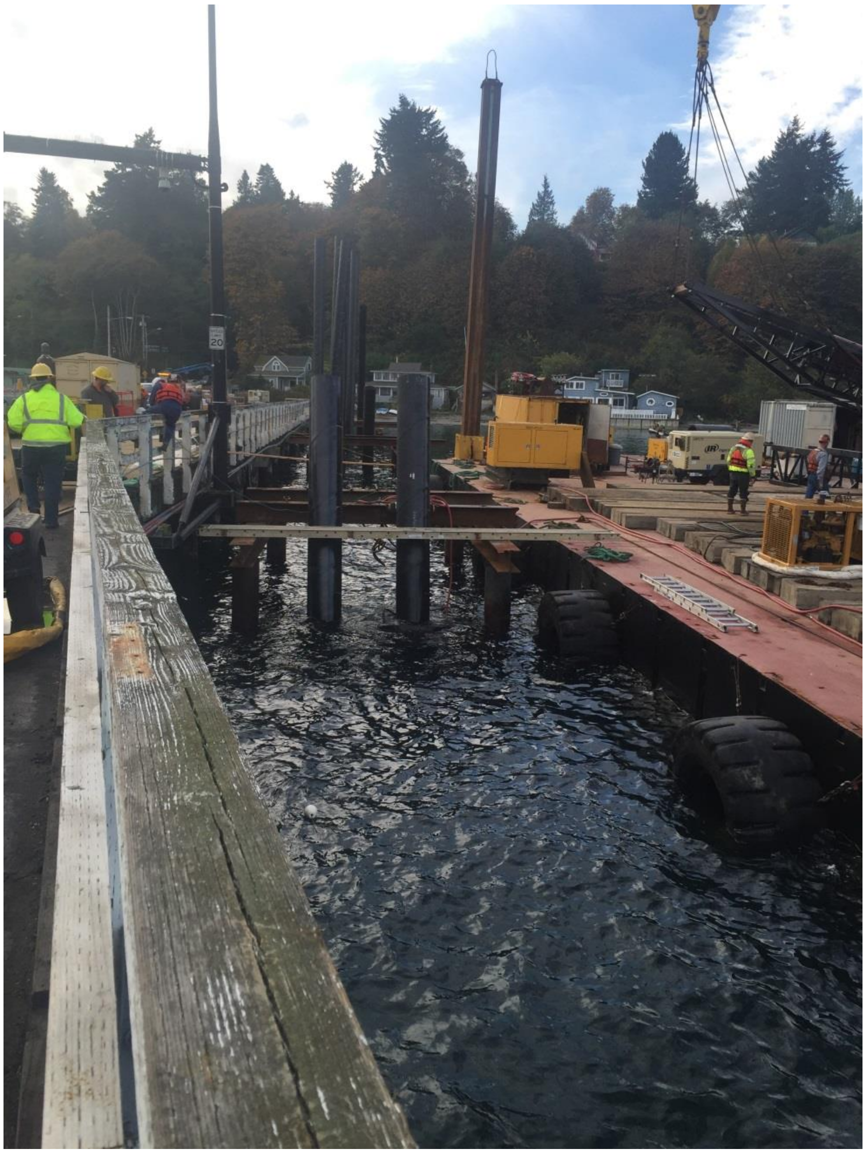
Underwater Sound Level Report: Vashon Timber Trestle and Terminal Replacement



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ACRONYMS AND ABBREVIATIONS

dB	decibel
Hz	hertz
μPa	micro-Pascal
NIST	National Institute of Standards and Technology
Pa	Pascal
RMS	root mean squared
s.d.	standard deviation
SEL	Sound Exposure Level
SL	sound level, regardless of descriptor
SPL	sound pressure level
USFWS	U.S. Fish and Wildlife Service
WSF	Washington State Ferries
WSDOT	Washington State Department of Transportation

EXECUTIVE SUMMARY

This technical report describes the data collected during impact pile driving and monitoring of underwater sound levels from driving the 24-inch diameter hollow steel piles for the Washington State Ferries (WSF) Vashon Terminal – Timber Trestle and Terminal Replacement Project between September 2015 and October 2015. Hydroacoustic data was collected for ten 24-inch diameter piles. All ten of the piles monitored were located on the west side of the existing Vashon Ferry Terminal located in the Puget Sound. A confined bubble curtain was deployed for all impact driven battered piles and an unconfined bubble curtain was deployed for all impact driven plumb piles to attenuate potential underwater noise effects. All measurements were collected at 10-11 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 the10 meter locations.

None of the monitored piles exceeded the cSEL threshold of 204 dB_{cSEL}. The peak attenuated sound levels measured ranged between 182 dB_{peak} and 201 dB_{peak}. Results of monitoring the impact pile driving operation are shown in Table 1.

Table 1: Summary of 24-inch Piles Attenuated Underwater Sound Levels.

Pile #	Date	Pile Diameter (inches)	Peak Threshold at 10m (dB)	cSEL Threshold at 10m (dB)	Peak at 10 meters (dB)	$RMS_{90\%}$ (dB)	Single Strike $SEL_{90\%}$ (dB)	Cumulative SEL (dB)	Exceedance?
1	9/2/15	24	204	202	197	182	171	192	No
2	9/2/15	24	204	202	199	183	171	196	No
3	9/2/15	24	204	202	196	179	169	195	No
4	9/9/15	24	204	202	194	177	166	195	No
5	9/9/15	24	204	202	182	173	165	184	No
6	10/6/15	24	204	202	198	179	167	195	No
7	10/21/15	24	204	202	197	184	169	185	No
8	10/21/15	24	204	202	201	180	172	189	No
9	10/21/15	24	204	202	196	180	166	179	No
10	10/21/15	24	204	202	189	177	164	181	No

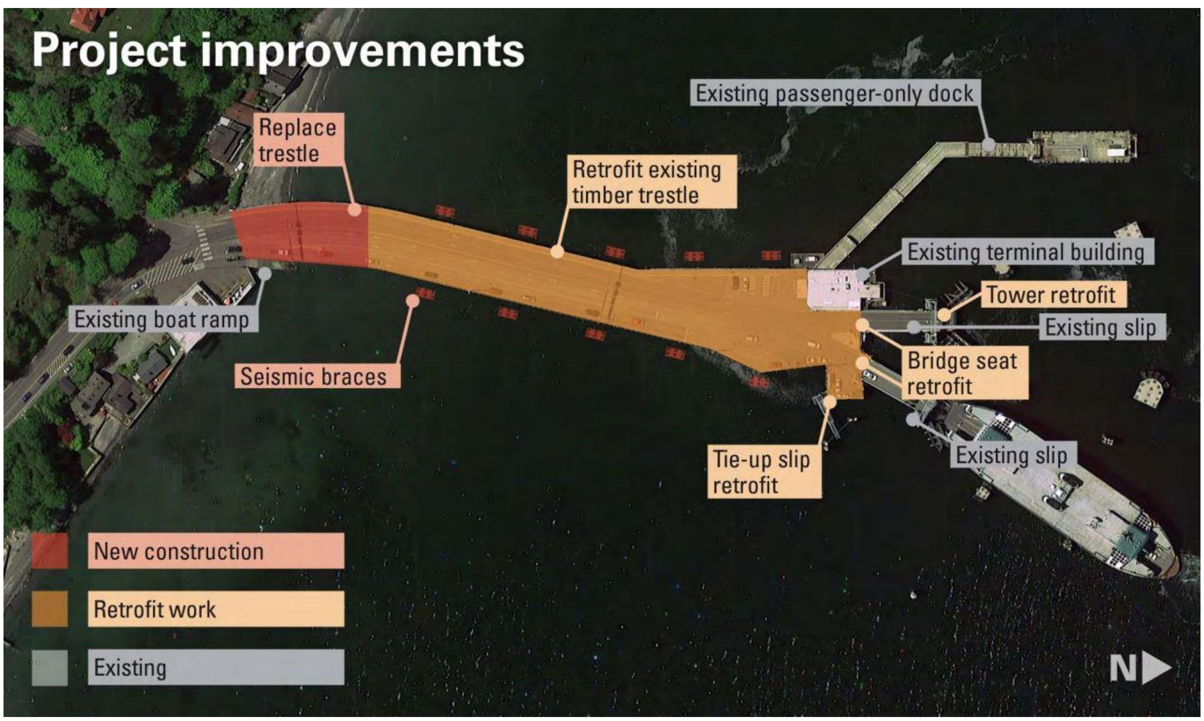
INTRODUCTION

WSF proposes to replace part of the existing Vashon Ferry Terminal trestle in the nearshore area, retrofit the remainder of the existing trestle and install seismic bracing along the perimeter of the trestle. The project results in an increase in overwater coverage and additional steel piles driven outside of the existing trestle footprint. For constructability reasons the project is broken into three phases: retrofitting the bridge seat, tower, and tie-up slip at the far edge of the dock in phase one, constructing and rehabilitating the trestle on the west side of the terminal in phase two and the east side in phase three.

Approximately 210-linear feet of the existing nearshore trestle will be replaced. Fifty-three 24-inch diameter hollow steel piles will be installed with a vibratory hammer for the first 40 feet and driven with an impact hammer for the final 10 feet. Seismic bracing will also be installed at up to 10 locations, consisting of a maximum of sixty-six 24-inch diameter hollow steel piles installed with an impact hammer. The goal of the project is to improve the safety of users, enhance the seismic stability of the dock, and increase the capacity of the Vashon Ferry Terminal.

The Washington State Department of Transportation (WSDOT) monitored hydroacoustic noise levels for ten 24-inch diameter hollow steel piles and monitored airborne noise levels for 3 such piles.

Figure 1: Vashon Terminal Project Improvements



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 2: SR 160 Vashon Terminal Project Work Area

PILE INSTALLATION LOCATION

Ten hollow steel piles installed during the initial pile driving activity on the west side of the Vashon ferry dock were monitored. Figure 3 indicates the approximate location of the ten 24-inch piles used to retrofit the east side of the dock area and build the seismic braces.

The hydrophone is located at 10-11 meters from the piles. Monitoring at a range of 3H, where H is the water depth at the pile, was not necessary because the distance 3H was 10 meters or less.

Hydroacoustic monitoring of steel 24-inch-pile driving included:

- Measurement of noise levels at 10 to 11 meters from the pile.

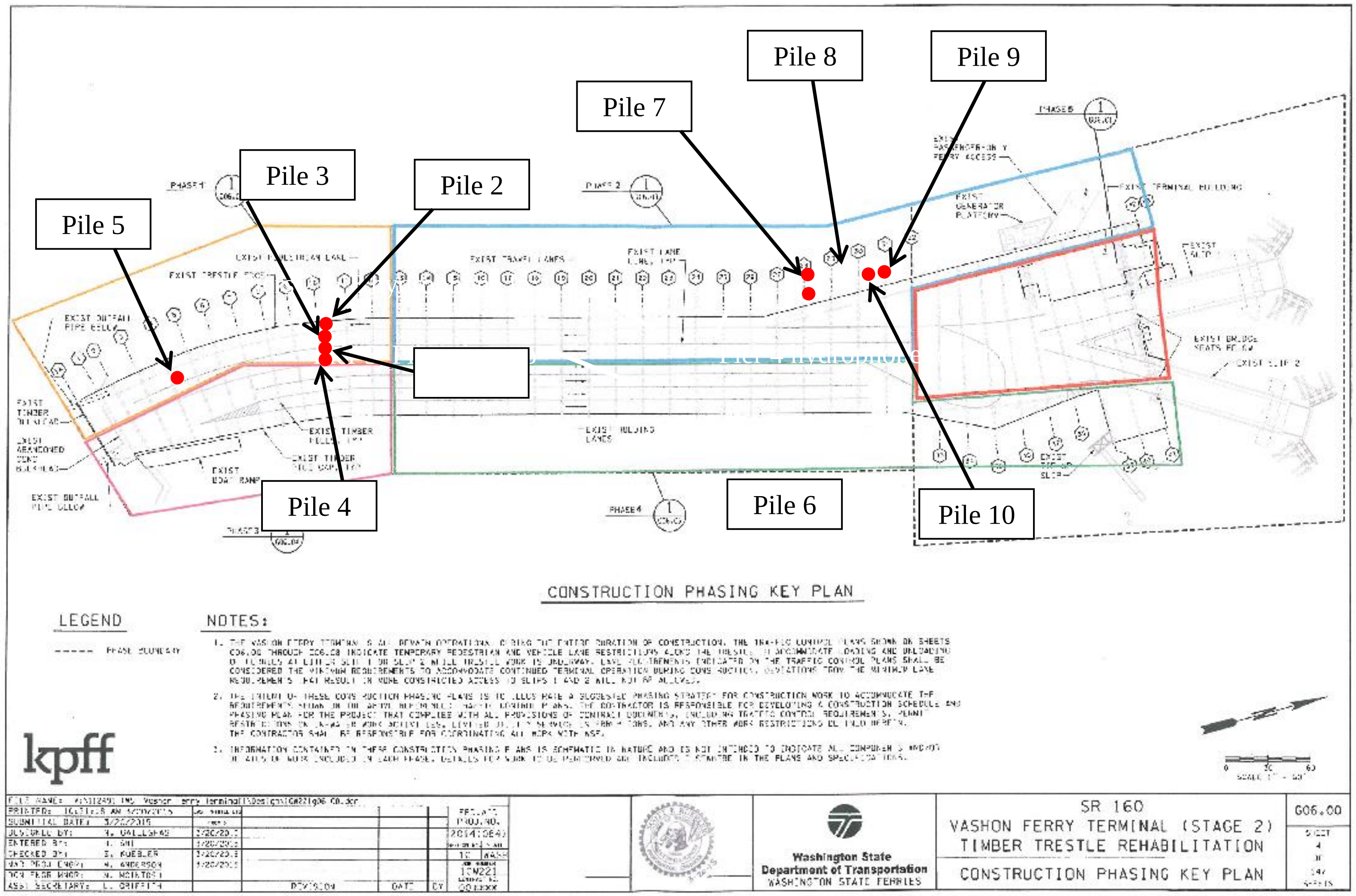
Table 2 lists the structure installed, the water depth, and the number and size of piles that were installed.

Table 2. Structures to be installed for the terminal retrofit and replacement

Structure		
Replacement Trestles	*5 feet to 12 feet*	*Fifty-three 24-inch steel piles*
Seismic Braces	*5 feet to 12 feet*	*Sixty-six 24-inch steel piles*

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 10-11 meters and midwater depth. Each pile has a clear acoustic line-of-sight between the pile and the hydrophone.

Figure 3: The locations of the ten monitored piles at the Vashon Ferry Terminal (not to scale)



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.

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.

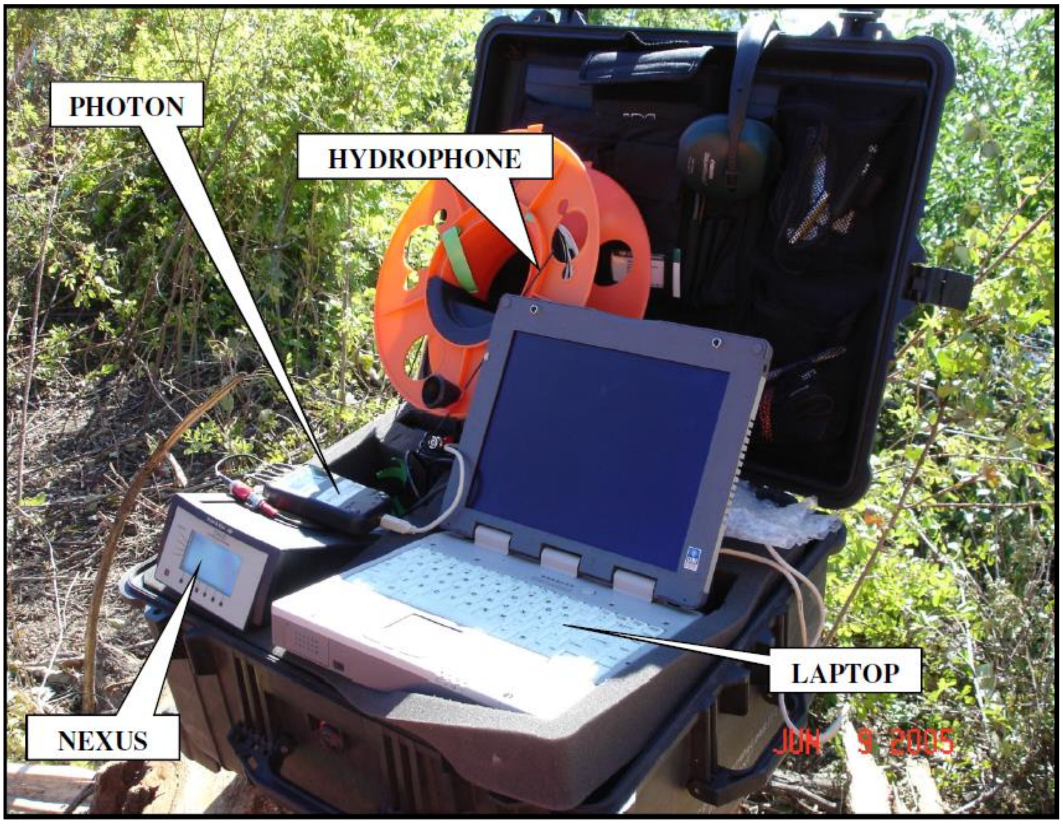
METHODOLOGY

Typical Equipment Deployment

The hydrophone was deployed from the shoreline near the piles. The monitoring equipment is outlined below and shown in Figure 4. The hydrophone was stationed and fixed with anchors and a surface float at a nominal distance of 10-11 meters from the pile.

A confined bubble curtain was deployed for all battered piles and an unconfined bubble curtain was deployed for all plumb piles driven to attenuate underwater noise.

Figure 4: Near Field Acoustical Monitoring Equipment



Ten 25-inch hollow steel piles, initially vibratory driven, were monitored with the sound attenuation bubble curtain system active when proofed with impact hammer. 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 10 meters in most cases 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 4. 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 4.

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.

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 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.

Sound thresholds for fish, marine mammals, and Marbled Murrelets were given in dB_{CSEL}, dB_{peak}, and dB_{RMS} at varying distances for the project. Since all of the project's piles were monitored at a distance of 10 meters, the given thresholds at a given distance from the pile were recalculated so that they reflected what that sound threshold would be at a uniform distance of 10 meters from the pile. These recalculations were performed using the following equation:

$$\text{Sound Level} = \text{Measured Level} + 10 \text{ LOG (Given Distance/10 meters)} \qquad \text{(eq. 3)}$$

The following thresholds were applied to this project.

For 24-inch piles

- 202 dB_{CSEL} at 32.8 feet (10 meters)
- 204 dB_{peak} at 32.8 feet (10 meters) for fish
- 195 dB_{RMS} at 32.8 feet (10 meters) for Cetaceans and Pinnipeds
- 182 dB_{RMS} at 32.8 feet (10 meters) for Cetaceans
- 176 dB_{RMS} at 32.8 feet (10 meters) for Pinnipeds
- 210 dB_{CSEL} at 32.8 feet (10 meters) for Marbled Murrelet auditory injury
- 212 dB_{CSEL} at 32.8 feet (10 meters) for Marbled Murrelet barotrauma injury

RESULTS

Underwater Sound Levels

WSDOT monitored a total of ten 24-inch steel hollow piles for underwater noise. Data from all piles are analyzed in the paragraphs below and summarized in Table 3.

Pile 1

Pile 1 is located approximately 180 feet from the shore of Vashon Island (Figure 3). The pile was driven with the unconfined bubble curtain and had an absolute attenuated peak value of 197 dB_{peak} at 11 meters which did not exceed the 204 dB_{peak} threshold for fish (Table 3). The attenuated $RMS_{90\%}$ was 182 $dB_{RMS90\%}$ which exceeds the 176 dB_{RMS} disturbance threshold for marine mammals but not the 182 dB_{RMS} injury threshold for cetaceans (Table 3). The cSEL at 10 meters was 192 dB cSEL calculated based on the accumulation of the single strike SEL for each pile strike (Table 3) and did not exceed the 202 dB_{cSEL} threshold for fish, the 210 dB_{cSEL} auditory injury, or the 212 dB_{cSEL} non-auditory injury cumulative thresholds for marbled murrelets (Table 3). The distance to the 176 dB_{RMS} threshold using the practical spreading model is 115 feet from the pile.

Pile 2

Pile 2 is located approximately 180 feet from the shore of Vashon Island and is adjacent to and to the west of Pile 1 (Figure 3) and was driven using an unconfined bubble curtain. The pile had an absolute attenuated peak value of 199 dB_{peak} at 10 meters which did not exceed the 204 dB_{peak} threshold for fish (Table 3). The attenuated $RMS_{90\%}$ was 183 $dB_{RMS90\%}$ at 10 meters which exceeds both the 176 dB_{RMS} disturbance threshold for marine mammals and the 182 dB_{RMS} injury threshold for cetaceans (Table 3). The cSEL at 10 meters calculated by accumulating the single strike SEL calculated for each pile strike is 196 dB_{cSEL} and did not exceed the 202 dB_{cSEL} threshold for fish, the 210 dB_{cSEL} auditory injury, or the 212 dB_{cSEL} non-auditory injury cumulative thresholds for marbled murrelets (Table 3). The distance to the 176 dB_{RMS} threshold using the practical spreading model from the pile location is 129 feet and the distance to the 182 dB_{RMS} threshold is 71 feet.

Pile 3

Pile 3 is located approximately 180 feet from the shore of the Vashon Island and adjacent to and to the west of Pile 1 (Figure 3) and was driven using an unconfined bubble curtain. The pile had an absolute attenuated peak value of 196 dB_{peak} at 10 meters which did not exceed the 204 dB_{peak} threshold for fish (Table 3). The attenuated $RMS_{90\%}$ was 179 $dB_{RMS90\%}$ at 10 meters which exceeds the 176 dB_{RMS} disturbance threshold for marine mammals but does not exceed the 182 dB_{RMS} injury threshold for cetaceans. The cSEL at 10 meters calculated by accumulating the single strike SEL calculated for each pile strike is 169 dB_{cSEL} and did not exceed the 202 dB_{cSEL} threshold for fish, the 210 dB_{cSEL} auditory injury, or the 212 dB_{cSEL} non-auditory injury cumulative thresholds for marbled murrelets (Table 3). The distance to the 176 dB_{RMS} threshold using the practical spreading model from the pile location is 85 feet.

Pile 4

Pile 4 is located approximately 180 feet from the shore of Vashon Island and adjacent to the east of Pile 1 (Figure 3) and was driven using an unconfined bubble curtain. The pile had an absolute attenuated peak value of 194 dB_{peak} at 10 meters which did not exceed the 204 dB_{peak} threshold for fish (Table 3). The attenuated $RMS_{90\%}$ was 177 $dB_{RMS90\%}$ at 10 meters which exceeds the 176 dB_{RMS} disturbance threshold for marine mammals but does not exceed the 182 dB_{RMS} injury threshold for cetaceans. The cSEL at 10 meters calculated by accumulating the single strike SEL calculated for each pile strike is 166 dB_{cSEL} and did not exceed the 202 dB_{cSEL} threshold for fish, the 210 dB_{cSEL} auditory injury, or the 212 dB_{cSEL} non-auditory injury cumulative thresholds for marbled murrelets (Table 3). The distance to the 176 dB_{RMS} threshold using the practical spreading model from the pile location is 71 feet.

Pile 5

Pile 5 is located approximately 78 feet from the shore of Vashon Island and approximately 96 feet to the south of Pile 1 (Figure 3) and was driven using an unconfined bubble curtain. The pile had an absolute attenuated peak value of 182 dB_{peak} at 10 meters which did not exceed the 204 dB_{peak} threshold for fish (Table 3). The attenuated $RMS_{90\%}$ was 173 $dB_{RMS90\%}$ at 10 meters which does not exceed the 176 dB_{RMS} disturbance threshold for marine mammals or the 182 dB_{RMS} injury threshold for cetaceans. The cSEL at 10 meters calculated by accumulating the single strike SEL calculated for each pile strike is 165 dB_{cSEL} and did not exceed the 202 dB_{cSEL} threshold for fish, the 210 dB_{cSEL} auditory injury, or the 212 dB_{cSEL} non-auditory injury cumulative thresholds for marbled murrelets (Table 3).

Pile 6

Pile 6 is located approximately 498 feet from the shore of Vashon Island and approximately 318 feet to the north of Pile 1 (Figure 3) and was driven using an unconfined bubble curtain. The pile had an absolute attenuated peak value of 198 dB_{peak} at 10 meters which did not exceed the 204 dB_{peak} threshold for fish (Table 3). The attenuated $RMS_{90\%}$ was 179 $dB_{RMS90\%}$ at 10 meters which exceeds the 176 dB_{RMS} disturbance threshold for marine mammals but does not exceed the 182 dB_{RMS} injury threshold for cetaceans. The cSEL at 10 meters calculated by accumulating the single strike SEL calculated for each pile strike is 167 dB_{cSEL} and did not exceed the 202 dB_{cSEL} threshold for fish, the 210 dB_{cSEL} auditory injury, or the 212 dB_{cSEL} non-auditory injury cumulative thresholds for marbled murrelets (Table 3). The distance to the 176 dB_{RMS} threshold using the practical spreading model from the pile location is 85 feet.

Pile 7

Pile 7 is a battered pile located approximately 498 feet from the shore of Vashon Island and adjacent to the west of Pile 6 (Figure 3) and was driven using a confined bubble curtain. The pile had an absolute attenuated peak value of 197 dB_{peak} at 10 meters which did not exceed the 204 dB_{peak} threshold for fish (Table 3). The attenuated $RMS_{90\%}$ was 184 $dB_{RMS90\%}$ at 10 meters which exceeds both the 176 dB_{RMS} disturbance threshold for marine mammals and the 182 dB_{RMS} injury threshold for cetaceans. The cSEL at 10 meters calculated by accumulating the single strike SEL calculated for each pile strike is 169 dB_{cSEL} and did not exceed the 202 dB_{cSEL} threshold for fish, the 210 dB_{cSEL} auditory injury, or the 212 dB_{cSEL} non-auditory injury cumulative thresholds for marbled murrelets (Table 3). The distance to the 176 dB_{RMS} threshold using the practical spreading model from the pile location is 184 feet and the distance to the 182 dB_{RMS} threshold is 78 feet.

Pile 8

Pile 8 is a battered pile located approximately 528 feet from the shore of Vashon Island and approximately 18 feet to the north of Pile 7 (Figure 3) and was driven using a confined bubble curtain. The pile had an absolute attenuated peak value of 201 dB_{peak} at 10 meters which did not exceed the 204 dB_{peak} threshold for fish (Table 3). The attenuated $RMS_{90\%}$ was 180 $dB_{RMS90\%}$ at 10 meters which exceeds the 176 dB_{RMS} disturbance threshold for marine mammals but does not exceed the 182 dB_{RMS} injury threshold for cetaceans. The cSEL at 10 meters calculated by accumulating the single strike SEL calculated for each pile strike is 172 dB_{cSEL} and did not exceed the 202 dB_{cSEL} threshold for fish, the 210 dB_{cSEL} auditory injury, or the 212 dB_{cSEL} non-auditory injury cumulative thresholds for marbled murrelets (Table 3). The distance to the 176 dB_{RMS} threshold using the practical spreading model from the pile location is 94 feet.

Pile 9

Pile 9 is located approximately 552 feet from the shore of Vashon Island and approximately 30 feet to the north of Pile 8 (Figure 3) and was driven using an unconfined bubble curtain. The pile had an absolute attenuated peak value of 196 dB_{peak} at 10 meters which did not exceed the 204 dB_{peak} threshold for fish (Table 3). The attenuated $RMS_{90\%}$ was 180 $dB_{RMS90\%}$ at 10 meters which exceeds the 176 dB_{RMS} disturbance threshold for marine mammals but does not exceed the 182 dB_{RMS} injury threshold for cetaceans. The cSEL at 10 meters calculated by accumulating the single strike SEL calculated for each pile strike is 166 dB_{cSEL} and did not exceed the 202 dB_{cSEL} threshold for fish, the 210 dB_{cSEL} auditory injury, or the 212 dB_{cSEL} non-auditory injury cumulative thresholds for marbled murrelets (Table 3). The distance to the 176 dB_{RMS} threshold using the practical spreading model from the pile location is 94 feet.

Pile 10

Pile 10 is located approximately 552 feet from the shore of Vashon Island and adjacent to the south of Pile 9 (Figure 3) and was driven using an unconfined bubble curtain. The pile had an absolute attenuated peak value of 189 dB_{peak} at 10 meters which did not exceed the 204 dB_{peak} threshold for fish (Table 3). The attenuated $RMS_{90\%}$ was 177 $dB_{RMS90\%}$ at 10 meters which exceeds the 176 dB_{RMS} disturbance threshold for marine mammals but does not exceed the 182 dB_{RMS} injury threshold for cetaceans. The cSEL at 10 meters calculated by accumulating the single strike SEL calculated for each pile strike is 164 dB_{cSEL} and did not exceed the 202 dB_{cSEL} threshold for fish, the 210 dB_{cSEL} auditory injury, or the 212 dB_{cSEL} non-auditory injury cumulative thresholds for marbled murrelets (Table 3). The distance to the 160 dB_{RMS} threshold using the practical spreading model from the pile location is 71 feet.

Table 3: Summary of Underwater Broadband Sound Levels for the SR 160 Vashon Ferry Terminal Project

Pile #	Date & Time	Pile Diameter (inches)	Hydrophone Range (m)	Hydrophone Depth (feet)	Bubble Curtain Status	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	9/2/2015 8:00 AM	24	11	5	On	420	197	182	171	3787±1039	675±176	192
2	9/2/2015 8:56 AM	24	10	5	On	656	199	183	171	5614±1559	1014±213	196
3	9/2/2015 10:44 AM	24	10	5	On	507	196	179	169	5029±777	892±118	195
4	9/9/2015 2:27 PM	24	10	5	On	374	194	177	166	3684±800	705±733	195
5	9/9/2015 3:10 PM	24	10	2.5	On	331	182	173	165	915±124	275±45	184
6	10/6/2015 12:15 PM	24	10	4	On	474	198	179	167	5047±760	1408±295	195
7	10/21/2015 11:35 AM	24	10	6	On	70	197	184	169	4563±1141	1116±193	185
8	10/21/2015 12:20 PM	24	10	6	On	78	201	180	172	6191±950	1811±279	189
9	10/21/2015 1:25 PM	24	10	6	On	33	196	180	166	3663±1030	744±164	179
10	10/21/2015 2:12 PM	24	10	6	On	82	189	177	164	2219±299	562±57	181

Daily Cumulative SEL

The daily cSEL's were calculated using an actual $SEL_{90\%}$ for each individual pile strike for each day and accumulated over that period (Table 4).

Table 4: Summary of daily cumulative SEL's

Day	10M
9/2/15	200
9/9/15	196
10/6/15	195
10/21/15	191

The daily cumulative SEL values ranged from 191 to 200 dB at the 10 meter location. There were no exceedances of the 202 dB_{cSEL} threshold during any of the four 24 hour periods.

Airborne Sound Levels

The airborne measurements were collected from the nearest location to the pile on the dock between 13 meters and 15 meters from the piles. Fifteen 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.

The overall A-weighted L_{Aeq} values for the entire pile drive ranged between 95 dBA and 96 dBA at 50 feet and the L_{max} ranged between 107 dBA and 108 dBA at 50 feet (Table 5). The overall un-weighted L_{eq} values for the entire pile drive was 93 dB at 50 feet and the L_{max} was 109 dB at 50 feet (Table 5). The measured levels are all standardized to a distance of 50 feet which is standard for reporting construction noise levels. Not all piles were monitored for airborne sound levels due to weather (rain) or insufficient staff to collect the measurements. However, we feel that the data collected is representative of the sound levels for all 24-inch steel piles at this location.

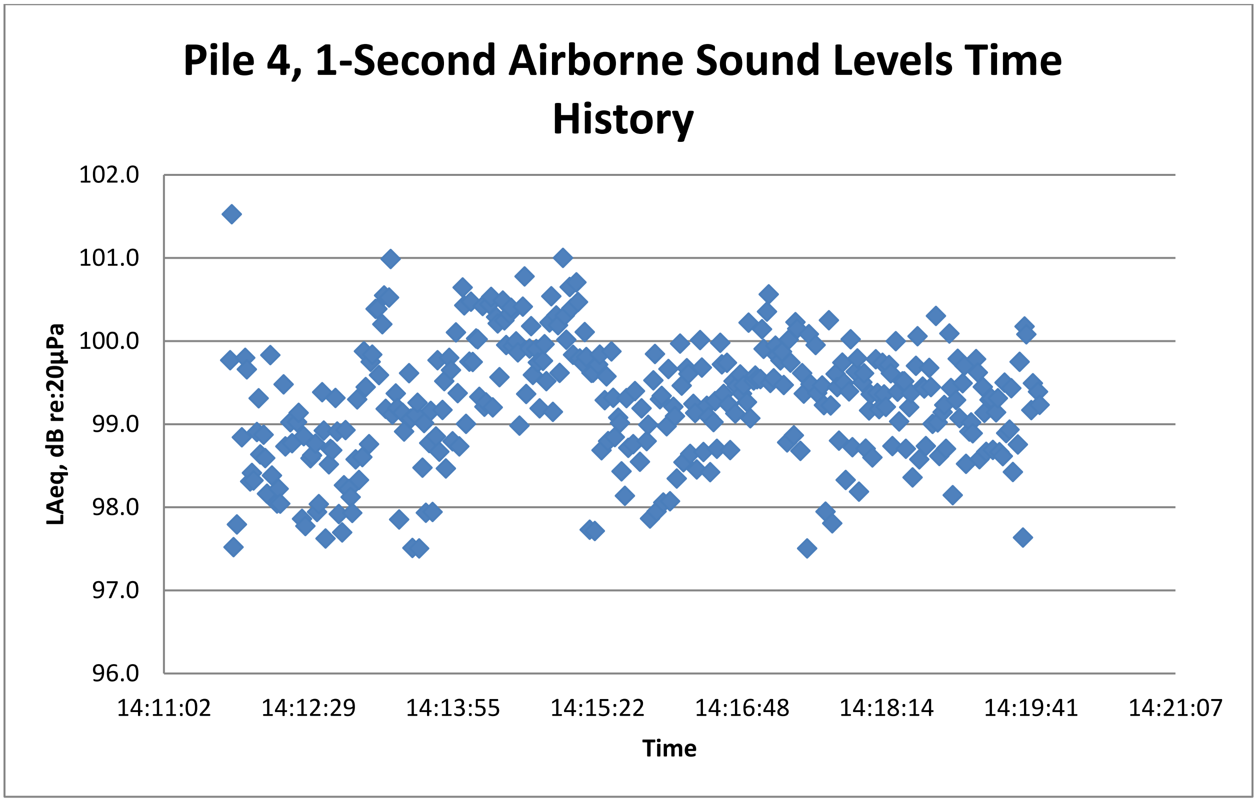
Table 5: Summary of 24-inch steel pile overall airborne sound levels collected between September 2, 2015 and October 21, 2015

Pile #	Distance from Pile (m)	15-min L_{Aeq} (dBA)	L_{Aeq} at 50 feet (dBA)	L_{max} (dBA)	L_{max} at 50 feet (dBA)
4	15	96	96	108	108
5*	15	93	93	109	109
6 part 1	13	96	95	109	108
6 part 2	13	96	95	108	107

*Un-weighted

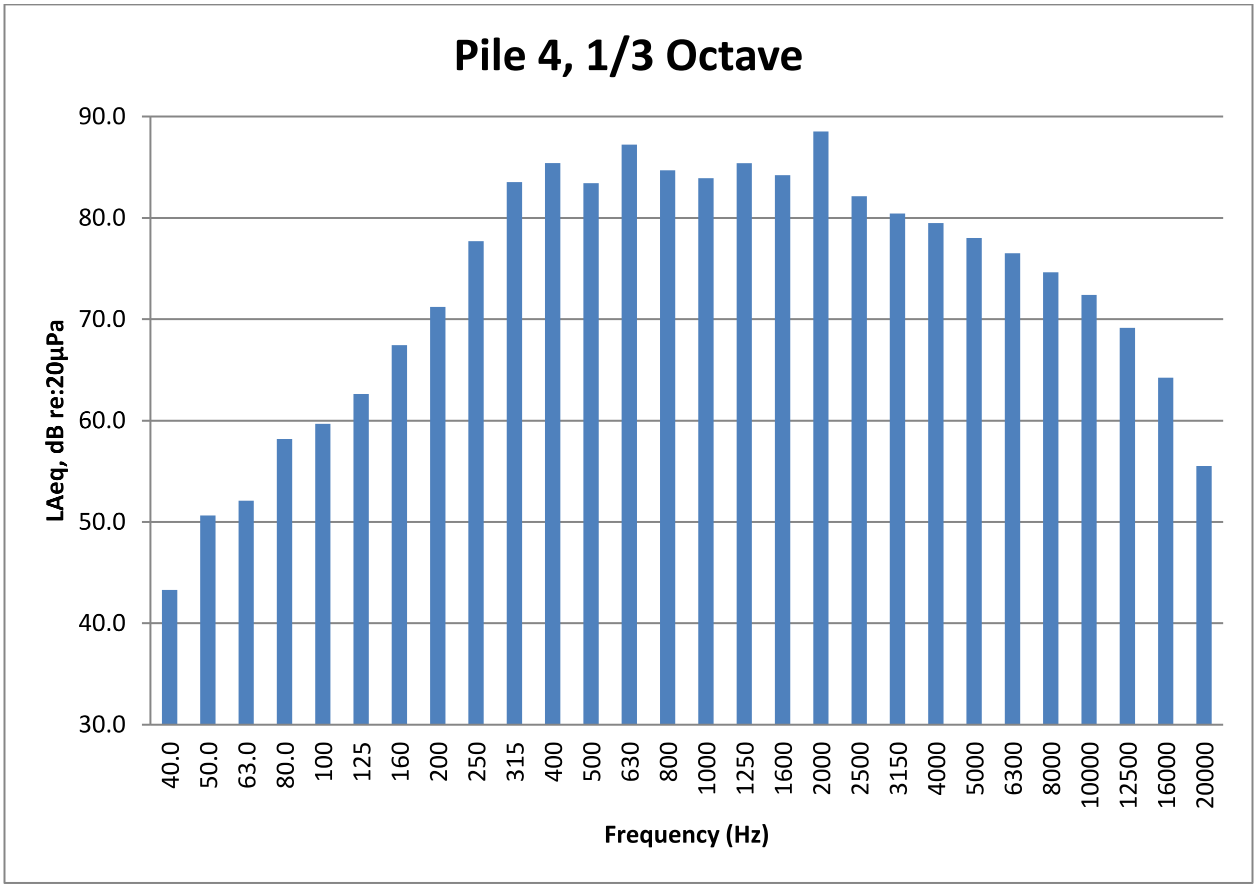
The A-weighted airborne time history plot of each individual pile strike measured for Pile 4 is shown in Figure 5. These results are typical of each A-weighted pile measured. The one second L_{Aeq} sound levels for each pile strike for Pile 4 ranged between approximately 97.5 dBA and 101.5 dBA. Time history plots of the other piles measured are in Appendix B.

Figure 5: One second time history of L_{Aeq} airborne sound levels for each pile strike for Pile 4



The 1/3rd octave band frequencies were averaged for each pile strike of Pile 4 and plotted in Figure 6. The plot shows a relatively normal distribution of sound levels between 40 Hz and 20 kHz with the dominant frequency at approximately 2 kHz with a secondary peak at approximately 630 Hz which is typical of impact pile driving sound levels. The results are typical of the other piles measured.

Figure 6: Average 1/3rd octave band frequencies (L_{Aeq}) for impact driving of Pile 4



CONCLUSIONS

A total of 10, 24-inch diameter hollow steel piles were monitored for the construction of the SR 160 Vashon Terminal Retrofit project. The underwater sound levels analyzed, produced the following results.

- Peak underwater attenuated sound levels at 10 meters varied in a range between 182 dB_{Peak} and 201 dB_{Peak} .
- The measured $RMS_{90\%}$ levels ranged between 173 dB_{RMS} and 184 dB_{RMS}.
- Cumulative Sound Exposure Levels (cSEL) for all piles driven on a particular day, ranged between 191 dB_{cSEL} and 200 dB_{cSEL}.
- The distance measured from the pile location to the 160 dB_{RMS} threshold ranged between 445 feet and 1,306 feet from the pile.

Three 24-inch steel piles were monitored for A-weighted airborne sound levels and one monitored for un-weighted airborne sound levels during impact driving. The measurements produced the following results.

- L_{Aeq} sound levels were measured to be between 95 and 96 dB re: 20 μPa at 50 feet.
- L_{max} levels ranged between 107 and 108 dB re: 20 μPa at 50 feet.

APPENDIX A WAVEFORM ANALYSIS FIGURES

Figure 7: Waveform Analysis of attenuated Pile 1, 11M

Vashon 24 inch Pile 1 at 11m Broadband

Figure a. Waveform

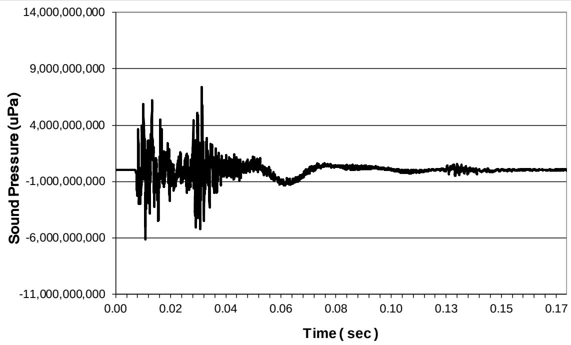


Figure b. Narrow Band Frequency Spectra

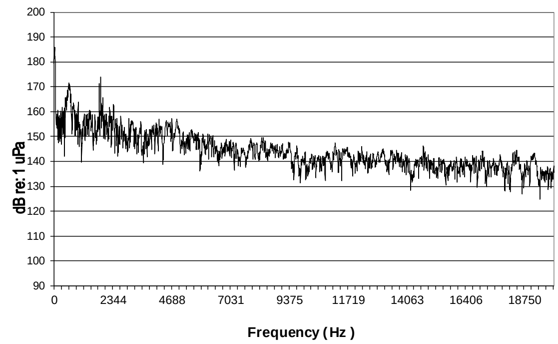


Figure c. Accumulation of Sound Energy

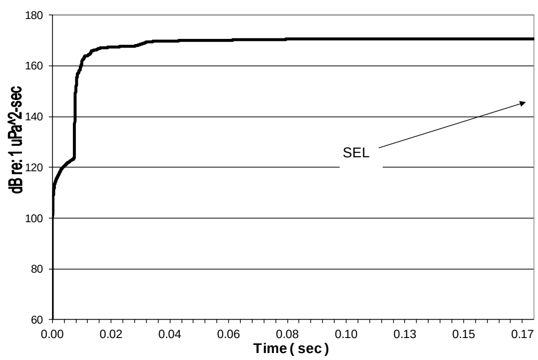


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
5-feet	197	182	171

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

Figure 8: Waveform analysis of attenuated Pile 2, 10M

Vashon 24 inch Pile 2 at 10m Broadband

Figure a. Waveform

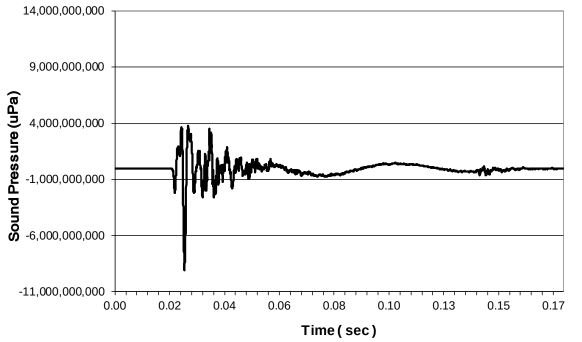


Figure b. Narrow Band Frequency Spectra

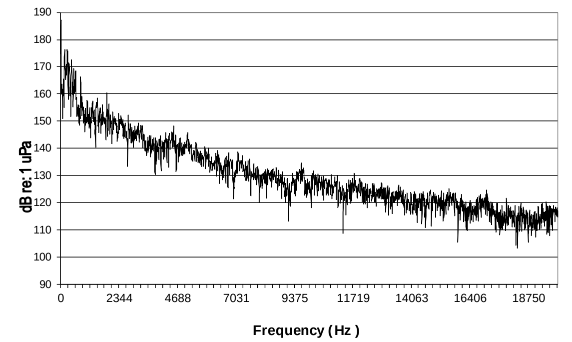


Figure c. Accumulation of Sound Energy

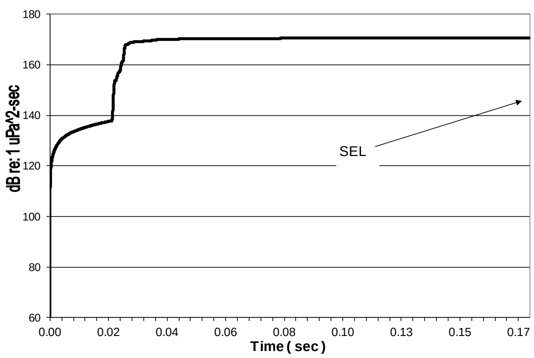


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
5-feet	199	183	171

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

Figure 9: Waveform analysis of attenuated Pile 3, 10M

Vashon 24 inch Pile 3 at 10m Broadband

Figure a. Waveform

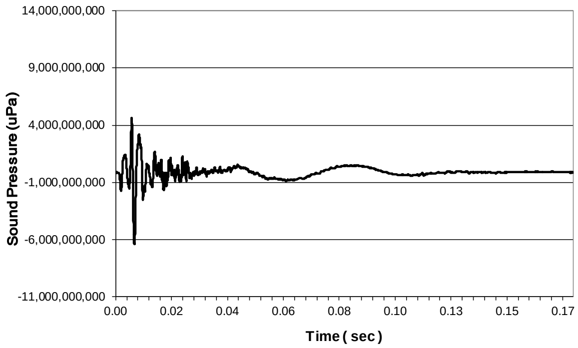


Figure b. Narrow Band Frequency Spectra

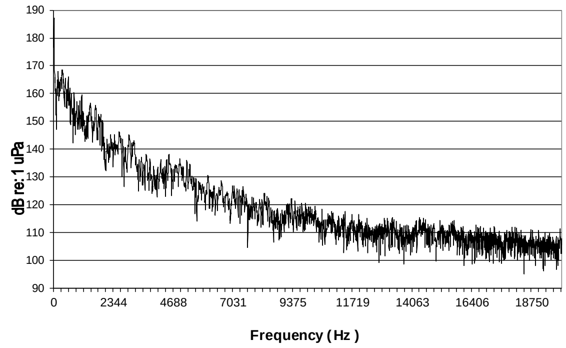


Figure c. Accumulation of Sound Energy

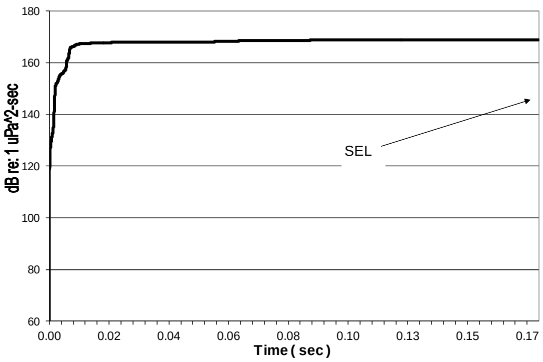


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
5-feet	196	179	169

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

Figure 10: Waveform analysis of attenuated Pile 4, 10M

Vashon 24 inch Pile 4 at 10m Broadband

Figure a. Waveform

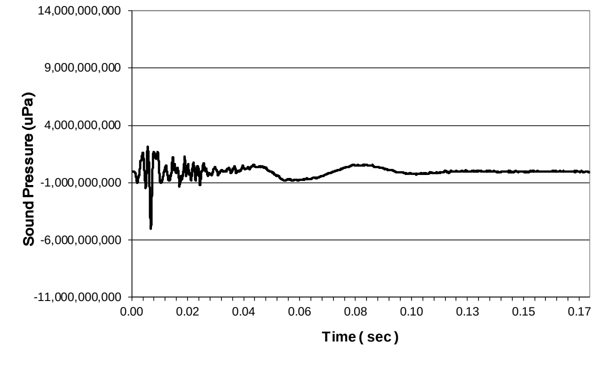


Figure b. Narrow Band Frequency Spectra

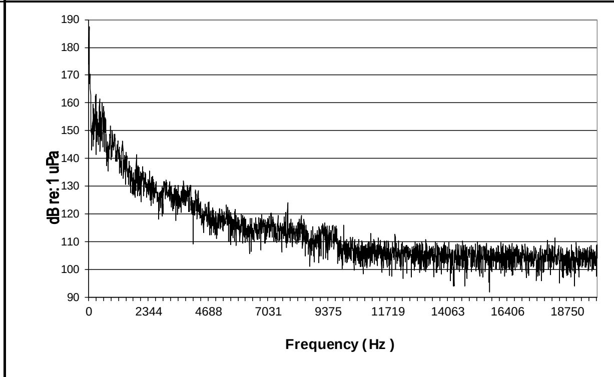


Figure c. Accumulation of Sound Energy

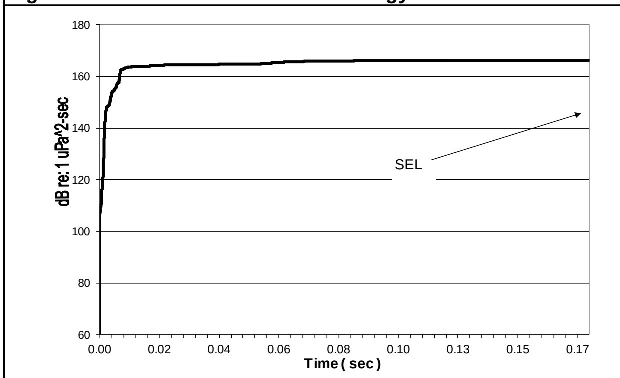


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	$RMS_{90\%}$*	SEL
5-feet	194	177	166

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

Figure 11: Waveform analysis of attenuated Pile 5, 10M

Vashon 24 inch Pile 5 at 10m Broadband

Figure a. Waveform

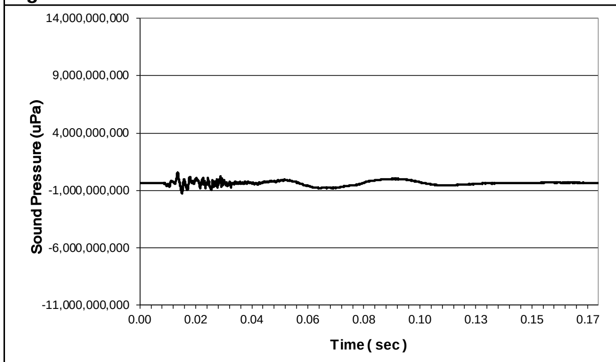


Figure b. Narrow Band Frequency Spectra

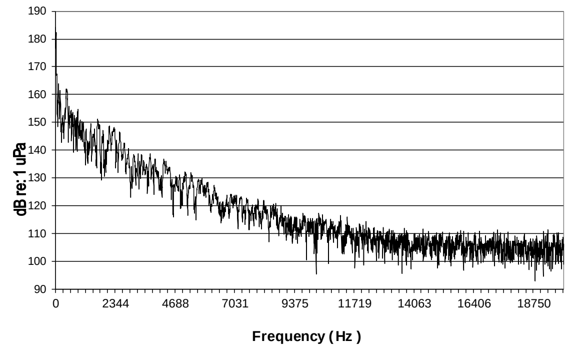


Figure c. Accumulation of Sound Energy

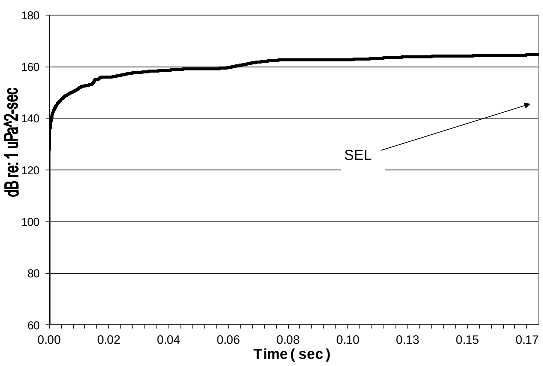


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
12:00:00	182	173	165

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

Figure 12: Waveform analysis of attenuated Pile 6, 10M

Vashon 24 inch Pile 6 at 10m Broadband

Figure a. Waveform

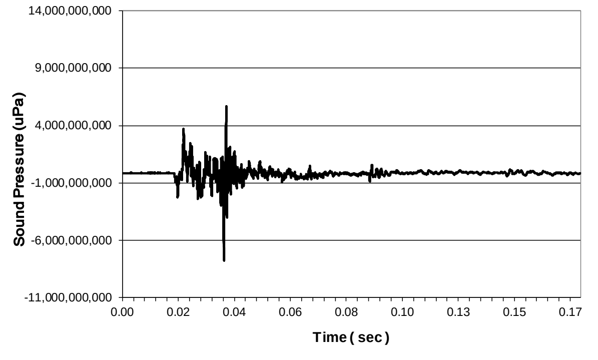


Figure b. Narrow Band Frequency Spectra

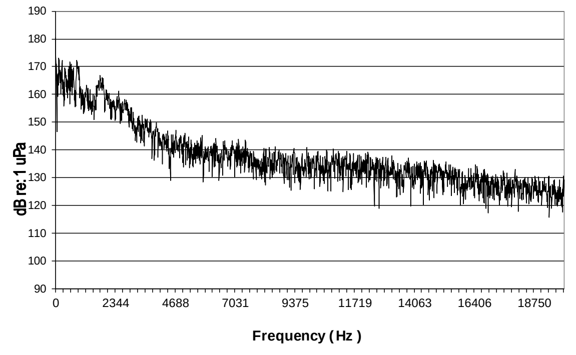


Figure c. Accumulation of Sound Energy

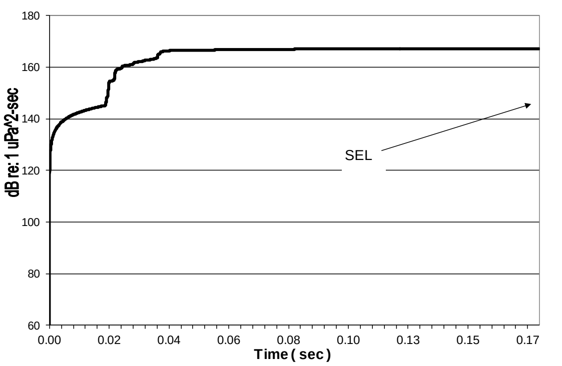


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	$RMS_{90\%}$*	SEL
0:00:00	198	179	167

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

Figure 13: Waveform analysis of attenuated Pile 7, 10M

Vashon 24 inch Pile 7 at 10m Broadband

Figure a. Waveform

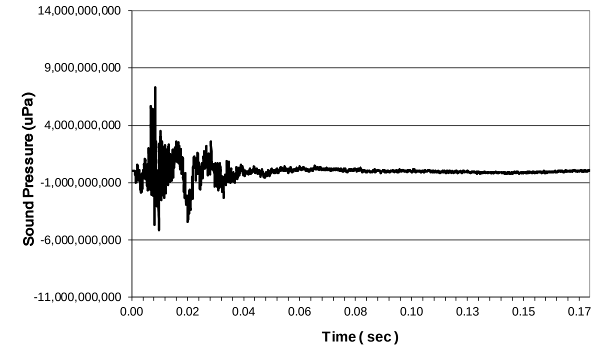


Figure b. Narrow Band Frequency Spectra

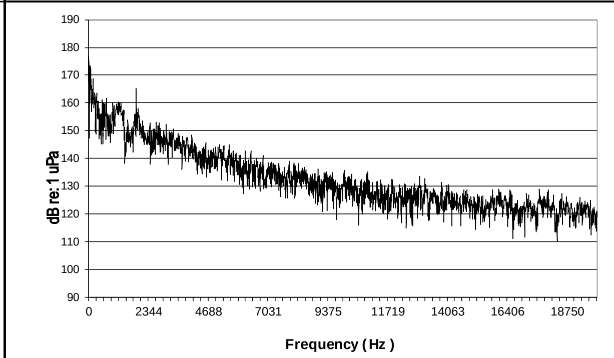


Figure c. Accumulation of Sound Energy

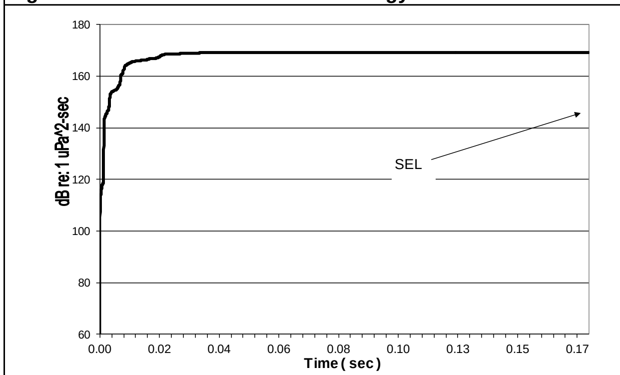


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
0:00:00	197	184	169

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

Figure 14: Waveform analysis of attenuated Pile 8, 10M

Vashon 24 inch Pile 8 at 10m Broadband

Figure a. Waveform

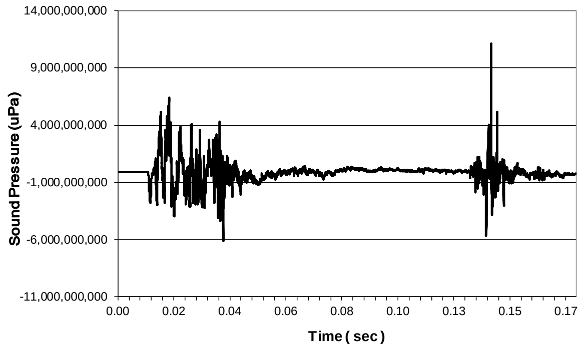


Figure b. Narrow Band Frequency Spectra

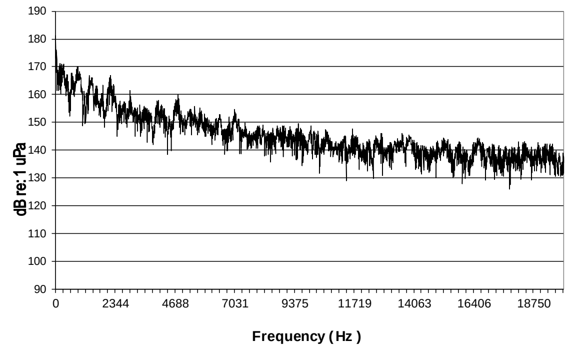


Figure c. Accumulation of Sound Energy

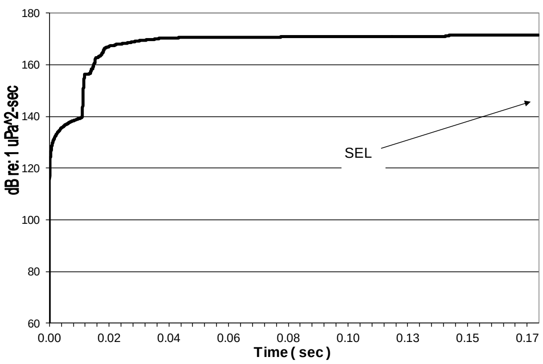


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
0:00:00	201	180	172

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

Figure 15: Waveform analysis of attenuated Pile 9, 10M

Vashon 24 inch Pile 9 at 10m Broadband

Figure a. Waveform

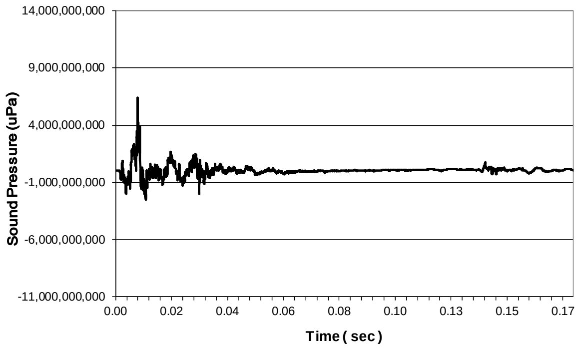


Figure b. Narrow Band Frequency Spectra

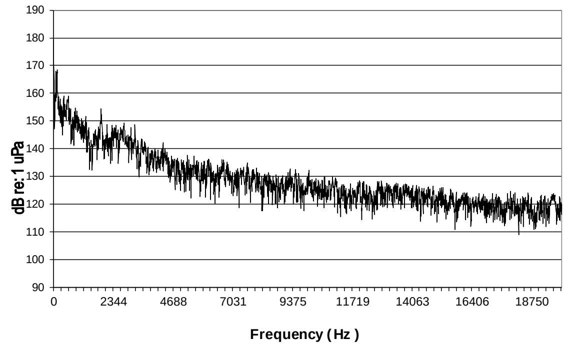


Figure c. Accumulation of Sound Energy

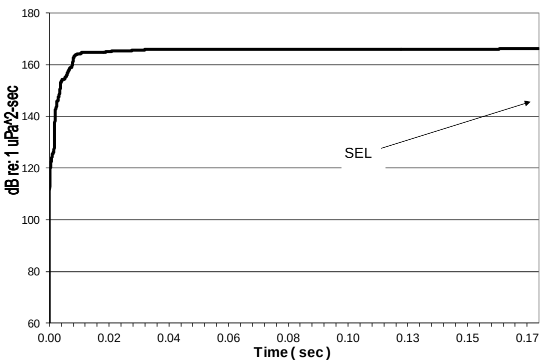


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
0:00:00	196	180	166

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

Figure 16: Waveform analysis of attenuated Pile 10, 10M

Vashon 24 inch Pile 10 at 10m Broadband

Figure a. Waveform

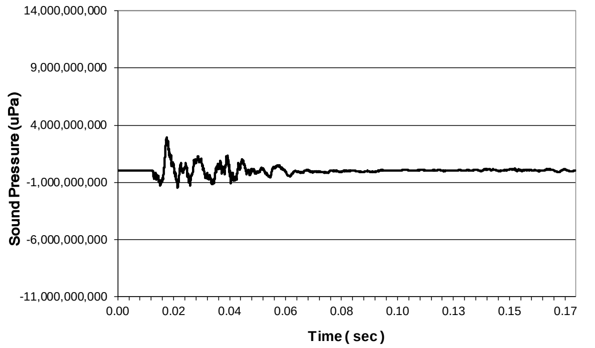


Figure b. Narrow Band Frequency Spectra

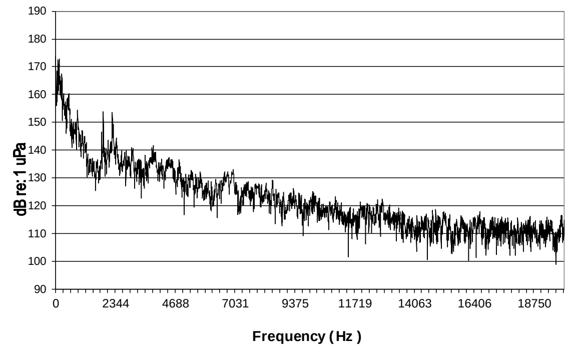


Figure c. Accumulation of Sound Energy

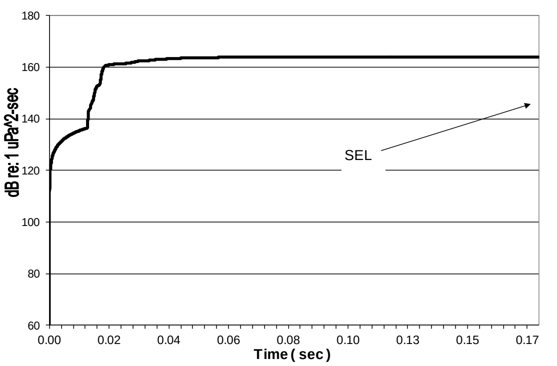


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
0:00:00	189	177	164

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

APPENDIX B AIRBORNE SOUND ANALYSIS FIGURES

Figure 17: Pile 4 One Second Airborne Time History

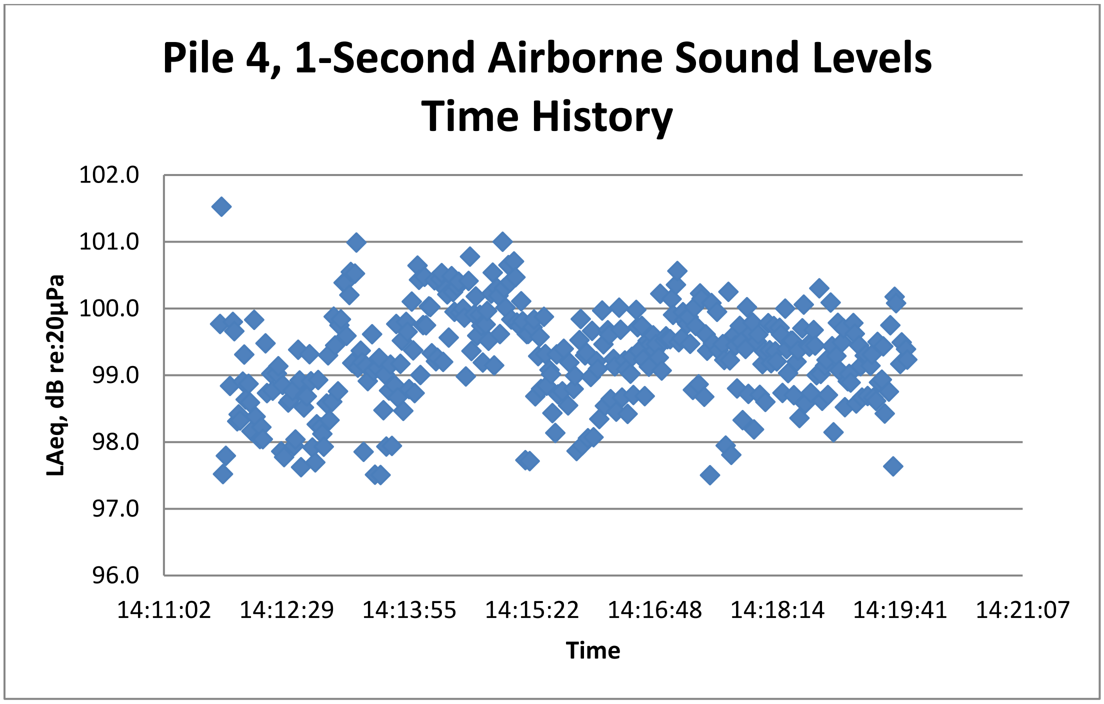


Figure 18: Pile 4 Airborne 1/3rd Octave

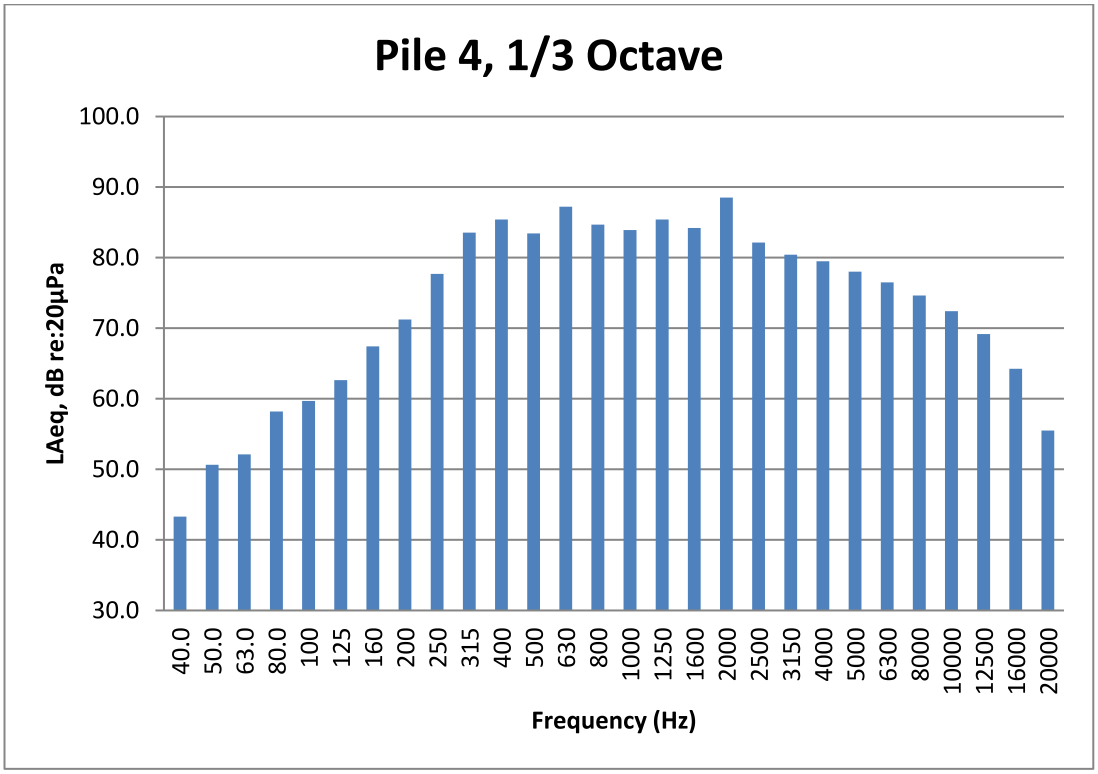


Figure 19: Pile 5 One Second Airborne Time History

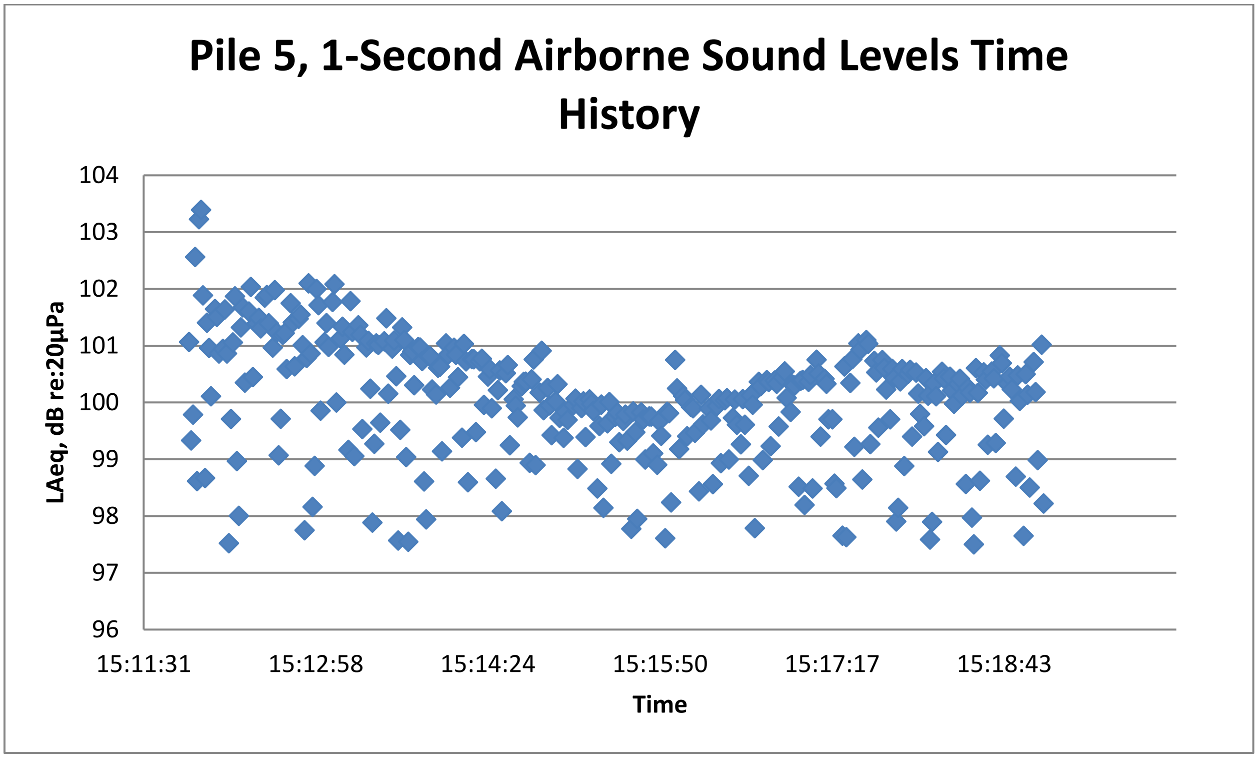


Figure 20: Pile 5 Airborne 1/3rd Octave

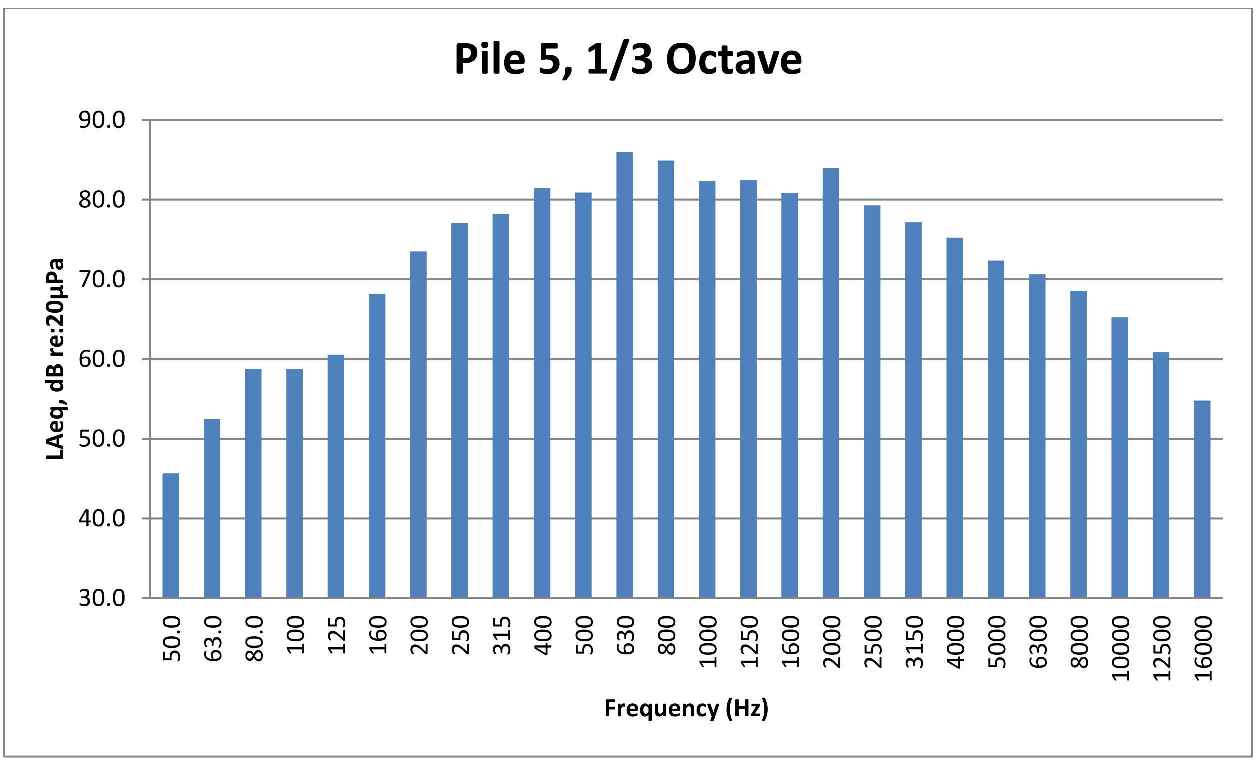


Figure 21: Pile 6 part 1 One Second Airborne Time History

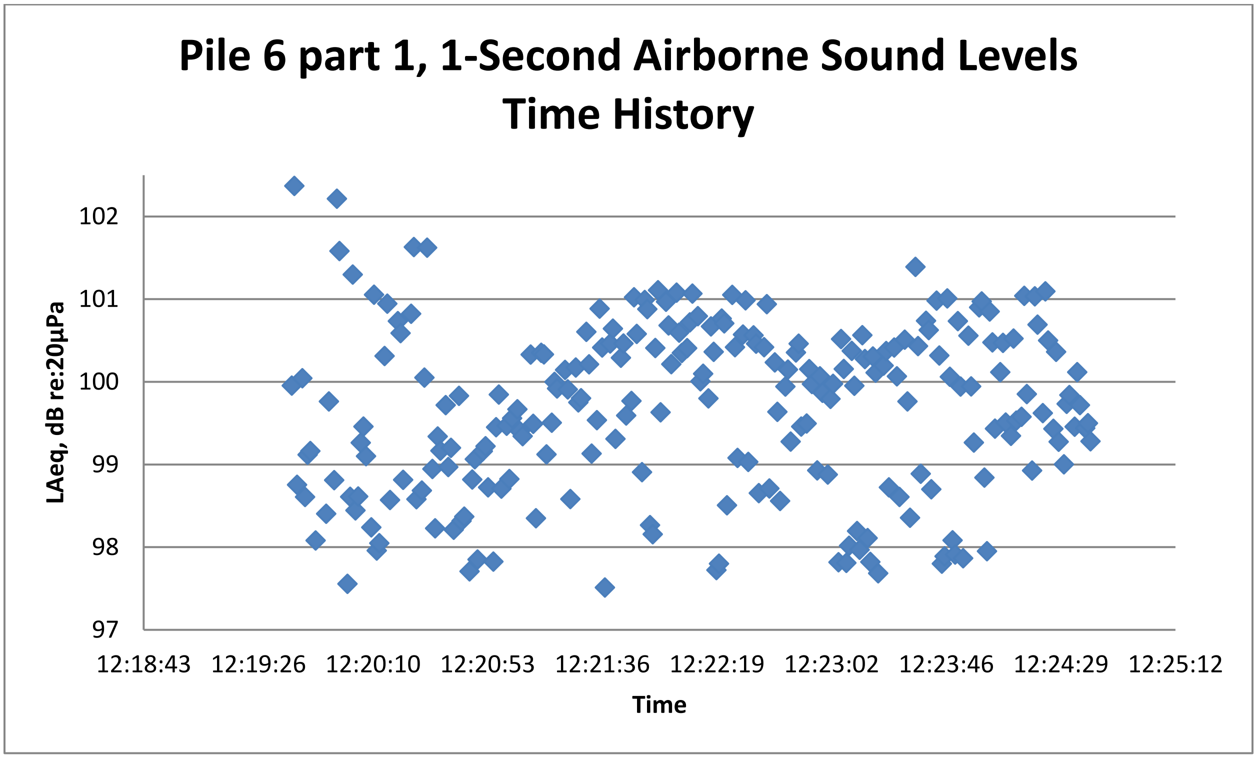


Figure 22: Pile 6 part 1 Airborne 1/3rd Octave

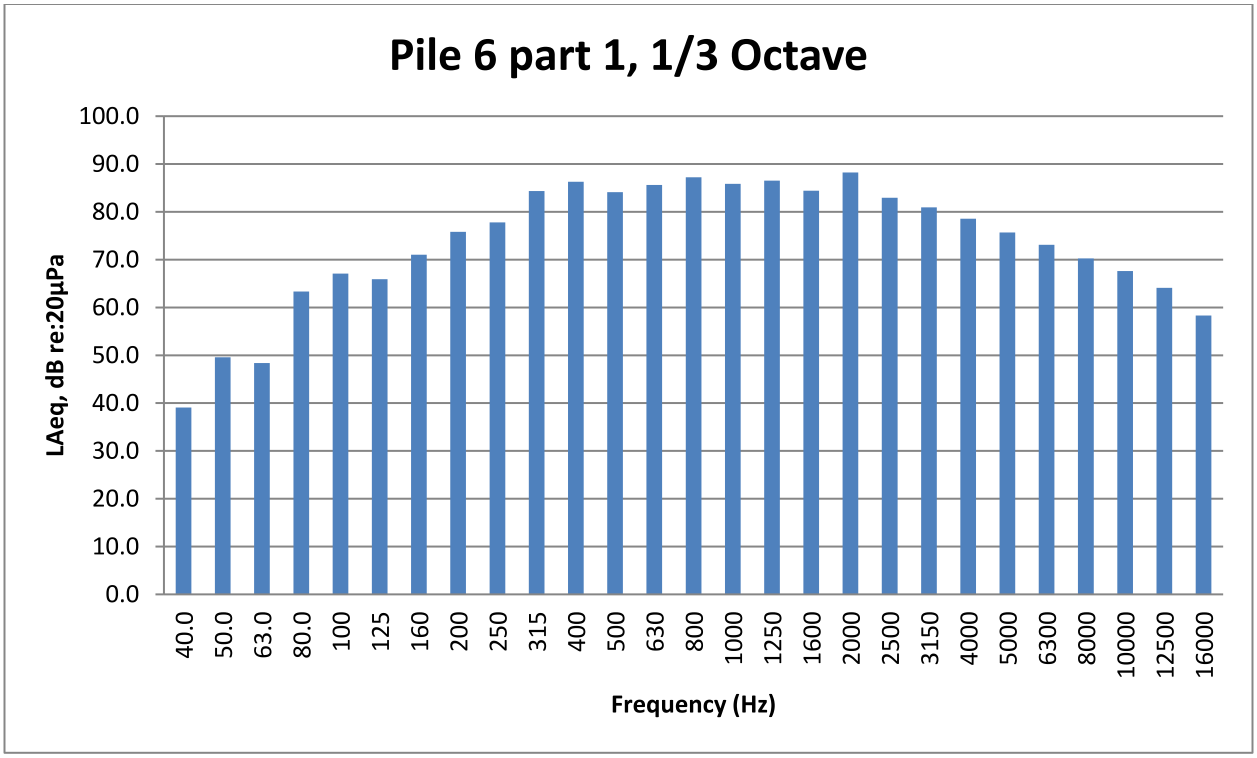


Figure 23: Pile 6 part 2 One Second Airborne Time History

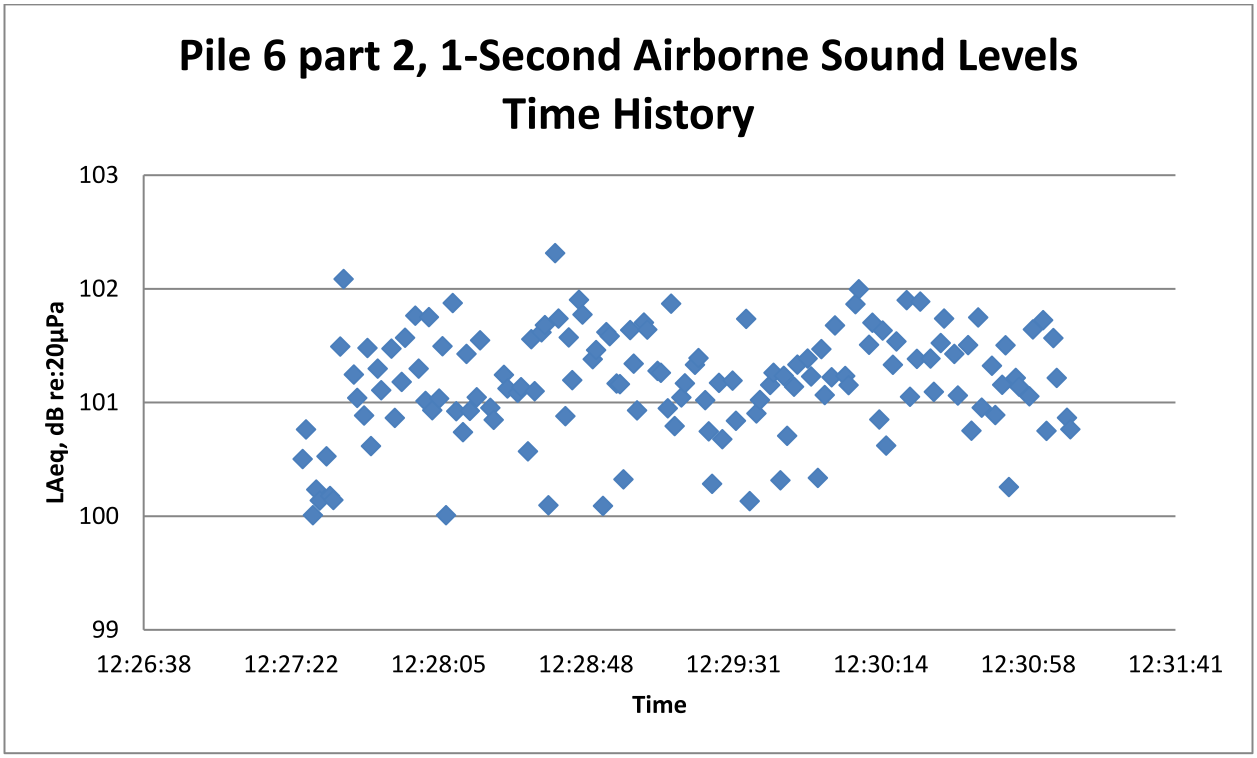


Figure 24: Pile 6 part 2 Airborne 1/3rd Octave