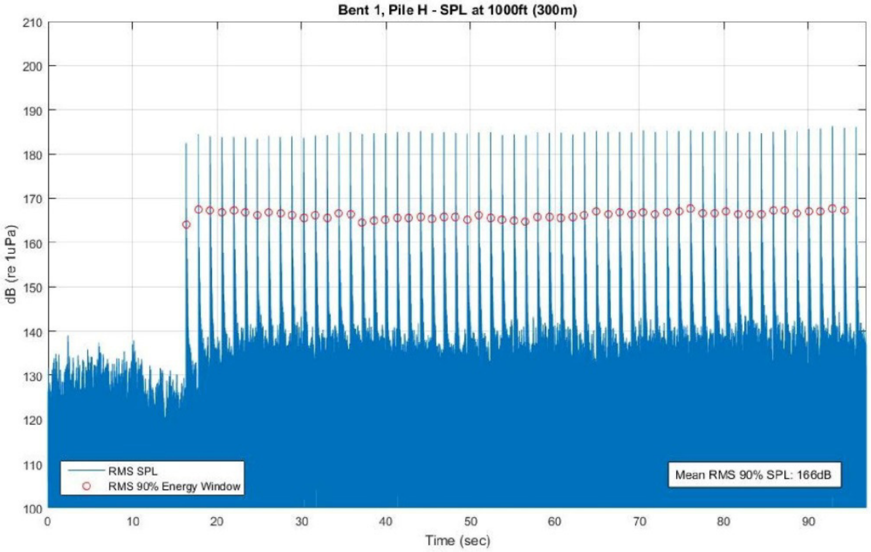


Figure 14 - Pile 1H SPL and RMS 90% Energy Window

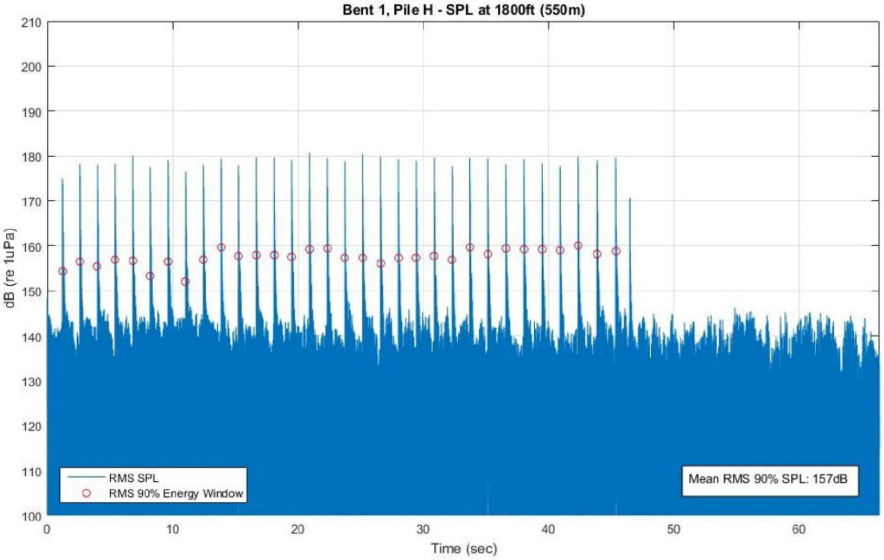


Figure 15 - Pile 1H SPL and RMS 90% Energy Window

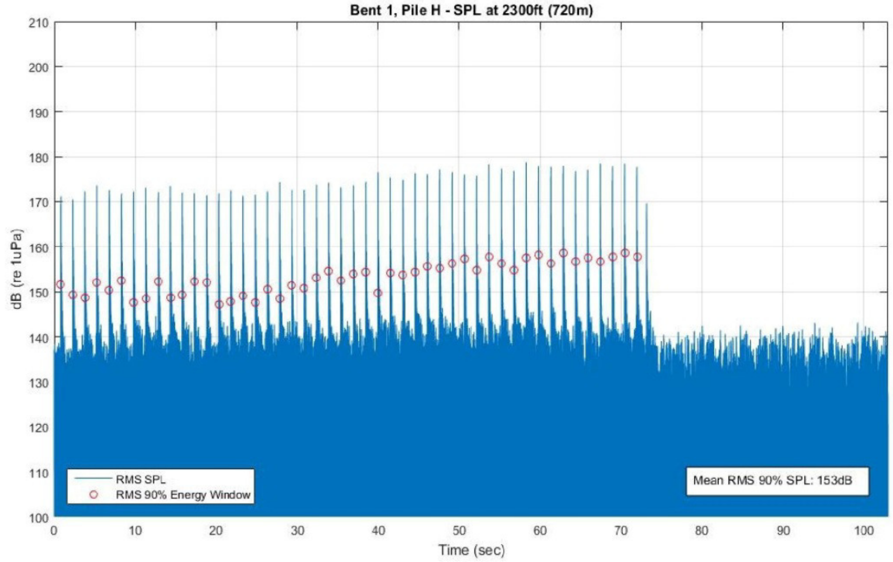


Figure 16 - Pile 1H SPL and RMS 90% Energy Window

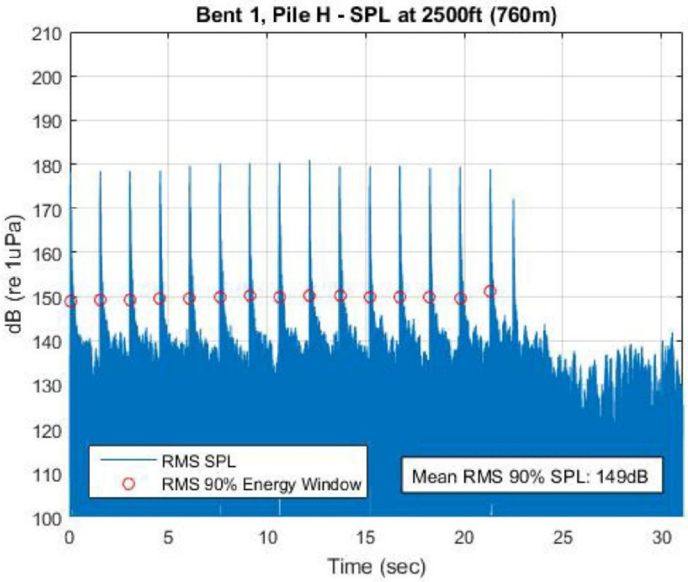


Figure 17 - Pile 1H SPL and RMS 90% Energy Window

The following plots show recordings made on the driving of the two Spin-Fin battered piles on Bent 2.

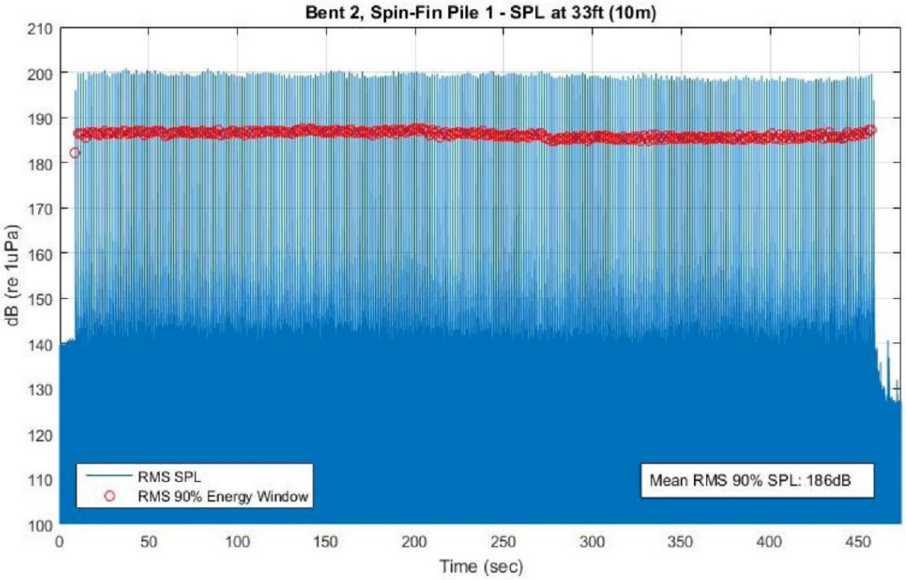


Figure 18 - Spin-Fin No. 1, Bent 2 SPL and RMS 90% Energy Window

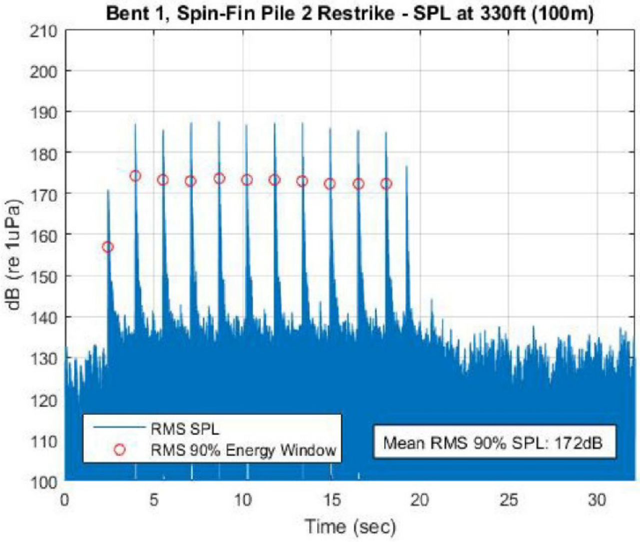


Figure 19 - Spin-Fin No. 2, Bent 2 SPL and RMS 90% Energy Window

The results of the above mean 90% RMS strike intensities were plotted by their average distance from the pile and the following regression gives an equation that closely approximates the attenuation and dispersion of pile driving sound pressure in the area around the Eastport pier. While equations exist that predict the "free field" attenuation of sound into an infinite body of a given material, local site conditions, such as the location, depth, and shape of the mudline will produce attenuation results that are unique to the site being observed.

Note that the regression is performed on the actual sound pressure, not the decibel values themselves. Because the transformation from pressure to decibels is non-linear, any regression or arithmetic must be performed on the original pressure data.

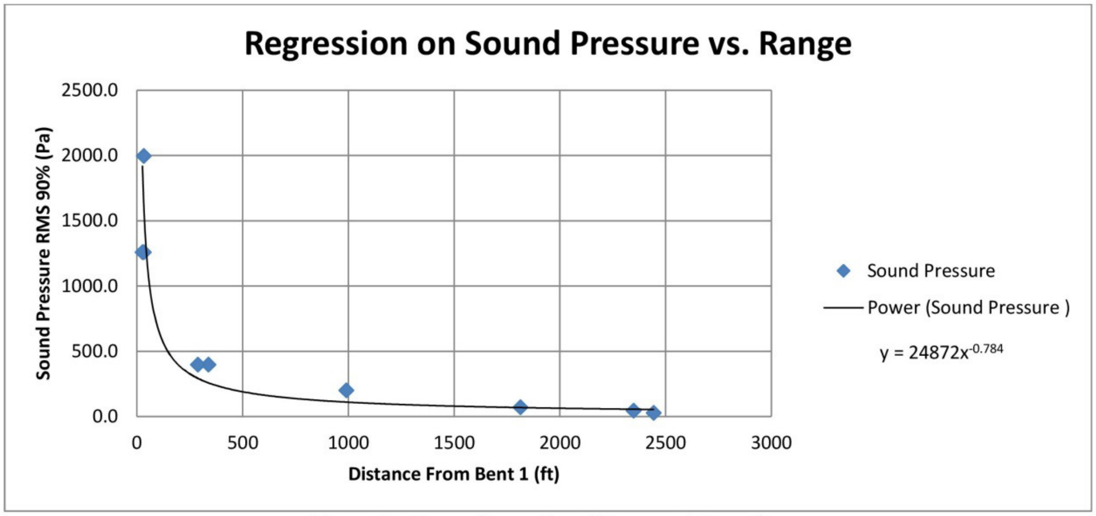


Figure 20 - Regression on Sound Pressure Attenuation

Based on the regression equation, it is possible to calculate the location of the 190dB, 180dB, and 160dB isopleths to establish the Level A and Level B harassment zones per the measured data.

UNH recommends the following locations for the revised zones. The Level A Exclusion Zone for Pinnipeds where RMS 90% SPL exceeds 190dB is 16 feet (5m). The Level A Exclusion Zone for Cetaceans where RMS 90% SPL exceeds 180dB is 66 feet (20m). Finally, the Level B Zone of Influence (ZOI) for all marine mammals where RMS 90% SPL drops below 160dB is 1,150 feet (350m).