WSF VASHON TEST PILE PROJECT

Underwater Sound Level Report: Vashon Test Pile Project 2016

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ACRONYMS AND ABBREVIATIONS

dB	decibel
Hz	hertz
NIST	National Institute of Standards and Technology
Pa	Pascal
RMS	root mean squared
s.d.	standard deviation
SEL	Sound Exposure Level
SPL	sound pressure level
WSF	Washington State Ferries
WSDOT	Washington State Department of Transportation

EXECUTIVE SUMMARY

This technical report describes the data collected during impact pile driving for the Washington State Ferries (WSF) Vashon Terminal – Test Pile Project during December 7 and 8, 2015. Hydroacoustic data was collected for a total of three piles: one 30-inch traditional steel control pile, one double walled steel test pile, and one mandrel steel test pile. All three of the piles monitored were located on the east side of the existing Vashon Ferry Terminal located in the Puget Sound. A bubble curtain was not deployed for impact driving of the control pile because the template used to drive the piles interfered with deployment of the bubble curtain. All measurements were collected at 20 meters from the pile at midwater depth. Measurements from 3H, where H is the water depth at the pile were not needed because 3H locations happened to be about the same distance as the 20 meter location. Table 1 summarizes the results for each pile monitored.

Both the double walled pile and the mandrel pile achieved some sound attenuation when compared to the control pile. The double walled pile achieved a reduction of 12 dB_{peak}, 10 $dB_{RMS90\%}$, and 9 $dB_{SEL90\%}$ compared to the control pile. The mandrel pile achieved a reduction of 12 dB_{peak}, 11 $dB_{RMS90\%}$, and 11 $dB_{SEL90\%}$ compared to the control pile.

Table 1: Summary of Control and Test Piles Underwater Sound Levels.

Pile #	Date	Pile Size (inches)	Pile Type	Peak at 20 meters (dB)	RMS (dB)	Single Strike SEL (dB)	Cumulative SEL (dB)	L_{50} Peak (dB)	L_{50} RMS (dB)	L_{50} $SEL_{90\%}$ (dB)	Total Number Of Strikes
1	12/7/15	30	Control	201	189	175	199	200	189	175	289
2	12/7/15	30	Double Wall	191	182	167	193	188	179	166	402
3	12/8/15	30	Mandrel	189	180	166	191	188	178	164	325

INTRODUCTION

This technical report presents results of underwater sound levels measured during the driving of one 30-inch traditional steel control pile, one 30-inch steel double walled test pile, and one 30-inch steel mandrel test pile at the Vashon Test Pile Project in December 2016.

The three piles were monitored at a constant water depth of 22 feet with the hydrophone placed at midwater depth (11 feet) and a range of 66 feet (20 meters). A bubble curtain was not used for any the control pile because the template used to drive the piles interfered with the deployment of the bubble curtain. Figure 1 shows the project area and Figure 2 shows the locations of monitored piles.

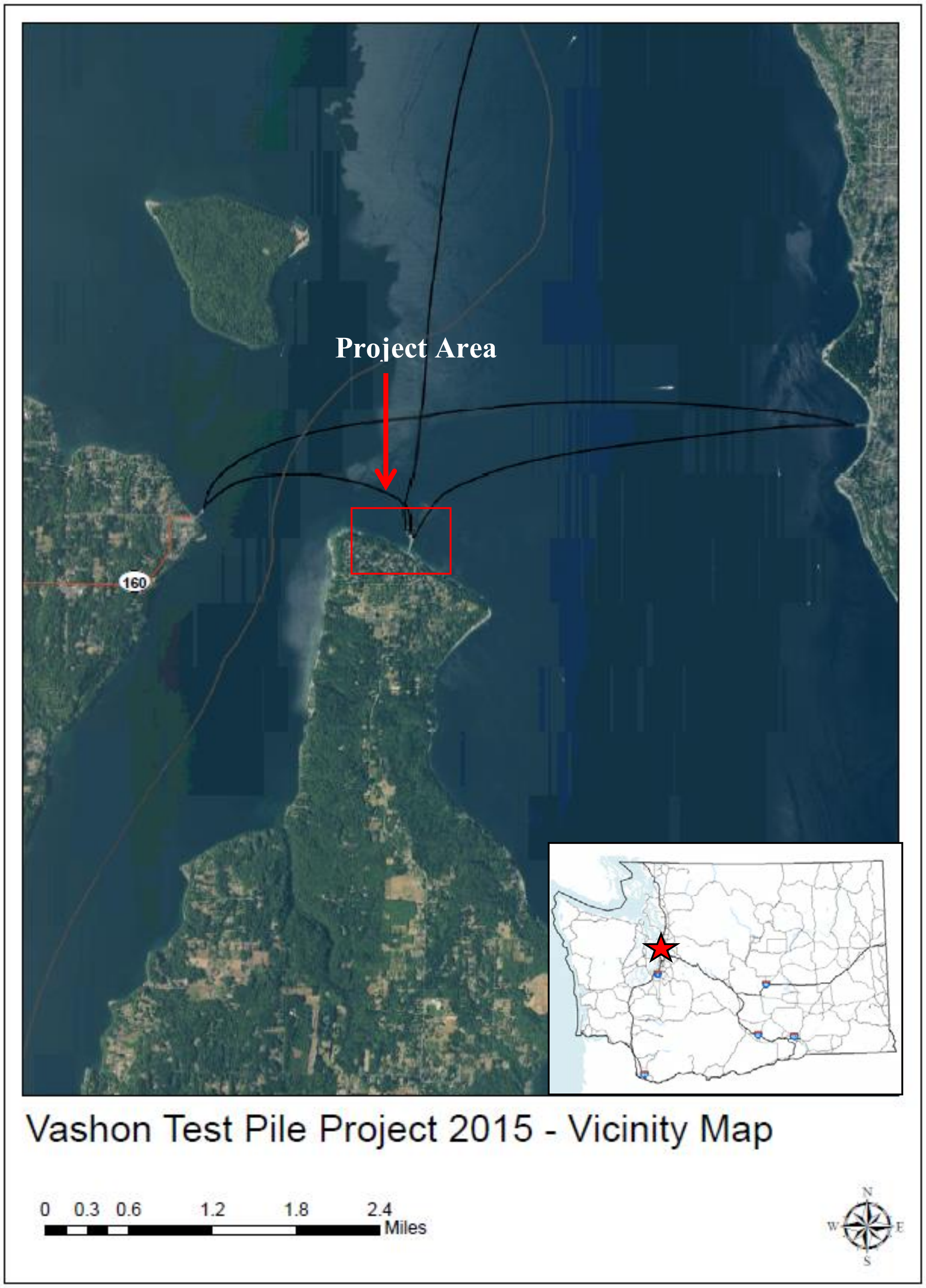
Project Description

The control and test piles were driven to determine if a new pile design for improved noise attenuation is feasible. The Test Pile Project addresses the potential for noise attenuation piles in ferry terminal design. The traditional steel single pile serves as the control pile with a steel doubled walled pile and steel mandrel pile serving as test piles to assess the impacts of alternative pile designs. The pile designs are discussed later in this report. The project location is east of the existing Vashon Ferry Terminal.

PROJECT AREA

The Vashon Island Ferry Terminal is located on the northern end of Vashon Island in King County, Washington. The terminal is located within Sections 6, Township 23 North, Range 3 East (USGS 1981).

Figure 1: Vashon Test Pile Project Area



PILE INSTALLATION LOCATION

A total of three piles were installed on the east side of the Vashon ferry dock were monitored. Figure 2 indicates the approximate location of the three 30-inch piles.

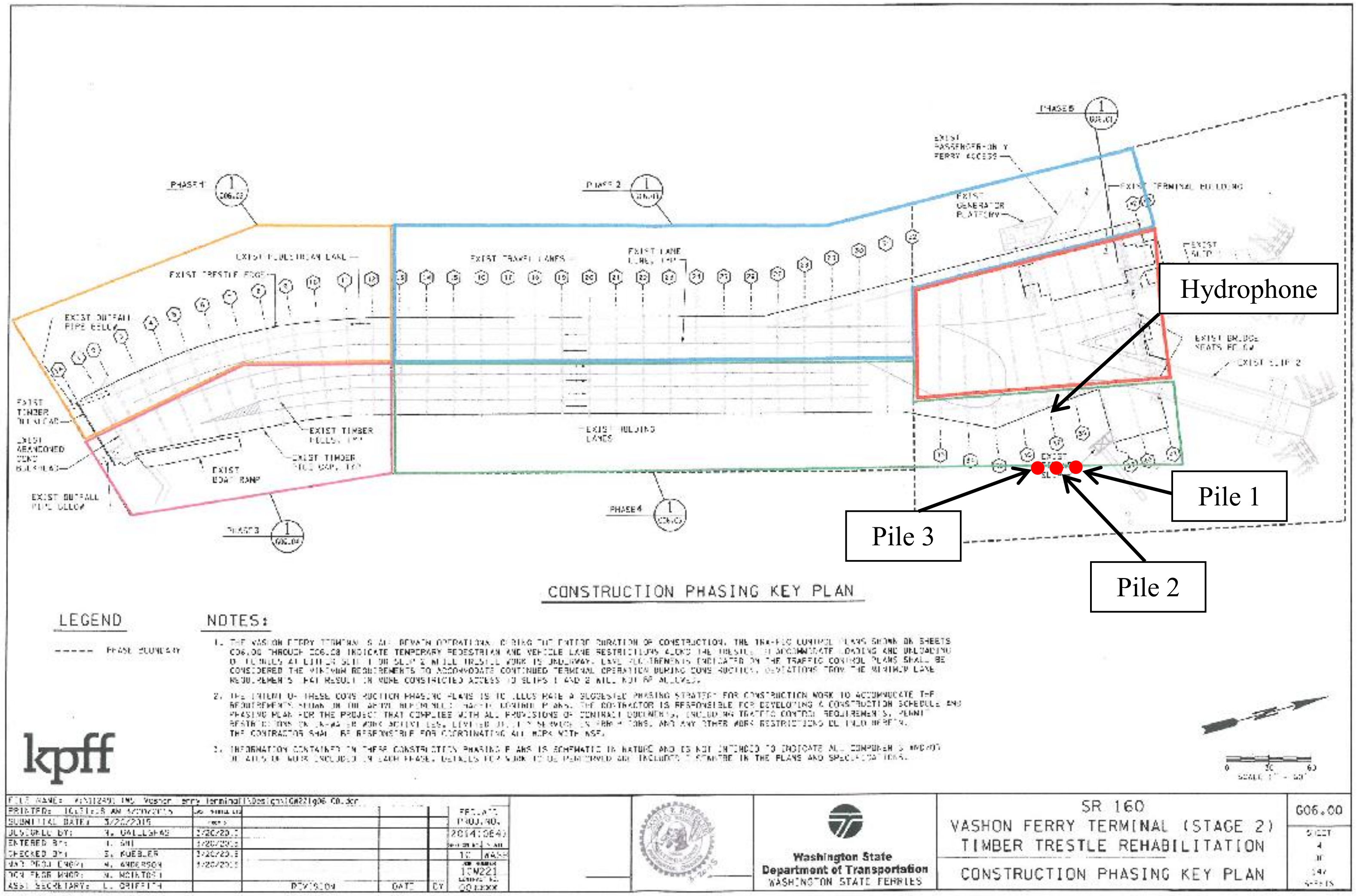
The hydrophone is located at 20 meters from the piles. Monitoring at a range of 3H, where H is the water depth of the pile, was not necessary because the distance 3H was 20 meters or less.

Hydroacoustic monitoring of steel pile driving included:

- Measurement of noise levels at 20 meters from the pile.

Figure 3 indicates the location of the piles monitored. The hydrophones were placed at least 1 m (3.3 feet) below the surface at a range of 20 meters and midwater depth. Each pile has a clear acoustic line-of-sight between the pile and the hydrophone.

Figure 2: The locations of the three monitored piles at the Vashon Ferry Terminal



UNDERWATER SOUND LEVELS

Characteristics of Underwater Sound

Several descriptors are used to describe underwater noise impacts. Two common descriptors are the instantaneous peak sound pressure level (SPL) and the Root Mean Square (RMS) pressure level during the impulse. The peak SPL is the instantaneous maximum or minimum overpressure observed during each pulse and can be presented in Pascals (Pa) or decibels (dB) referenced to a pressure of 1 micropascal (μPa). Since water and air are two distinctly different media, a different sound level reference pressure is used for each. In water, the most commonly used reference pressure is 1 μPa whereas the reference pressure for air is 20 μPa. The majority of literature uses peak sound pressures to evaluate barotrauma injury to fish. Except where otherwise noted, sound levels reported in this report are expressed in dB re: 1 μPa. The equation to calculate the sound pressure level is:

Sound Pressure Level (SPL) = 20 log (p/p_{ref}), where p_{ref} is the reference pressure (i.e., 1 μPa for water)

The RMS level is the square root of the energy divided by the impulse duration. This level, presented in dB re: 1 μPa, is the mean square pressure level of the pulse. It has been used by the National Marine Fisheries Service (NMFS) in criteria for judging effects to marine mammals from underwater impulse-type sounds.

The L_{50} or 50^{th} percentile is a statistical measure of the median value over the measurement period where 50 percent of the measured values are above the L_{50} and 50 percent are below.

One-third octave band analysis offers a more convenient way to look at the composition of the sound and is an improvement over previous techniques. One-third octave bands are frequency bands whose upper limit in hertz is $2^{1/3}$ (1.26) times the lower limit. The width of a given band is 23% of its center frequency. For example, the 1/3-octave band centered at 100 Hz extends from 89 to 112 Hz, whereas the band centered at 1000 Hz extends from 890 to 1120 Hz. The 1/3-octave band level is calculated by integrating the spectral densities between the band frequency limits. Conversion to decibels is:

dB = 10*LOG (sum of squared pressures in the band) (eq. 1)

Sound levels are often presented for 1/3-octave bands because the effective filter bandwidth of mammalian hearing systems is roughly proportional to frequency and often about 1/3-octave. In other words, a mammal's perception of a sound at a given frequency will be strongly affected by other sounds within a 1/3-octave band around that frequency. The overall level (acoustically summing the pressure level at all frequencies) of a broadband (20 Hz to 20 kHz) sound exceeds the level in any single 1/3-octave band.

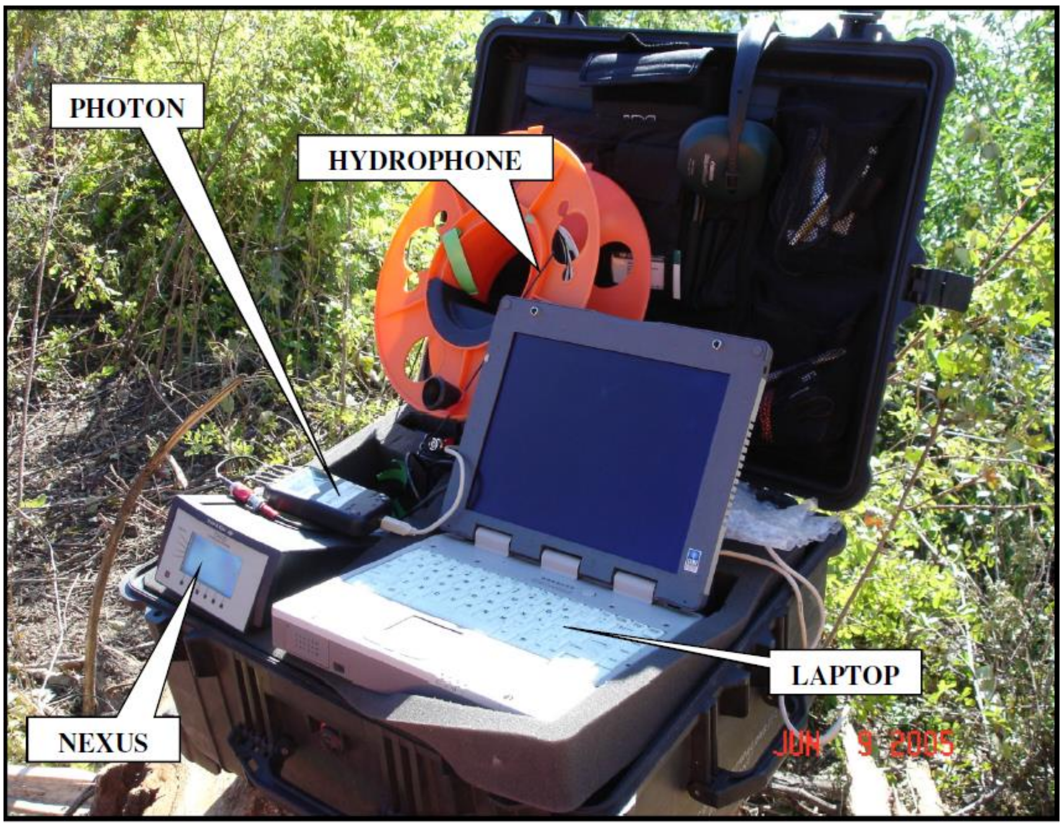
METHODOLOGY

Typical Equipment Deployment

The hydrophone was deployed from the Vashon trestle near the piles. The monitoring equipment is outlined below and shown in Figure 3. The hydrophone was stationed and fixed with an anchor and a surface float at a nominal distance of 20 meters from the pile.

A bubble curtain was not deployed for the control pile because the template in which the piles were driven interfered with the deployment of the bubble curtain.

Figure 3: Near Field Acoustical Monitoring Equipment



Underwater sound levels were measured near the piles using a Reson TC 4013 hydrophone deployed on a weighted nylon cord from the monitoring location. The hydrophone was positioned at a distance of 20 meters and at mid-water depth. The measurement system includes a Brüel and Kjær Nexus type 2692 4-channel signal conditioner, which kept the high underwater sound levels within the dynamic range of the signal analyzer, shown in Figure 3. The output of the Nexus signal conditioner is received by a Brüel and Kjær Photon 4-channel signal spectrum analyzer that is attached to a Dell ATG laptop computer similar to the one shown in Figure 3.

The equipment captures underwater sound levels from the pile driving operations in the format of an RTPro signal file for processing later. The WSDOT has the system and software calibration checked annually against NIST traceable standard.

Signal analysis software provided with the Photon was set at a sampling rate of one sample every 20.8 μs (18,750 Hz). This sampling rate provides sufficient resolution to catch the peaks and other relevant data. The anti-aliasing filter included in the Photon also allows the capture of the true peak.

Due to the variability between the absolute peaks for each pile impact strike, an average peak and RMS value is computed along with the standard deviation (s.d.) to give an indication of the amount of variation around the average for each pile. Additionally, the L50, which is a statistical measure of the median of all values for a given measurement period, was calculated for each pile and each of the Peak, RMS90% and SEL90% metrics.

The $RMS_{90\%}$ was calculated for each individual impact strike. Except where otherwise noted the $SEL_{90\%}$ was calculated for each individual impact strike using the following equation:

$$SEL_{90\%} = RMS_{90\%} + 10 \text{ LOG } (\tau) \qquad \text{(eq. 2)}$$

Where τ is the 90% time interval over which the $RMS_{90\%}$ value is calculated for each impact strike. Then the cumulative SEL (cSEL) is calculated by accumulating each of these values for each pile and each day.

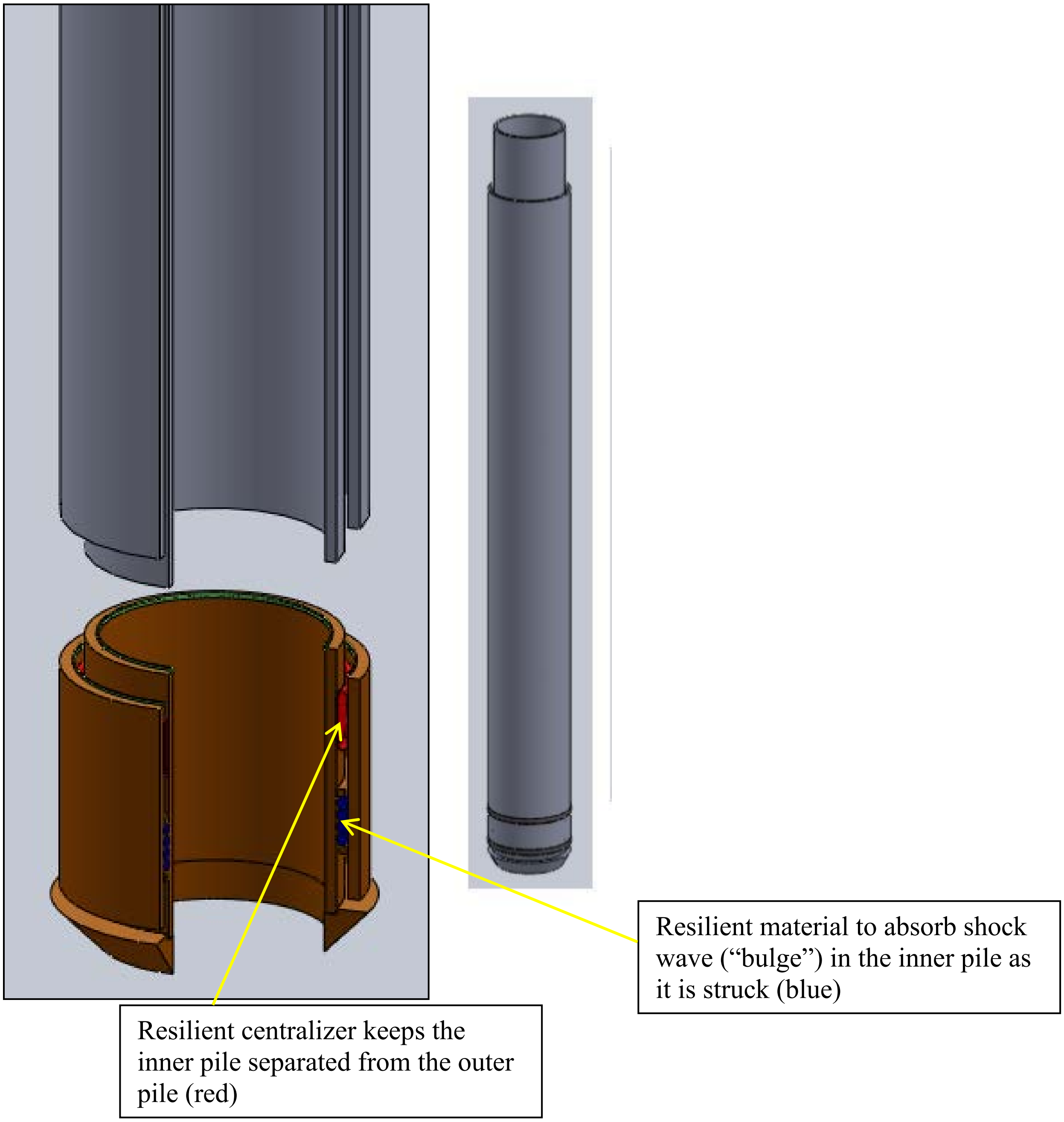
For those recordings where it was not possible to calculate the $SEL_{90\%}$ for each pile strike the cumulative SEL was calculated using the following equation.

$$cSEL = SEL_{90\%} + 10 \text{ LOG (total number of pile strikes)} \qquad \text{(eq. 3)}$$

Test Pile Design

Two test piles were tested as a part of this test pile project. The first pile tested is a double walled steel pile, shown in Figure 4. The double walled pile functions by creating an air space between the inner and outer piles and the inner pile only makes contact at the driving shoe at the bottom of the outer pile while the inner pile is struck with the hammer. This isolation impedes the propagation of noise and works to attenuate the sound. The inner and outer pile remain attached once pile driving is completed. The inner pile or the space between the inner and outer pile can then be filled with concrete. The second test pile is a mandrel pile, which is very similar to the double wall pile shown in Figure 4. Mandrel piles function similarly as double walled piles, except that the inner pile can be removed after being driven and reused on another mandrel pile. The inner pile only makes contact with the driving shoe during impact driving and is acoustically isolated from the outer pile.

Figure 4: Double Walled Test Pile



RESULTS

Underwater Sound Levels

WSDOT monitored a total of three 30-inch steel piles for underwater noise, one traditional control steel pile, one steel double walled test pile, and one steel mandrel test pile. Data from all piles are analyzed in the paragraphs below and summarized in Table 2.

Pile 1

Pile 1 is located approximately 650 feet from the shore of Vashon Island (Figure 2). The pile was a traditional steel control pile and had an absolute peak value of 201 dB_{peak} at 20 meters, an $RMS_{90\%}$ of 189 $dB_{RMS90\%}$ and a $SEL_{90\%}$ of 177 $dB_{SEL90\%}$. The cumulative SEL (cSEL) for Pile 1 was 175 dB_{cSEL} calculated based on the accumulation of the single strike $SEL_{90\%}$ for each pile strike (Table 2).

The dB_{peak}, $RMS_{90\%}$, $dB_{SEL90\%}$ for each pile strike are plotted in Figures 5, 6, and 7. These plots are typical scatterplots for traditional steel pipe piles being impact driven over time with some degree of variability amongst the individual pile strikes represented by the diamond shapes. The solid horizontal lines in these figures represent the L_{50} .

Figure 5: Control Pile, dB_{peak} levels for each pile strike with the L_{50}

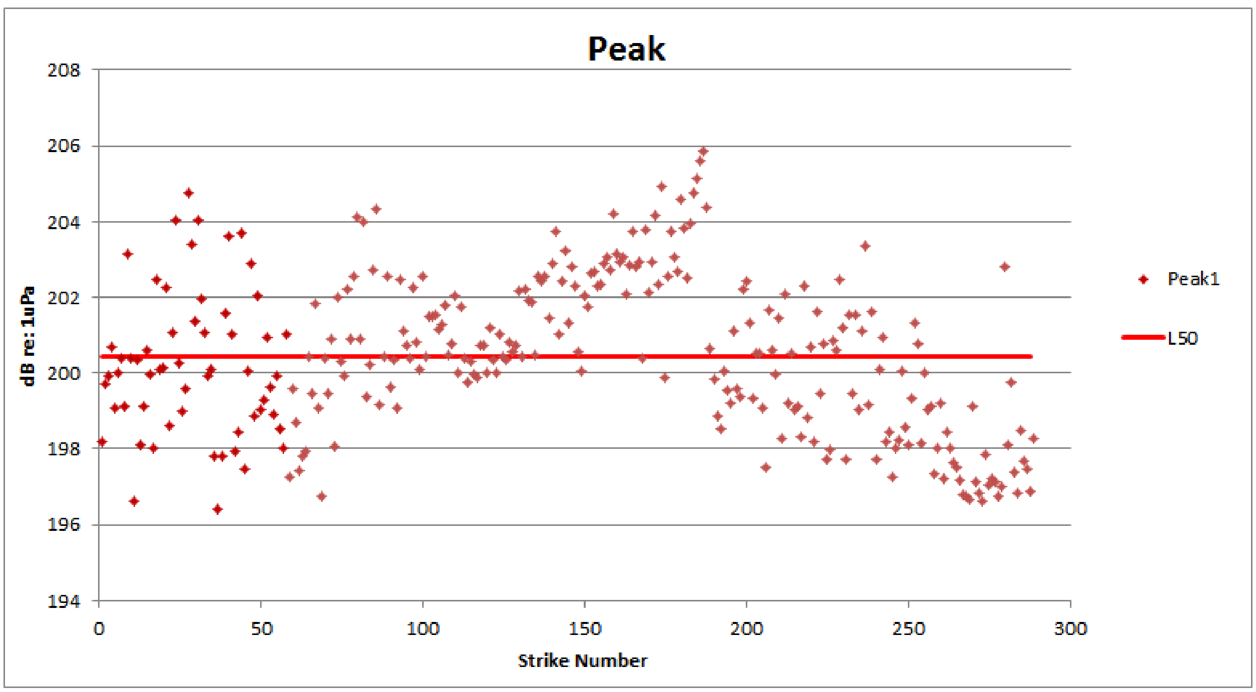


Figure 6: Control Pile, $RMS_{90\%}$ levels for each pile strike with the L_{50}

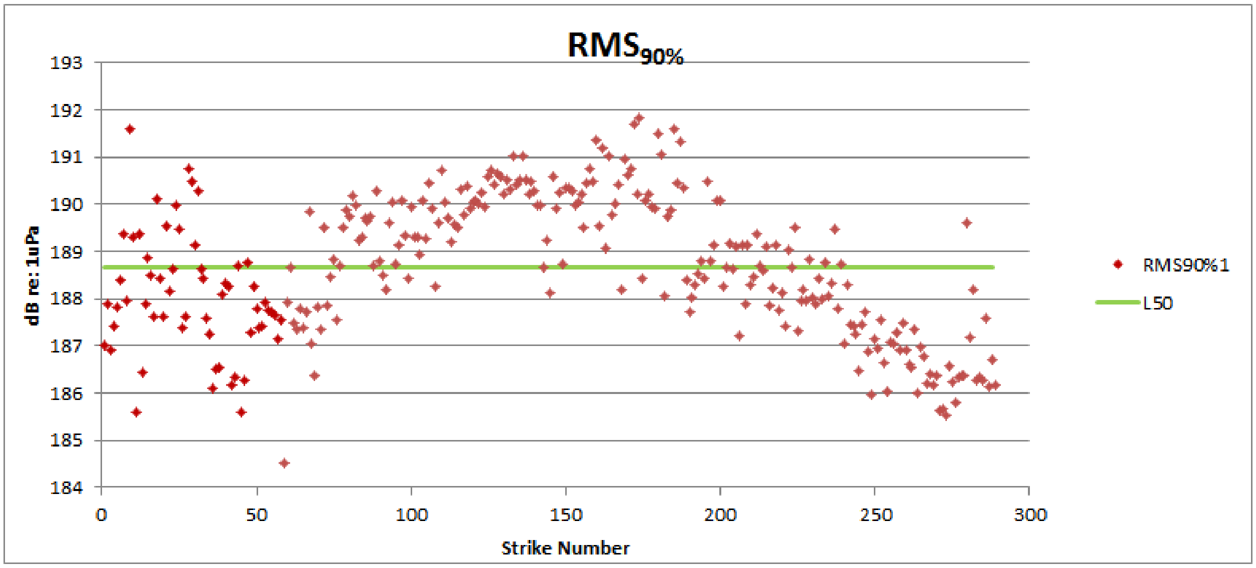
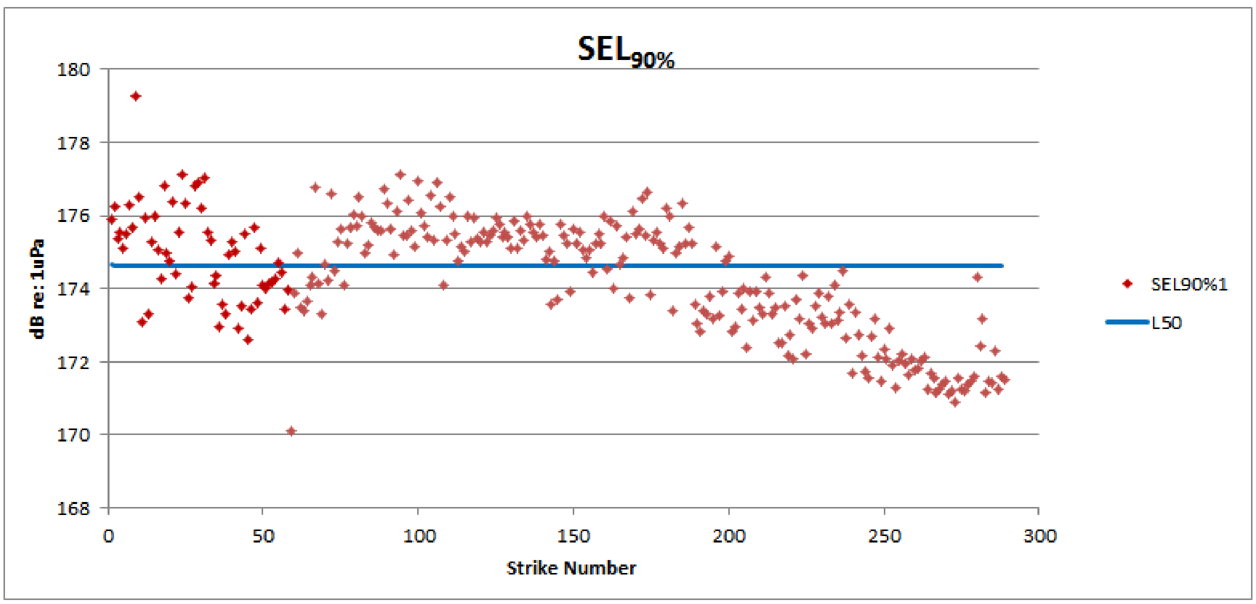


Figure 7: Control Pile, $SEL_{90\%}$ levels for each pile strike with the L_{50}



Pile 2

Pile 2 is located approximately 650 feet from the shore of Vashon Island and is adjacent to Pile 1 (Figure 2). The pile was a double walled steel test pile with an air gap between the inner and outer piles (Figure 4) and had an absolute peak value of 199 dB_{peak} at 20 meters, an $RMS_{90\%}$ of 186

$dB_{RMS90\%}$ and a $SEL_{90\%}$ of 172 $dB_{SEL90\%}$. The cumulative SEL (cSEL) for Pile 2 is 193 dB cSEL and calculated based on the accumulation of the single strike $SEL_{90\%}$ for each pile strike (Table 2).

The dB_{peak}, $RMS_{90\%}$, $dB_{SEL90\%}$ for each pile strike are shown in Figures 8, 9, and 10 along with the L_{50}. These figures show an atypical plot over time with a gradual rise at the beginning of the drive, then at about 175 strikes there was a transition phase after which the sound levels decreased gradually. There also appears to be less variability in the individual measured values compared to the Control pile. The solid lines represent the L_{50} for the entire drive, the dotted lines the L_{50} for the first 175 strikes and the dashed line the L_{50} for the strikes after strike 175. We did not see this pattern in the control pile.

Figure 8: Double Walled Pile, dB_{peak} for each pile strike with the L_{50}.

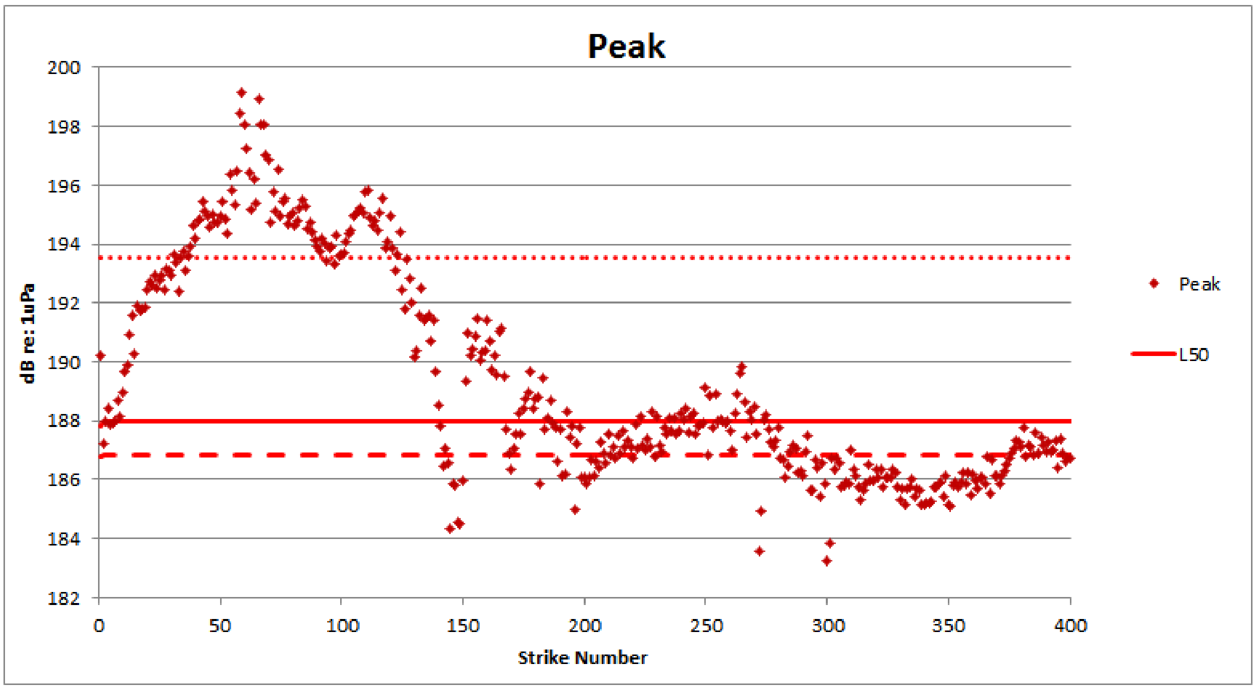


Figure 9: Double Walled Pile, RMS90% levels for each pile strike with the L50.

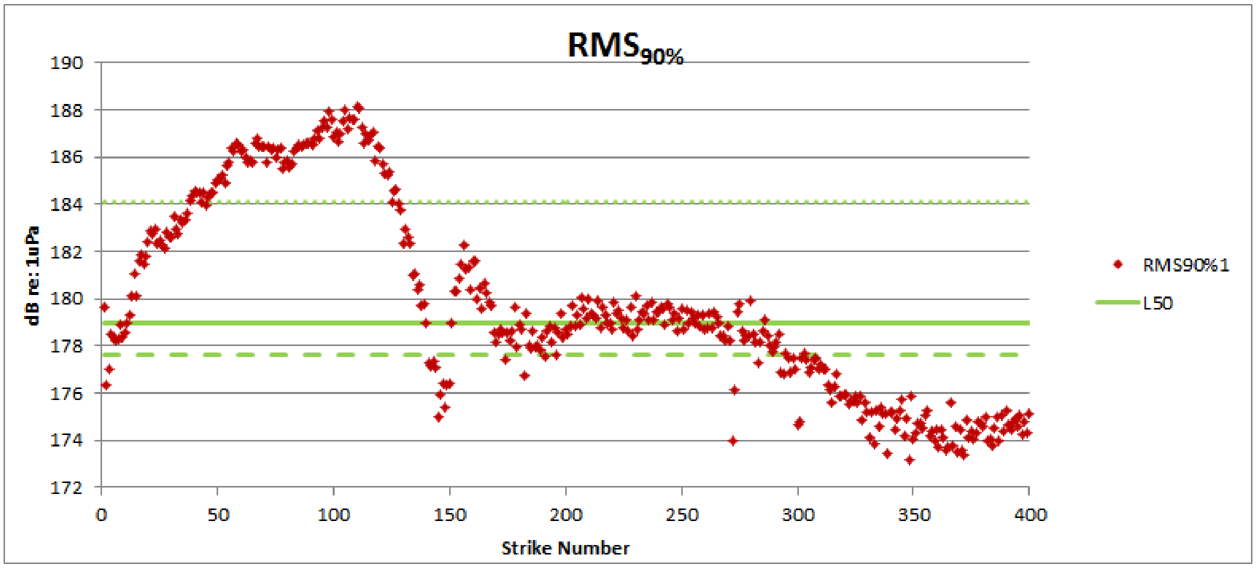


Figure 10: Double Walled Pile, SEL90% levels for each pile strike with the L50.

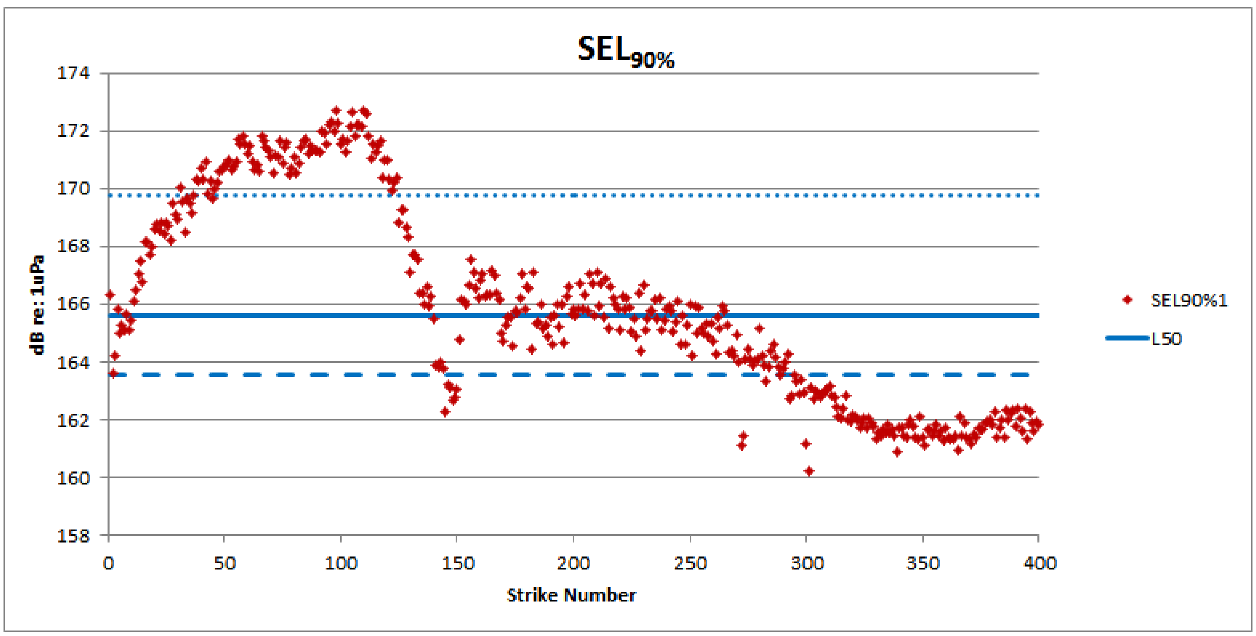
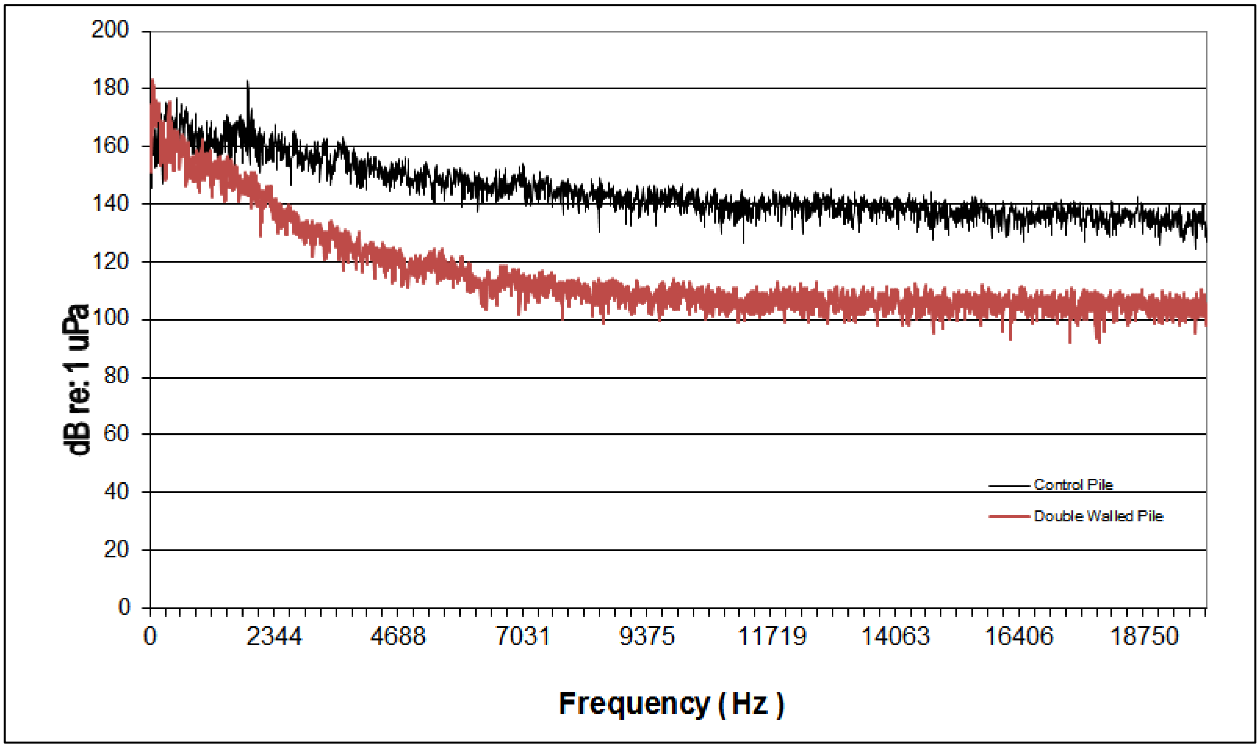


Figure 11 shows an overlay of the Narrow Band Frequency Spectra for the control pile and the Double Walled pile. This figure shows the differences in the dB levels an average of three consecutive pile strikes recorded at various frequencies. This graph suggests that the two piles have similar dB levels at frequencies below approximately 1000 Hz and then above this frequency the double walled pile becomes quieter than the control pile.

Figure 11: Narrow Band Frequency Spectra overlay for Control pile and Double Walled pile



A waveform of a single pile strike for the Double Walled pile is shown in Figure 12. The waveform is unique and shows a slight delay and then the initial arrival of the sound wave from the pile (first wave) through the substrate. Then a relatively quiet period followed by the arrival of the second sound wave (second wave) and then a third and smaller sound wave (third wave) followed by relatively rapid attenuation of the sound. We believe that this demonstrates that the Double Walled pile is performing as it was intended with the dominant noise source at the driving tip of the pile and very little energy coming from the outer pile.

When compared to the single strike waveform for the Control pile (Figure 13) it can be seen that there is much less sound energy produced by the Double Walled pile. Item 1 in the figure indicates the initial sound wave arriving from the control pile through the water column but this is not seen in the Mandrel pile. Item 2 shows the arrival of the second sound wave returning from the bottom of the pile through the substrate and the same sound wave from the Mandrel pile but at lower levels. Item 3 indicates the arrival of the third sound wave from the top of the pile through the water column and again this is not seen in the Mandrel pile.

Figure 12: Double Walled Pile, single pile strike waveform.

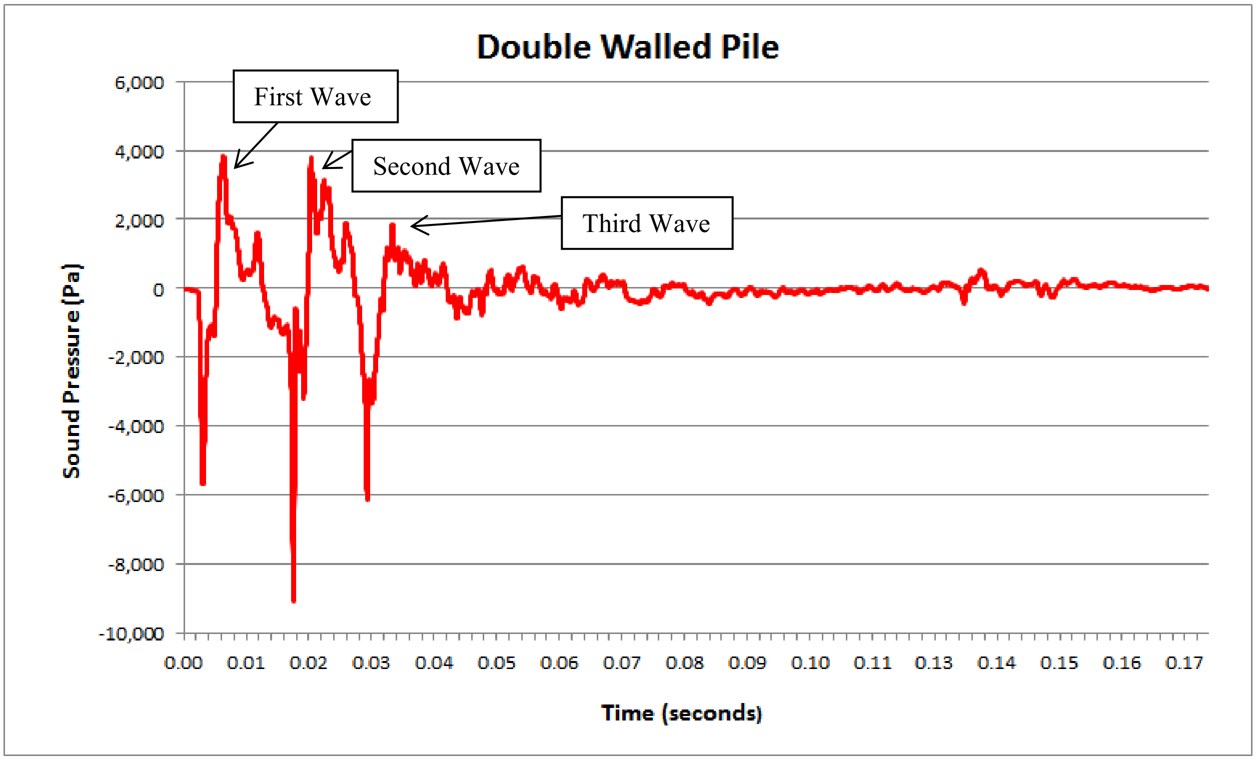


Figure 13: Single strike waveform analysis, control pile and double walled pile comparison

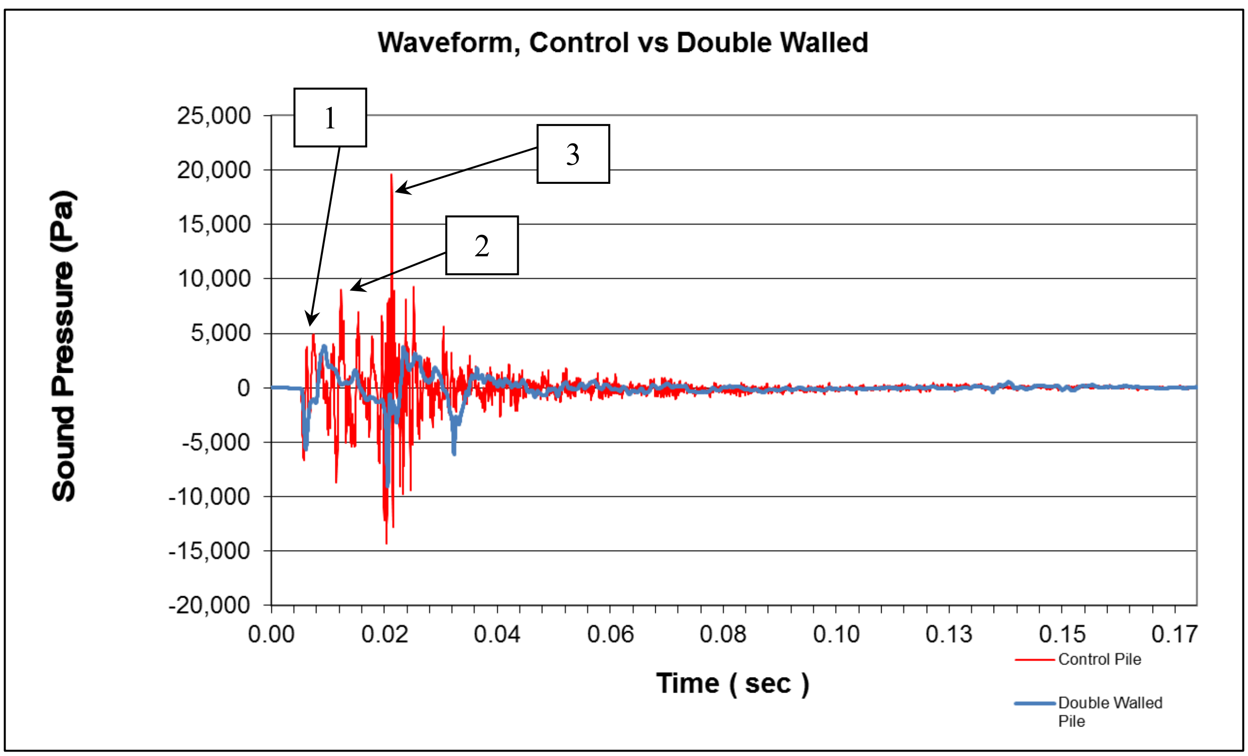
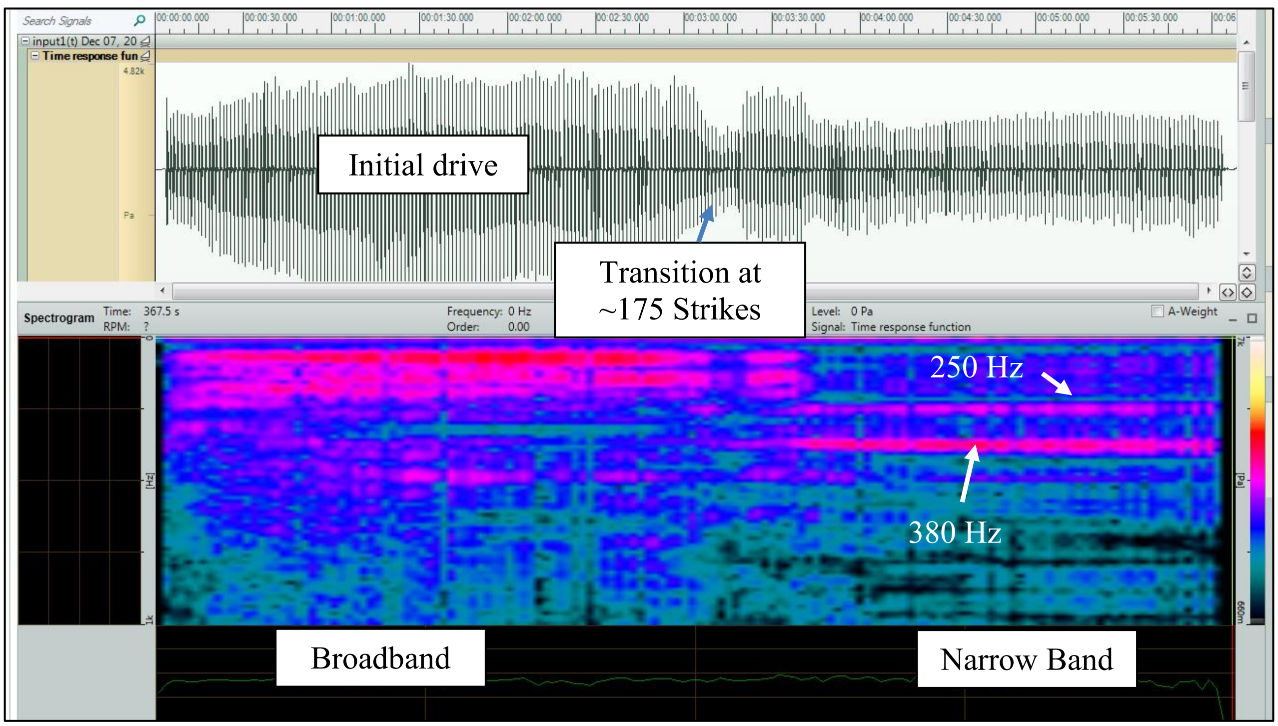


Figure 14 shows the time history of the entire pile drive over time in the upper part of the figure. Each vertical line represents a single pile strike. The initial part of the drive was louder than the latter part of the drive which corresponds to the previous figures. The lower part of the figure shows a spectrograph or frequency content of the pile drive with lower frequencies at the upper part of the spectrograph and higher frequencies as you move down. The brighter the color the louder the sound level. The initial part of the drive is considered 'Broadband' sound levels since the frequencies are spread continuously across the spectrum. In both the upper and lower parts of the Figure 11 there is a kind of transition period where something changed after approximately 175 strikes. After that point the spectrograph shows that the sound levels are narrow band where the energy is distributed over two relatively narrow frequency bands. There were two distinct bands or tones with one centered at 250 Hertz (Hz) and a second one at 380 Hz. This would sound like a thumping or banging sound in the broadband section to more of a ringing tone in the narrow band section.

Figure 14: Double Walled Pile, time history and spectrograph for the entire pile drive



Pile 3

Pile 3 is located approximately 650 feet from the shore of the Vashon Island and adjacent to Pile 2 (Figure 3). The pile is a mandrel steel test pile which is similar to the double wall pile with an air gap between the inner and outer pile (see Figure 4). The difference is that the inner pile can be removed after driving and reused on another mandrel pile. This pile had an absolute peak value of 196 dB_{peak} at 20 meters, an $RMS_{90\%}$ of 184 $dB_{RMS90\%}$ and a $SEL_{90\%}$ of 191 $dB_{SEL90\%}$. The cumulative SEL (cSEL) is 191 dB_{cSEL} and was calculated based on the accumulation of the single strike $SEL_{90\%}$ for each pile strike (Table 2). The dB_{peak}, $dBRMS_{90\%}$, $dB_{SEL90\%}$ for each pile strike are shown in Figure 15, Figure 16, and Figure 17 and includes the L_{50} for the entire drive. These plots show an atypical plot over time with a gradual rise at the beginning of the drive, then at about 175 strikes there was a transition phase after which the sound levels decreased gradually. There also appears to be less variability in the measured values compared to the Control pile. The solid lines represent the L_{50} for the entire drive, the dotted lines the L_{50} for the first 175 strikes and the dashed line the L_{50} for the strikes after strike 175. We did not see this pattern in the control pile but is very similar to the Double Wall pile.

Figure 15: Mandrel Pile, dB_{peak} levels for each pile strike with the L_{50}

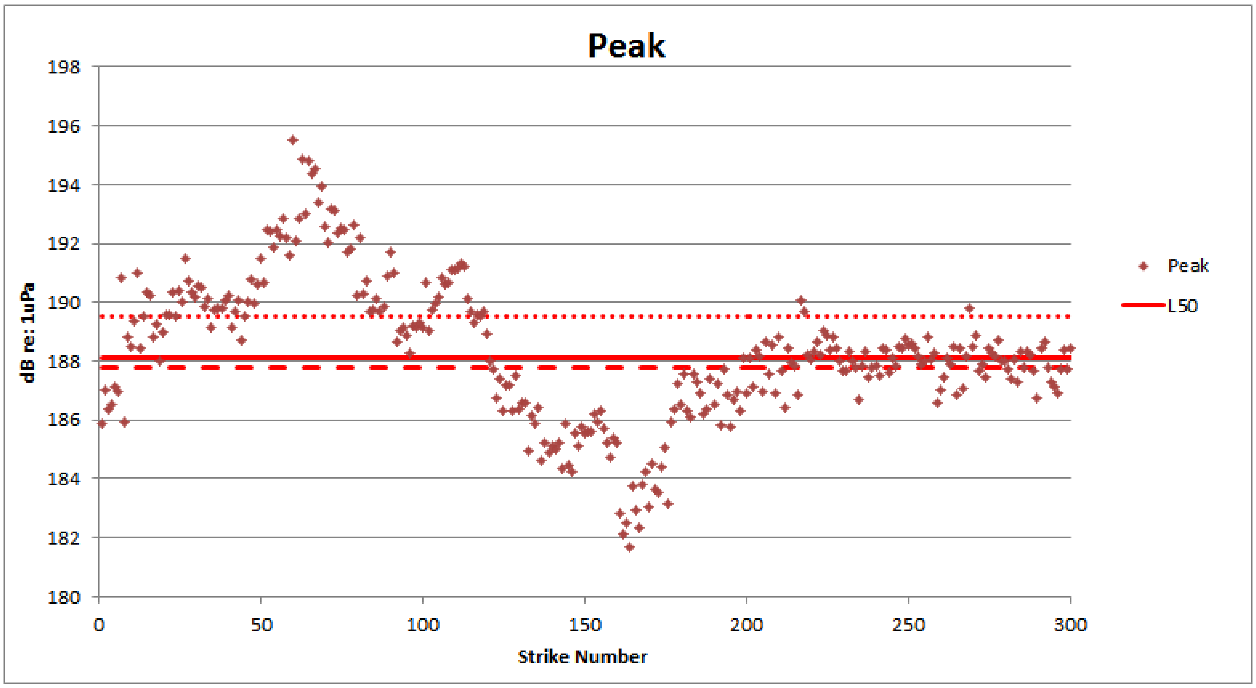


Figure 16: Mandrel Pile, RMS90% levels for each pile strike with the L50

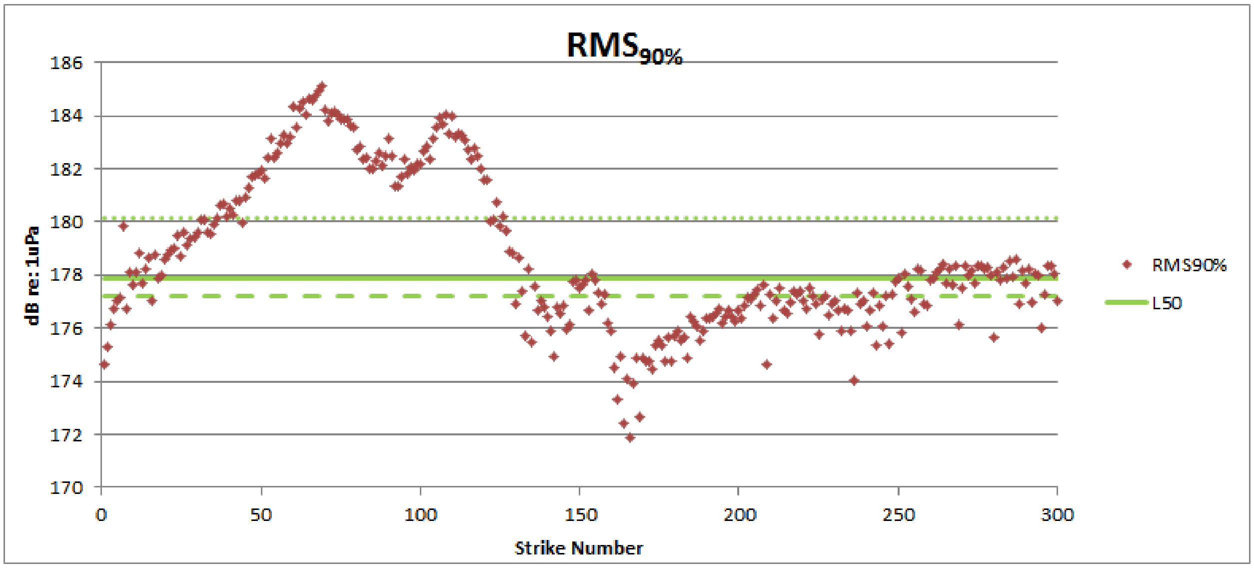


Figure 17: Mandrel Pile, SEL90% levels for each pile strike with the L50

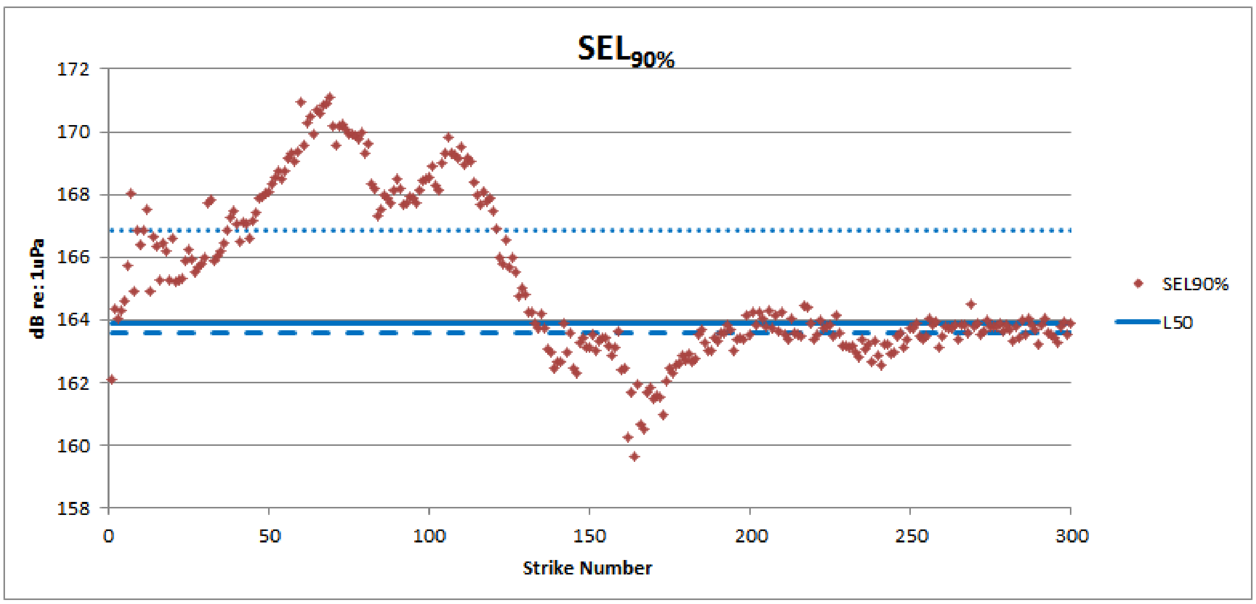
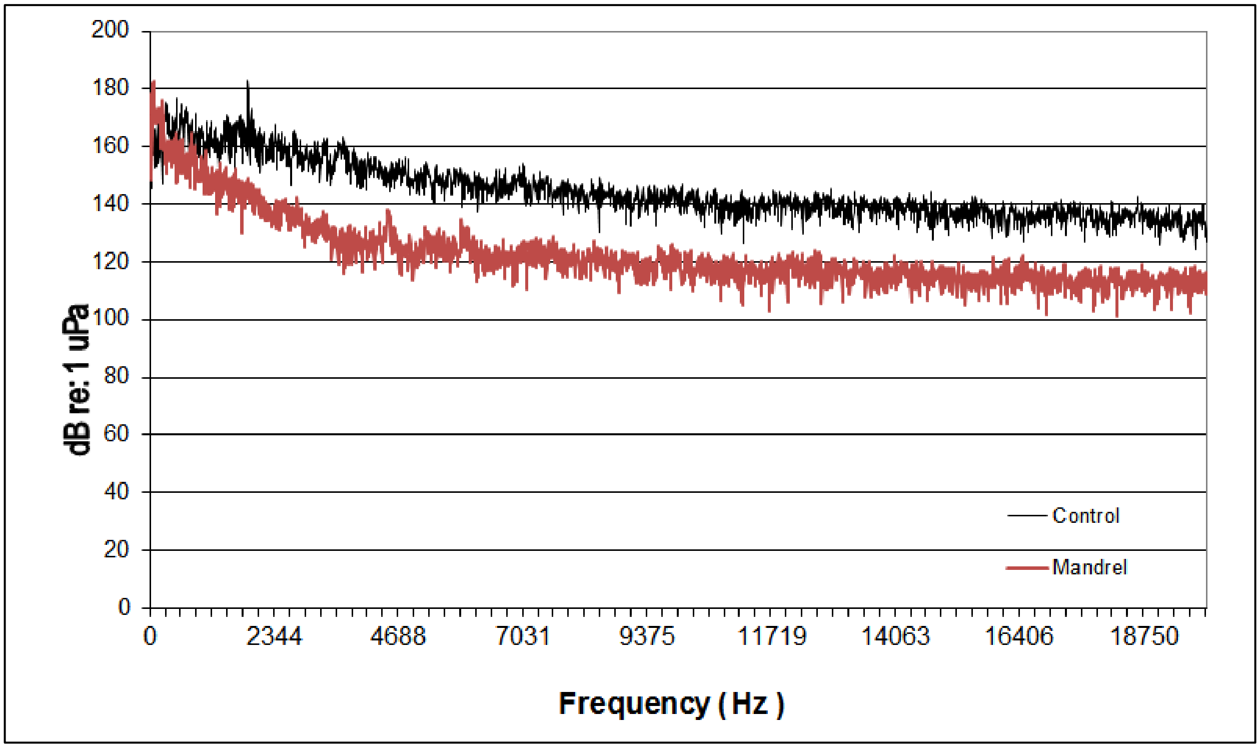


Figure 18 shows an overlay of the Narrow Band Frequency Spectra for the Control pile and the Mandrel pile. This figure shows the differences in the dB levels recorded at various frequencies. This figure suggests that the two piles have similar dB levels at low frequencies, but after the frequency reaches approximately 600 Hz, the mandrel pile becomes quieter than the control pile.

Figure 18: Narrow Band Frequency Spectra overlay for Control pile and Mandrel pile



A waveform of a single pile strike for the Mandrel pile is shown in Figure 19. The waveform is unique and very similar to the waveform for the Double Walled pile. The figure shows the initial arrival of the sound wave from the pile (first wave) through the substrate. Then a relatively quiet period followed by the arrival of the second sound wave (second wave) and then a third and smaller sound wave (third wave) followed by relatively rapid attenuation of the sound. We believe that this demonstrates that the Mandrel pile is performing as it was intended with the dominant noise source at the driving tip of the pile through the substrate. When compared to the single strike waveform for the Control pile (Figure 20) it can be seen that there is much less sound energy produced by the Mandrel pile. Item 1 indicates the initial sound wave arriving from the control pile through the water column but this is not seen in the Mandrel pile. Item 2 shows the arrival of the second sound wave returning from the bottom of the pile through the substrate and the same sound wave from the Mandrel pile but at lower levels. Item 3 indicates the arrival of the third sound wave from the top of the pile through the water column and again this is not seen in the Mandrel pile.

Figure 19: Single strike waveform analysis for a Mandrel pile

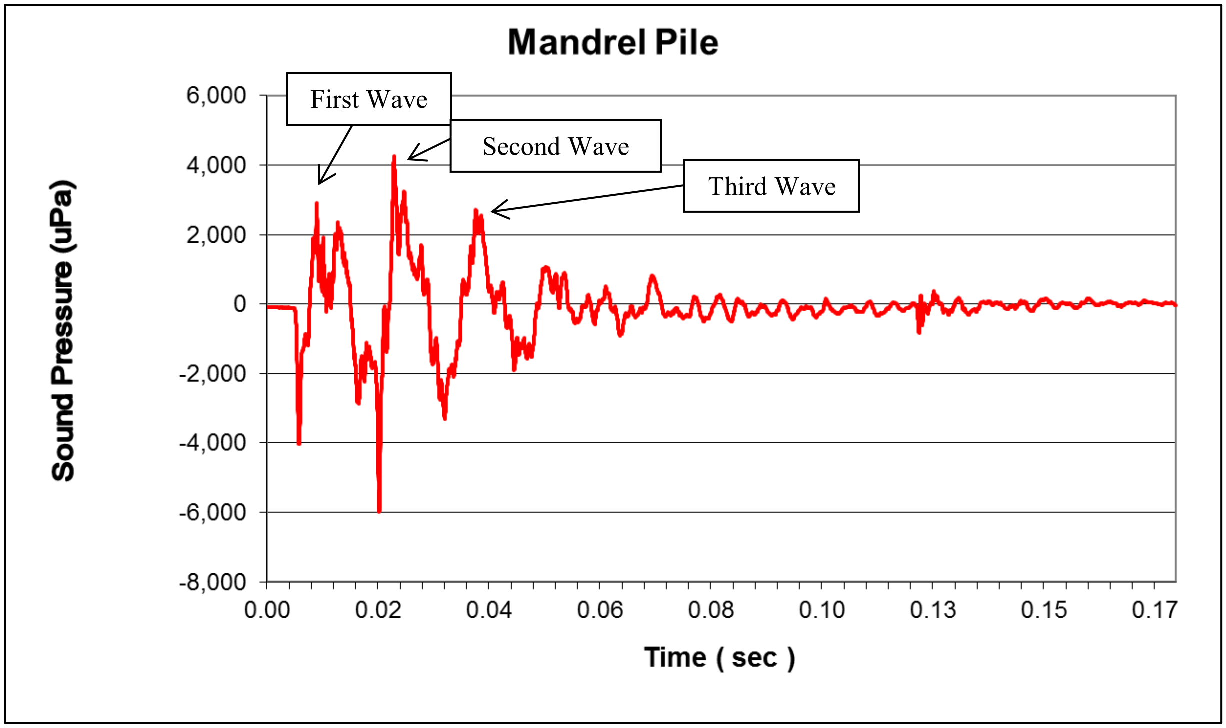


Figure 20: Single strike waveform analysis, Control pile and Mandrel pile comparison

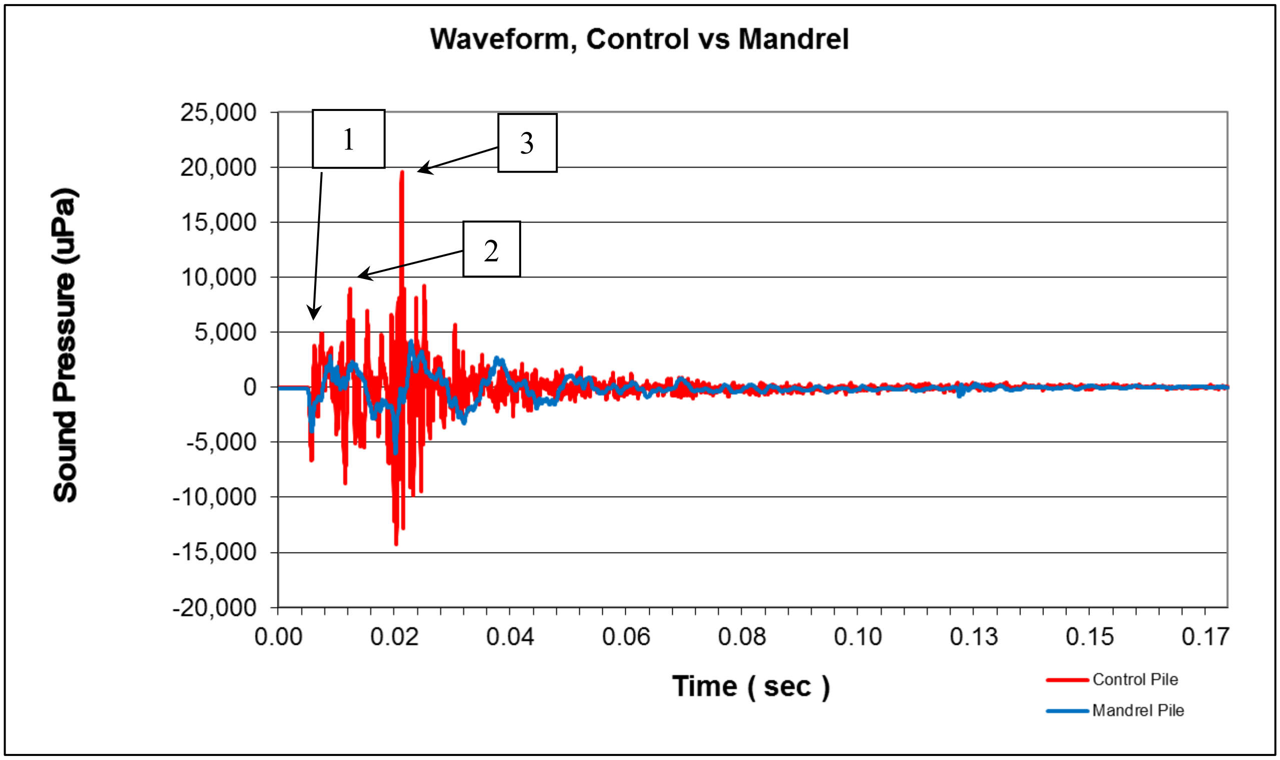


Figure 21 shows the time history of the entire pile drive over time in the upper part of the figure. Each vertical line represents a single pile strike. The initial part of the drive was louder than the latter part of the drive which corresponds to the previous figures for the Mandrel pile. The lower part of the figure shows a spectrograph or frequency content of the pile drive with lower frequencies at the upper part of the spectrograph and higher frequencies as you move down. The brighter the color the louder the sound level. The initial part of the drive is considered 'Broadband' sound levels which is similar to what was found for the Double Walled pile. In both the upper and lower parts of the Figure 21 there is a kind of transition period where something changed after approximately 175 strikes. After that point the spectrograph shows that the sound levels are narrow band which we also observed in the Double Walled pile. There were two distinct bands or tones with one centered at 244 Hz and another at 368 Hz. This would sound like a thumping or banging sound in the broadband section to more of a ringing tone in the narrow band section

Figure 21: Mandrel Pile, time history and spectrograph for the entire pile drive

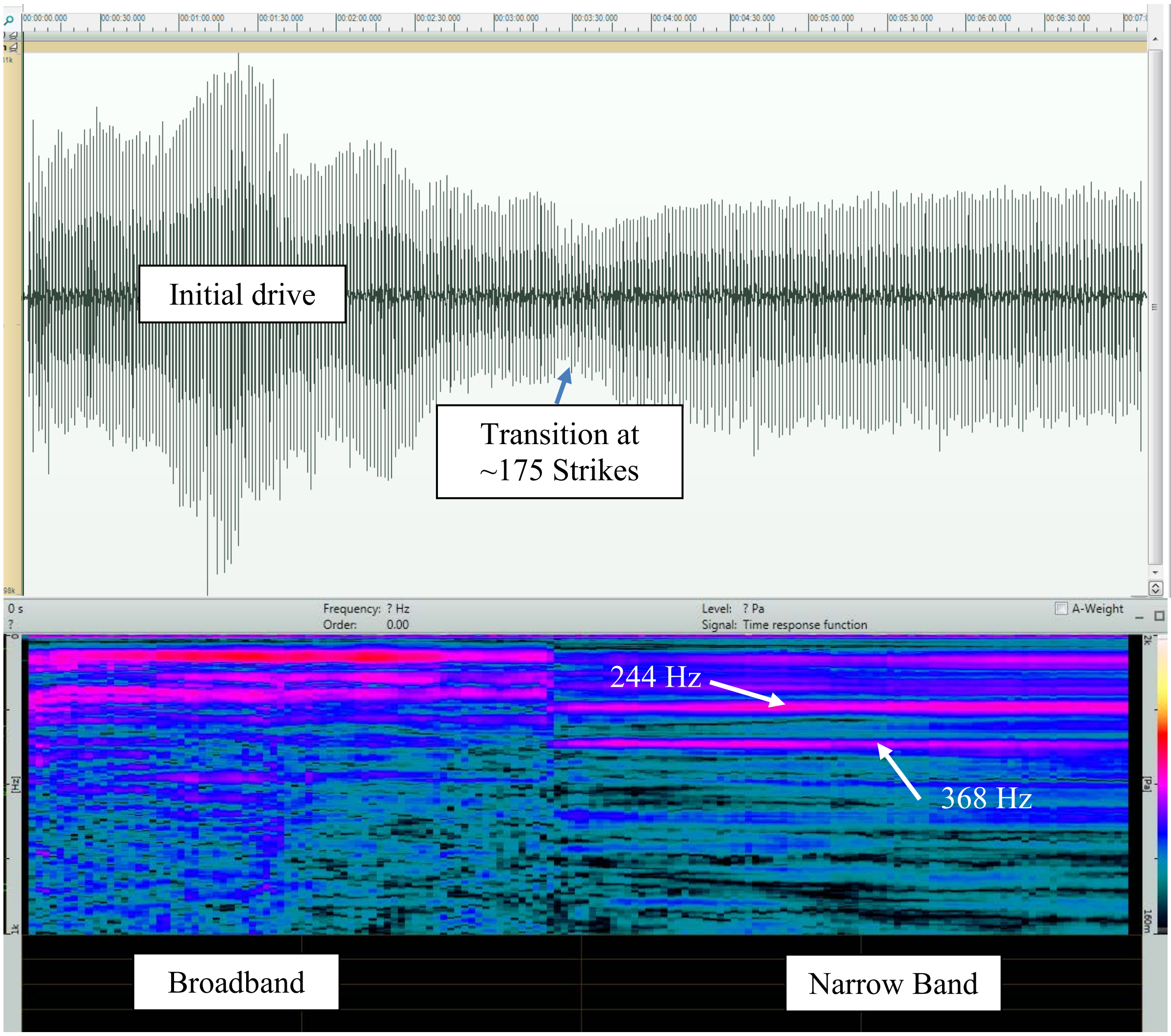


Table 2: Summary of Underwater Broadband Sound Levels for the Vashon Test Pile Project

Pile #	Date & Time	H-Pile Diameter (inches)	Hydrophone Range (m)	Hydrophone Depth (feet)	Pile Type	Total Number Of Strikes	Highest Absolute Peak (dB)	$RMS_{90\%}$ (dB)	Single Strike $SEL_{90\%}$ (dB)	Avg. Peak ± s.d. (Pascal)	Avg. RMS ± s.d. (Pascal)	Cumulative SEL (dB)
1	12/7/2015 12:03 PM	30	20	11	Control	289	206	191	176	10825 ±2667	2736 ±478	199
2	12/7/2015 14:46 PM	30	20	11	Double Walled	402	199	186	172	3230 ±1537	1096 ±564	193
3	12/8/2015 10:04 AM	30	20	11	Mandrel	325	196	184	171	2695±763	763 ±316	191

Daily Cumulative SEL

The daily cSEL's were calculated using the calculated $SEL_{90\%}$ for each individual pile strike for each day and accumulated over that period (Table 3).

Table 3: Summary of daily cumulative SEL's

Day	10M
12/7/15	200
12/8/15	164

The daily cumulative SEL values ranged from 164 to 200 dB at the 20 meter location.

Airborne Sound Levels

Both A-weighted and un-weighted airborne sound level measurements were collected from the nearest location to the pile on the ferry trestle, 20 meters from the piles. Five minute measurements were collected along with 1-second time histories to attempt to capture the sound levels for most of the pile strikes. Since the meter is able to collect a measurement every one second and pile strikes occur approximately every 1.5 seconds some pile strikes were not able to be recorded accurately.

The A-weighted L_{Aeq} values for the entire pile drive ranged between 94 dBA and 99 dBA at 50 feet and the L_{max} ranged between 104 dBA and 110 dBA at 50 feet (Table 4). The measured levels are all standardized to a distance of 50 feet which is standard for reporting construction noise levels. The un-weighted Leq values for the entire pile drive ranged between 97 and 101 dB at 50 feet and the Lmax ranged between 107 dB and 113 dB at 50 feet.

Table 4: Summary of Control and test pile airborne A-weighted and un-weighted sound levels collected between December 7, 2015 and December 8, 2015

Pile Type	Distance from Pile (m)	L_{Aeq} at 66 feet	L_{Aeq} at 50 feet	L_{max} at 66 feet	L_{max} at 50 feet
A-Weighted (dBA)					
Control	20	93	94	108	110
Double Walled	20	98	99	109	110
Mandrel	20	94	95	103	104
Un-Weighted (dB)					
Control	20	96	97	112	113
Double Walled	20	100	101	111	113
Mandrel	20	97	98	106	107

The time history plot of A-weighted airborne sound levels for each individual pile strike measured for the Control pile, Double Walled pile, and Mandrel pile are shown in Figures 22-25. The L_{Aeq} sound levels for each pile strike for the Control pile ranged between approximately 95 dBA and 102 dBA. The double walled pile was impact driven on two occasions roughly two hours apart. Due to these distinct driving incidences, two time history plots have been created for the double walled pile. The L_{Aeq} sound levels for each pile strike for the Double Walled pile ranged between approximately 98 dBA and 102 dBA. The L_{Aeq} sound levels for each pile strike for the Mandrel pile ranged between approximately 95 dBA and 97 dBA.

Figure 22: Time history of L_{Aeq} airborne sound levels for each pile strike for the Control Pile

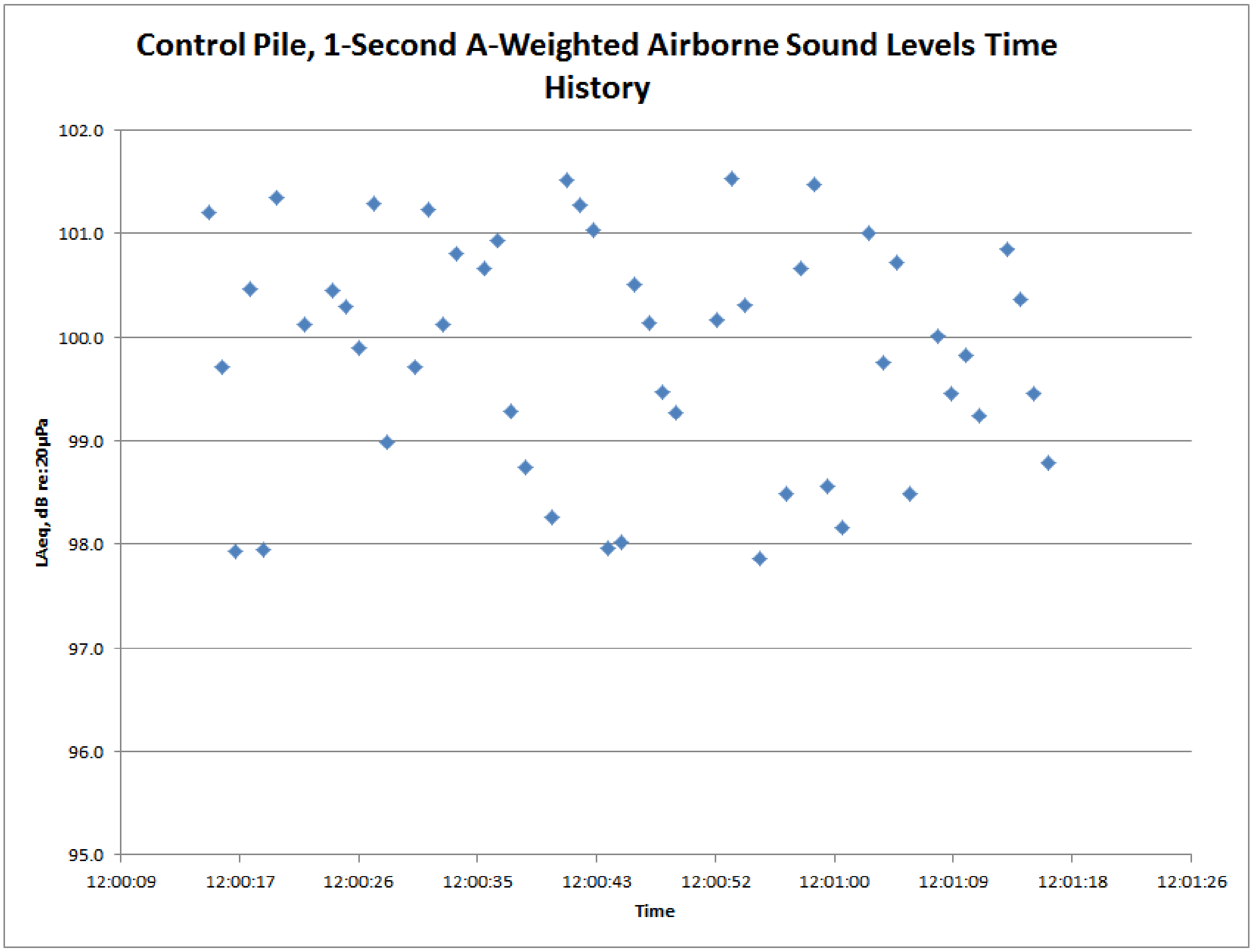


Figure 23: Time history of L_{Aeq} airborne sound levels for each pile strike for the Double Walled Pile (part 1)

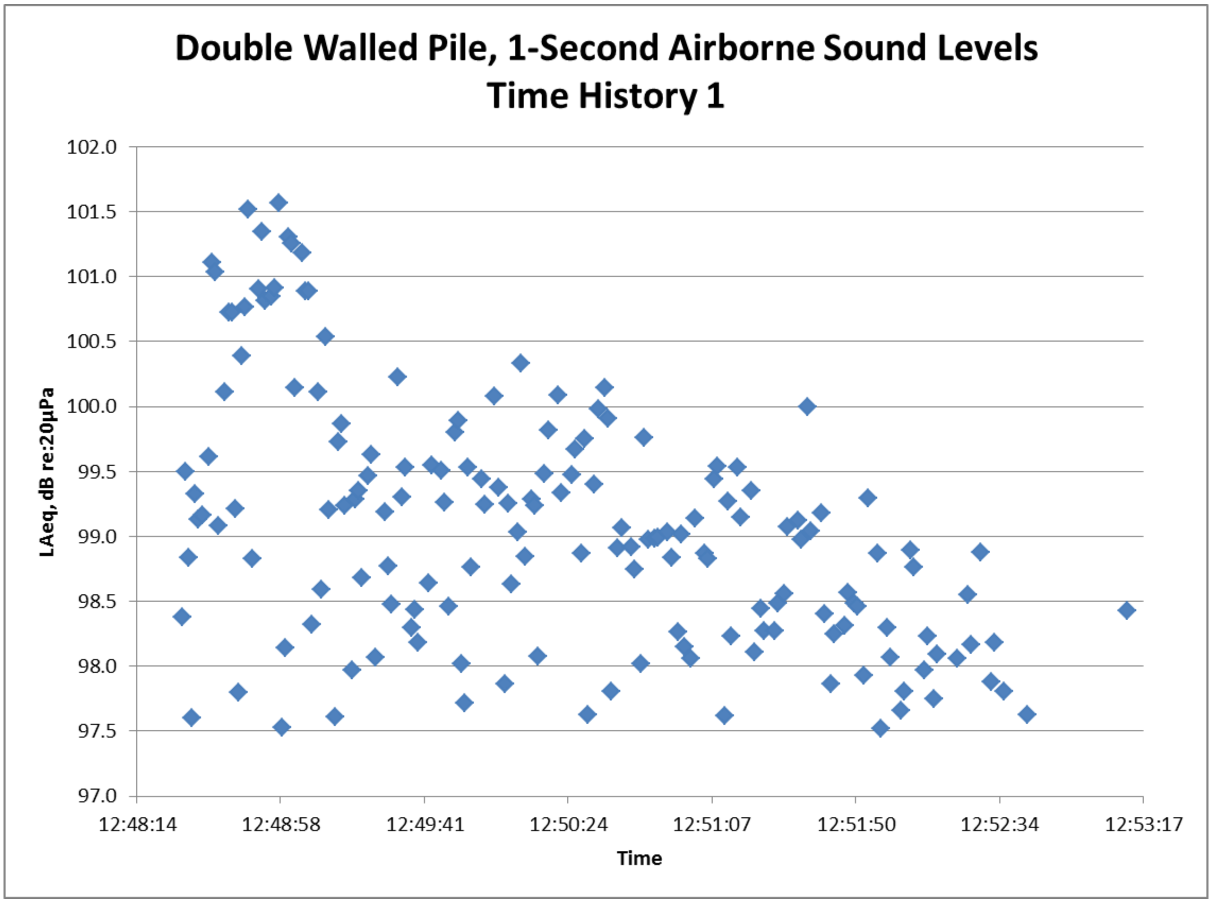


Figure 24: Time history of L_{Aeq} airborne sound levels for each pile strike for the Double Walled Pile (part 2)

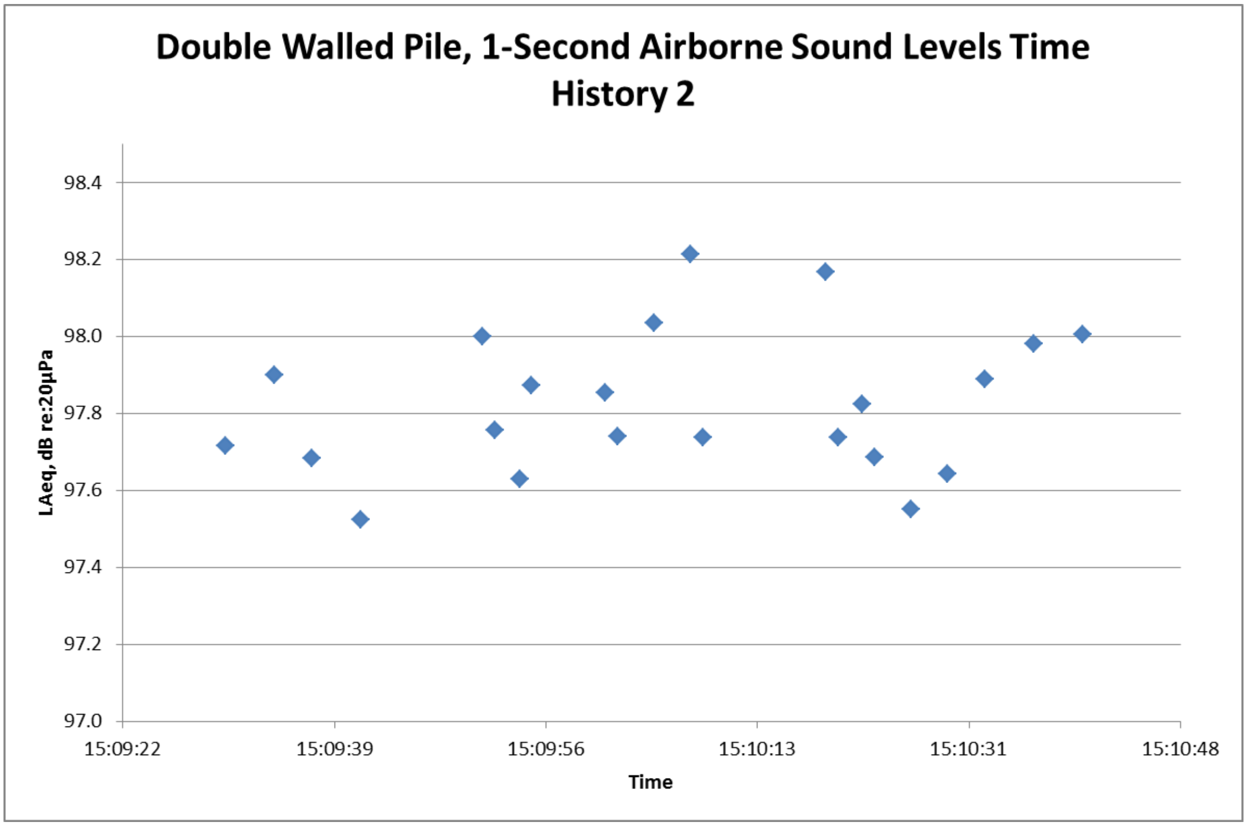
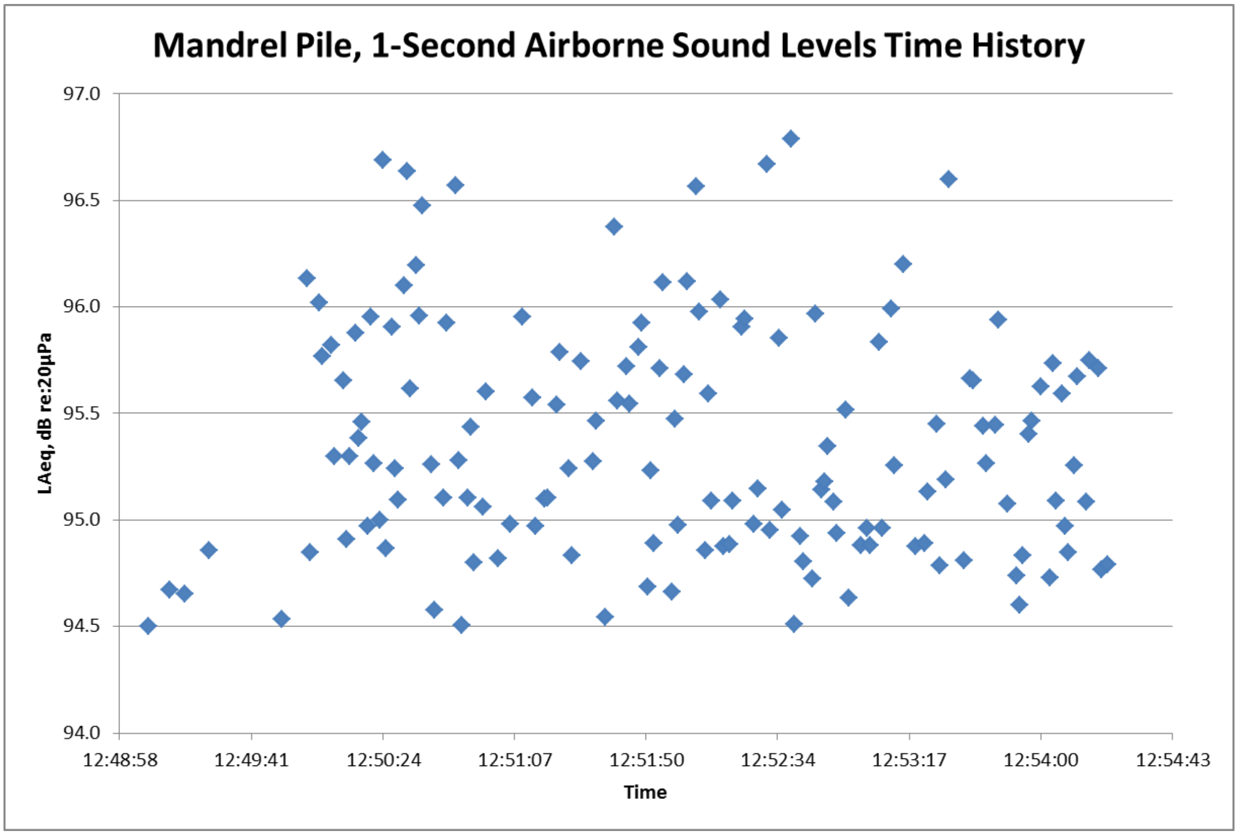
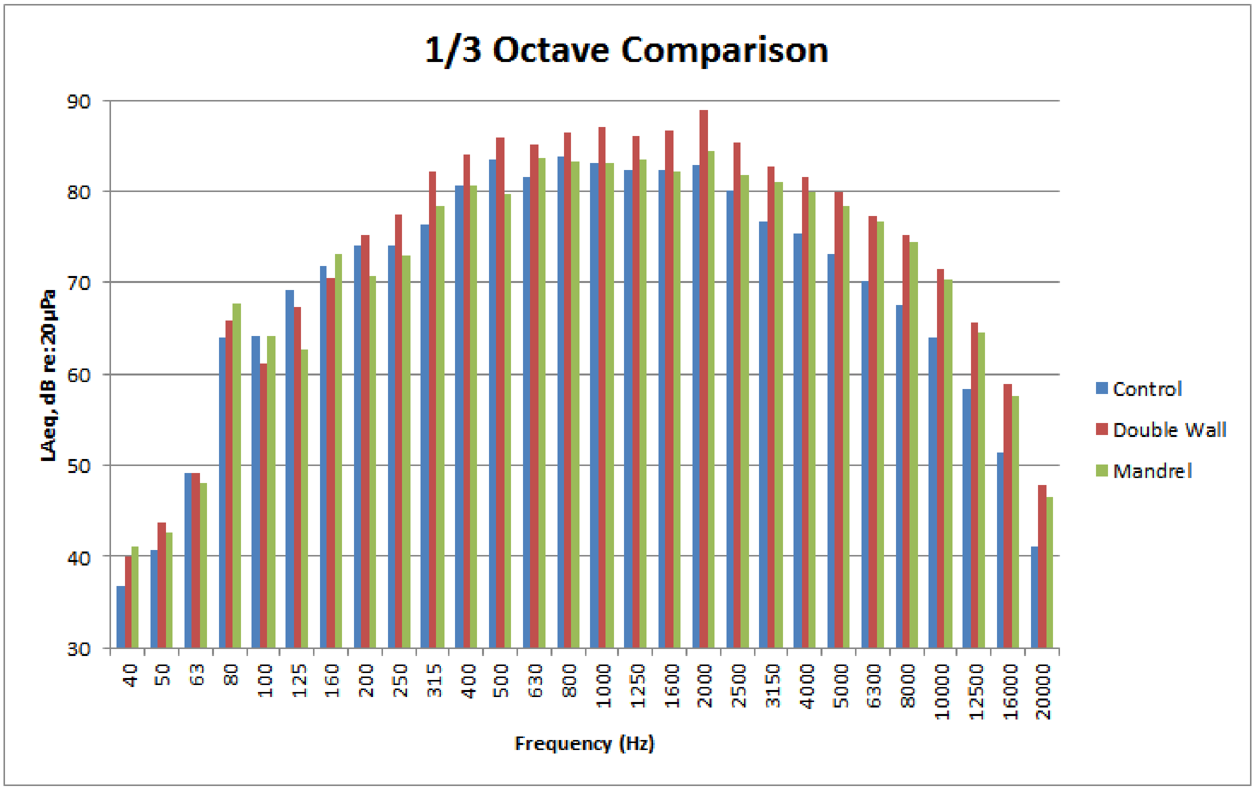


Figure 25: Time history of L_{Aeq} airborne sound levels for each pile strike for the Mandrel Pile



The overall airborne 1/3rd octave band frequencies were averaged for each of the three piles and plotted in Figure 26. The figure shows a relatively normal distribution of sound levels between 40 Hz and 20 kHz with the dominant frequency at approximately 500 Hz for the Control pile which is typical for airborne sound levels during impact driving of steel piles in the 400 Hz to 800 Hz range. For both the Double Wall and Mandrel piles the dominant frequency is 2 kHz which is a higher frequency than is typically seen for impact driving of steel piles. As the figure shows the Double Wall Pile was slightly louder than the Control Pile and Mandrel Pile in frequencies above 200 Hz. Both the Double Wall and Mandrel Piles were slightly louder than the control pile at frequencies above 2 kHz. The reasons for this are unclear but could be due to the configuration of the Double Walled and Mandrel piles requiring more energy to drive them or an interaction between the outer walls of these piles with the pile template.

Figure 26: Average 1/3rd octave band frequencies (L_{eq}) for impact driving of the Control, Double Wall and Mandrel Piles



CONCLUSIONS

Three 30-inch steel piles, one traditional control pile, one double walled test pile, and one mandrel test pile, were monitored for the Vashon Test Pile Project. The underwater sound levels analyzed, produced the following results.

- Peak underwater un-attenuated sound levels at 20 meters varied in a range between 206 dB_{Peak} for the Control pile, 199 dB_{Peak} for the Double Walled pile and 196 dB_{Peak} for the Mandrel pile.
- The measured $RMS_{90\%}$ levels ranged between 191 dB_{Peak} for the Control pile, 186 dB_{Peak} for the Double Walled pile and 184 dB_{Peak} for the Mandrel pile.
- Cumulative Sound Exposure Levels (cSEL) for all piles driven on a particular day, ranged between 164 dB_{cSEL} and 200 dB_{cSEL}.
- The Double Wall and Mandrel pile produced atypical results in the latter part of the drive after about 175 strikes. These piles exhibited a sudden decrease in the sound levels for each pile strike and produced narrow band sound levels compared to the typical broadband sound levels for most steel piles. The reasons for this are as of this report are unclear and may be due to interaction of the piles with the steel template, a change in the test pile structure or the substrate with depth.

All three piles were also monitored for airborne sound levels during impact driving. The measurements produced the following results.

- Overall L_{Aeq} sound levels were measured to be between 94 and 99 dB re: 20 µPa at 50 feet with L_{max} levels ranging between 104 and 101 dB re: 20 µPa at 50 feet.
- The Double Walled and Mandrel Piles were slightly louder than the Control pile.
- L_{Aeq} and L_{max} levels were measured at 94 and 110 dB re: 20 µPa at 50 feet for the Control pile.
- L_{Aeq} and L_{max} levels were measured at 99 and 110 dB re: 20 µPa at 50 feet for the Double Walled pile.
- L_{Aeq} and L_{max} levels were measured at 95 and 104 dB re: 20 µPa at 50 feet for the Mandrel pile.

Figure 27: Vashon Test Pile: Control Pile at 20m

Vashon Test Piles Control Pile 1 at 20m Broadband

Figure a. Waveform

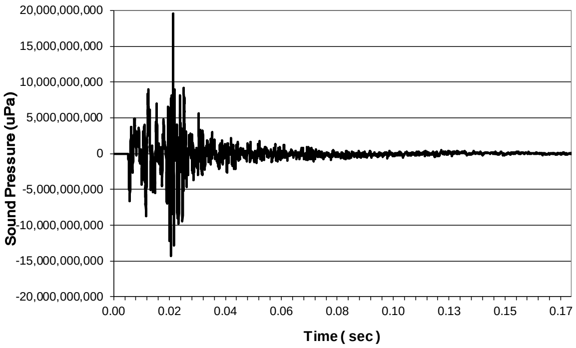


Figure b. Narrow Band Frequency Spectra

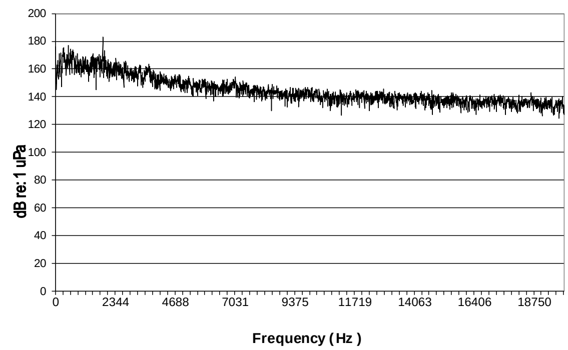


Figure c. Accumulation of Sound Energy

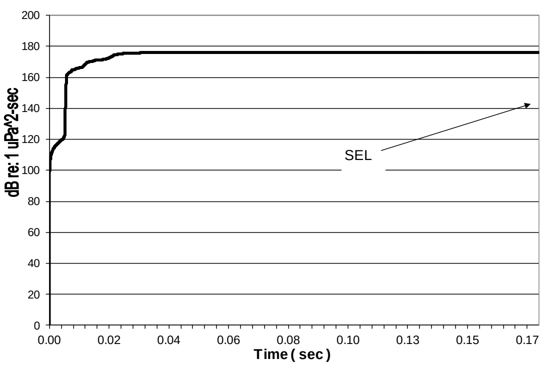


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
11 feet	206	191	176

*Impulse averaged over 90% of accumulated energy (5% to 95%)

Figure 28: Vashon Test Pile: Double Walled Pile at 20m

Vashon Test Piles Double Walled Pile at 20m Broadband

Figure a. Waveform

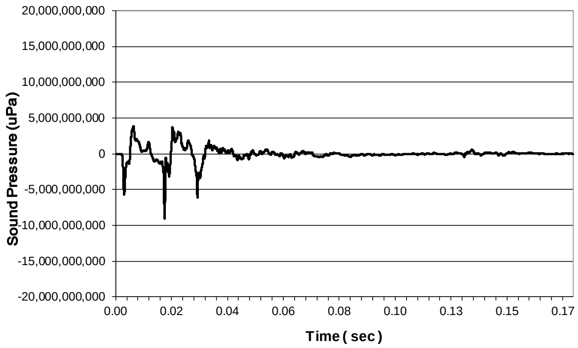


Figure b. Narrow Band Frequency Spectra

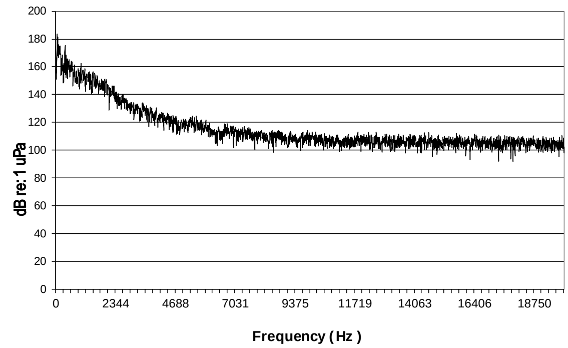


Figure c. Accumulation of Sound Energy

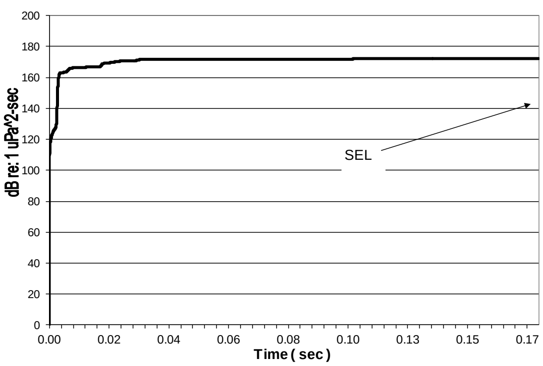


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	$RMS_{90\%}$*	SEL
11 feet	199	186	172

*Impulse averaged over 90% of accumulated energy (5% to 95%)

Figure 29: Vashon Test Pile: Mandrel Pile at 20m

Vashon Test Piles Mandrel Pile at 20m Broadband

Figure a. Waveform

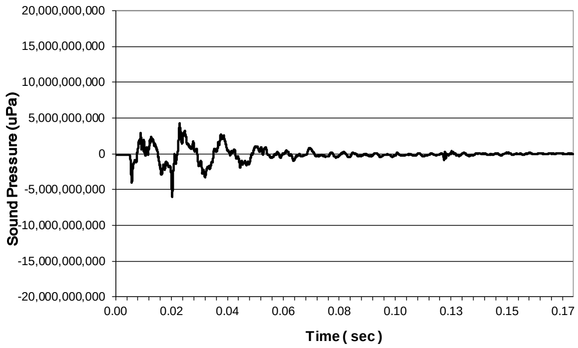


Figure b. Narrow Band Frequency Spectra

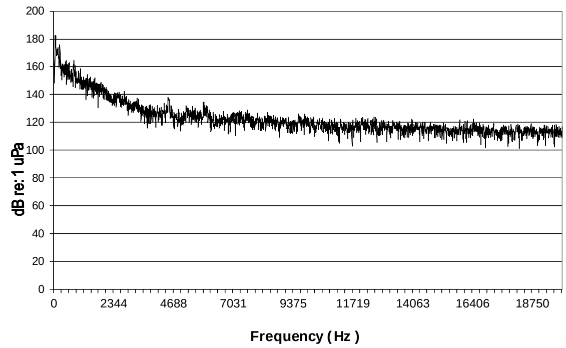


Figure c. Accumulation of Sound Energy

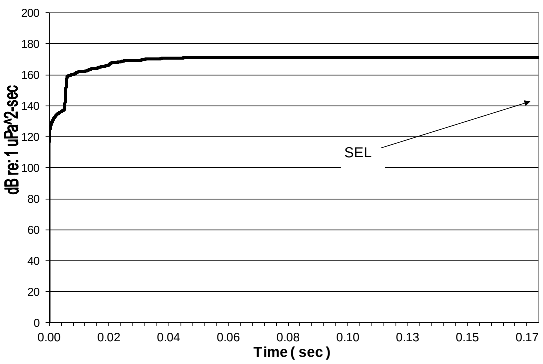


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
11 feet	196	184	171

*Impulse averaged over 90% of accumulated energy (5% to 95%)