SR 20/Coupeville Ferry Terminal Timber Towers Preservation Project

UNDERWATER NOISE MONITORING REPORT

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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
WSDOT	Washington State Department of Transportation

1 EXECUTIVE SUMMARY

This technical report describes the data collected during impact pile driving and monitoring of underwater sound levels from driving the 24-inch steel piles for the Washington State Department of Transportation (WSDOT) at the Coupeville Ferry Terminal in September of 2016. Data was collected for four, 24-inch piles. Unconfined bubble curtains were deployed for all piles impact driven to attenuate potential underwater noise effects. All measurements were collected 10 meters from the pile.

None of the attenuated piles monitored exceeded the 206 dB_{peak} threshold for fish. The peak attenuated sound levels measured ranged between 197 dB_{peak} and 206 dB_{peak} while monitoring the impact pile driving operation as shown in Table 1. The daily cSEL for fish for all four piles monitored exceeded the threshold of 187 dB_{cSEL} at 10 meters. All four piles had exceedences for the 150 dB_{RMS} for Murrelet and 160 dB_{RMS} for Marine Mammal behavioral disturbances.

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

Pile #	Date	Hydro-phone Range (m)	Peak Threshold (dB)	Cumulative SEL (dB)	Lower Frequency Range (Hz)	RMS 90% (dB)	Single Strike SEL90 % (dB)	Absolute Highest Peak (dB)
1	9/15/16	10	206	198	Broadband	190	175	204
					7	190	175	204
					50	190	175	204
					60	190	175	204
					150	190	175	204
					275	188	173	203
2	9/16/16	12	206	200	Broadband	193	178	206
					7	193	178	206
					50	193	178	206
					60	193	178	206
					150	193	178	206
					275	192	176	204
3	9/17/16	10	206	194	Broadband	180	170	197
					7	185	170	197

Pile #	Date	Hydro-phone Range (m)	Peak Threshold (dB)	Cumulative SEL (dB)	Lower Frequency Range (Hz)	RMS 90% (dB)	Single Strike SEL90% (dB)	Absolute Highest Peak (dB)
					50	186	170	197
					60	186	170	197
					150	186	170	197
					275	185	169	195
4	9/17/16	10	206	198	Broadband	187	174	201
					7	190	173	201
					50	190	173	201
					60	190	173	201
					150	189	173	201
					275	184	171	200

2 INTRODUCTION

The Washington State Ferries (WSF) proposes to seismically retrofit the existing timber towers at the Coupeville Ferry Terminal. This project will refurbish two existing timber towers at the Ferry Terminal by installing four additional 24-inch steel piles at each tower, and a reinforced concrete cap at the headframe of the towers in order to strengthen and provide enhanced resistance to seismic motion. See vicinity map (Figure 1).

Figure 1. Vicinity map of SR 20/Coupeville Ferry Terminal

This report summarizes the impacted pile driving results measured at the Coupeville Ferry Terminal in an effort to collect site-specific data on underwater and airborne noise levels.

The report presents data collected during the pile driving at the Coupeville Ferry Terminal facility on Whidbey Island during the months of September 2016. Four 24-inch diameter steel piles were monitored on three separate days as they were driven with an impact hammer. This report applies frequency filters to the underwater acoustic measurements.

• Underwater sound levels quoted in this report are given in decibels relative to the standard underwater acoustic reference pressure of 1 micropascal.

• Airborne noise levels were measured as A-weighted and un-weighted sound levels. Airborne noise levels in this report use the acoustic reference pressure of 20 micropascal.

The intrusive sounds that frequently occurred for a period associated with the use of impact hammer may produce injury; harassment-level or disturbance-level take of ESA listed marine mammals. This occurs when the sound exceeds the thresholds shown in Table 2.

Table 2: Marine Mammal, Fish and Marble Murrelet thresholds for Marine Construction Activity

Functional Hearing Group	**Airborne Noise Thresholds**	**Underwater Noise Thresholds**		
	In air Sound Pressure Level (RMS)	**Impact Pile Driving Disturbance Threshold**	**Auditory Injury Threshold**	
		dB RMS	dB Peak SPL	dB Cumulative SEL
Low-frequency Cetaceans	NA	160 dB RMS	219	183
Mid-frequency Cetaceans	NA	160 dB RMS	230	185
High-frequency Cetaceans	NA	160 dB RMS	202	155
Harbor Seals	90 dB RMS (un-weighted, re: 20 µPa²sec)	160 dB RMS	218	185
Non-harbor seal pinnipeds	100 dB RMS (un-weighted, re: 20 µPa²sec)	160 dB RMS	232	203
Fish ≥ 2 grams	NA	Behavior effects threshold 150 dB RMS	206	187
Fish < 2 grams	NA		206	183
Marble Murrelet	NA	Potential Behavior Response Zone 150 dB RMS	208	202

Marine Mammal Injury and Disturbance Thresholds Hearing Frequency Groups:

Low-frequency Cetaceans = baleen whales (includes humpback, Northern minke, Sei, gray, blue)

Mid-frequency Cetaceans = dolphins, toothed whales, beaked whales, bottle nose whales (includes sperm whale, killer whale, bottlenose dolphin, Pacific White-sided dolphin)

High-frequency Cetaceans = true porpoises, river dolphins, cephalorhynchid. (Dall's Porpoise)

Phocid Pinnipeds – true seals (harbor seal, Northern elephant sea, ribbon seal).

Non-Harbor seal Pinnipeds – sea lions, fur seals (California and Stellars sea lion, northern fur seal)

These are the thresholds that NMFS has determined would result in Level A Harassment (injury) and Level B Harassment (disturbance) to marine mammals, Fish and Marble Murrelet.

All the four monitored piles exceeded the cSEL threshold of 155 dB_{cSEL} to 183 dB_{cSEL} for all marine mammals except for the Non-harbor seal pinnipeds at 275 Hz. Pile 2 has exceeded the peak sound pressure level threshold of 202 dB_{peak} for the High-frequency Cetaceans. All the four monitored piles exceeded the behavior effects threshold RMS of 160 dB_{RMS} for all marine mammals, fish and marble Murrelet of 160 dB_{RMS}, and all piles have exceeded the auditory injury threshold for all Cetaceans and Harbor Seals. Results of monitoring the impact pile driving operation are shown in Table 1.

3 PROJECT AREA

The Coupeville Ferry Terminal is located on Whidbey Island, Harbor/Admiralty Inlet, Island County, Washington. The terminal is located in Section 22, Township 31 North, Range 1 East. The terminal serves State Route 20. The project is in the USGS hydrologic unit for Puget Sound, 171100.

The towers at the Coupeville Ferry Terminal needed to be upgraded due to scour from the ferry propellers that were reducing pile embedment. Eight, 24-inch diameter hollow steel piles were installed to support the towers, and concrete caps were installed on top of the towers in order to support the headframe that houses the pulleys for the transfer span cables. Five to seven 12-inch timber piles were removed to allow room for the new steel piles to be installed.

The project was completed in one in-water work window. The work took place from a barge containing a derrick, crane and other necessary equipment.

4 PILE INSTALLATION LOCATION

Four hollow steel piles installed during the initial pile driving activity at the Coupeville Ferry Terminal were monitored. Figure 2 indicates the approximate location of the Coupeville Ferry Terminal timber towers to be replaced and the location of the eight, 24-inch steel piles to be driven as part of the towers preservation project.

The hydrophone was located at 10 meters from each pile monitored and placed at mid-water depth. The depth of the water where the hydrophone was deployed ranged between 15 feet to 18.6 feet deep.

Figure 2. Approximate Location of the Coupeville Ferry Terminal Timber Towers

5 UNDERWATER SOUND LEVELS

5.1 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 Pascal (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 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

$$dB = 10*LOG\ (\text{sum of squared pressures in the band}) \qquad \text{(eq. 1)}$$

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.

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:

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

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 the recordings where $SEL_{90\%}$ calculation is not possible, to for each pile strike the cumulative SEL can be calculated using the following equation.

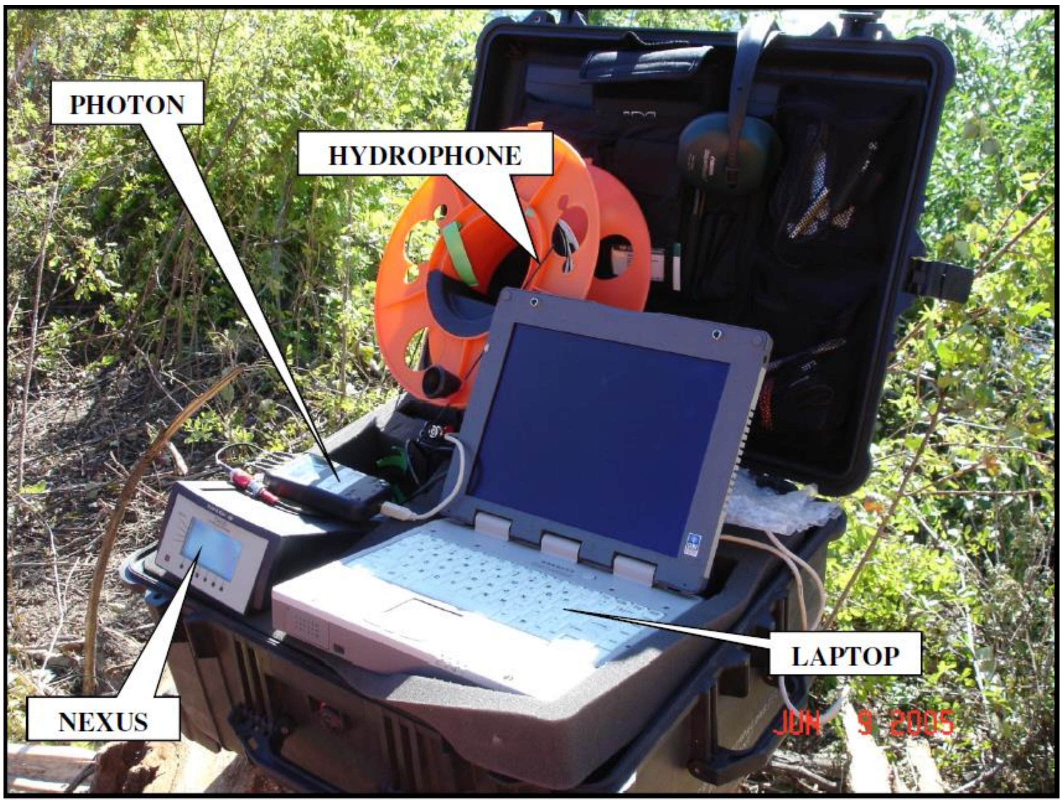
$$cSEL = SEL_{90\%} + 10\ LOG\ (\text{total number of pile strikes}) \qquad \text{(eq. 3)}$$

6 METHODOLOGY

6.1 TYPICAL EQUIPMENT DEPLOYMENT

The hydrophone was deployed from the ferry dock. 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 distance of 10 meters from the pile. An unconfined bubble curtain was deployed for all piles driven to mitigate potential underwater noise effects.

Figure 3: Near Field Acoustical Monitoring Equipment



All impact driven piles monitored were with the sound attenuation bubble curtain system active. No un-attenuated pile strikes were measured on this project.

Underwater sound levels were measured near the piles using one Reson TC 4013 hydrophone deployed on a weighted nylon cord from the ferry dock. The hydrophone was positioned at a distance of 10 meters from each pile 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 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 15.3 μs (25,600 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.

For purposes of characterizing pile driving source levels relevant to marine mammals, analysis of collected data was eliminated for frequencies below the range of functional hearing of marine mammals (described in Southall et al. 2007). A high-pass filter was applied to the data to evaluate the source levels for each functional hearing group. The list below identifies common species that occur in inland waters of Washington State by functional hearing group.

Common marine mammal species that occur in inland waters of Washington State:

- Low-frequency cetaceans: humpback, gray and minke whales
- Mid-frequency cetaceans: killer whales (resident and transient)
- High-frequency cetaceans: harbor and Dall's porpoises
- Non-Harbor Seal Pinnipeds: Steller and California sea lions, and northern elephant seals
- Harbor Seals

7 PILE INSTALLATION RESULTS

7.1 UNDERWATER SOUND LEVELS

WSDOT conducted hydroacoustic monitoring for 4, 24-inch steel piles struck with an impact hammer.

Data from all piles analyzed in the paragraphs below are also summarized in Table 3. Hydroacoustic monitoring of 24-inch hollow steel piles with impact driving included 4 piles out of a total of 8 piles driven for the project.

Pile 1

Pile 1 is located on the northwest corner of the west terminal timber tower. The pile had an absolute attenuated peak value of 204 dB_{peak} at 10 meters. The attenuated RMS90% was calculated at 190 $dB_{RMS90\%}$ and the attenuated cSEL was calculated to be 198 dB_{cSEL}. Pile 1 has exceeded cSEL threshold for all marine mammal thresholds, except the 203 dB_{cSEL} at 275 Hz for the Non-harbor seal pinnipeds, the behavior effects threshold RMS of 160 dB_{RMS} for all marine mammals, as well as the auditory injury threshold for all Cetaceans and Harbor Seals. The distance to the 160 dB_{RMS} threshold using the practical spreading model is 3,281 feet from the pile.

Pile 2

Pile 2 is located south of Pile 1, on the southwest corner of the west terminal timber tower. The pile had an absolute attenuated peak value of 206 dB_{peak} at 12 meters. The attenuated RMS90% was calculated at 193 $dB_{RMS90\%}$ and the attenuated cSEL was calculated to be 200 dB_{cSEL}. Pile 2 exceeded the peak sound pressure level threshold of 202 dB_{peak} for the High-frequency Cetaceans. It has exceeded cSEL threshold for all marine mammals, except the 203 dB_{cSEL} at 275 Hz for the Non-harbor seal pinnipeds, the behavior effects threshold RMS of 160 dB_{RMS} for all marine mammals, as well as the auditory injury threshold for all Cetaceans and Harbor Seals. The distance to the 160 dB_{RMS} threshold using the practical spreading model from the pile location is 18,274 feet.

Pile 3

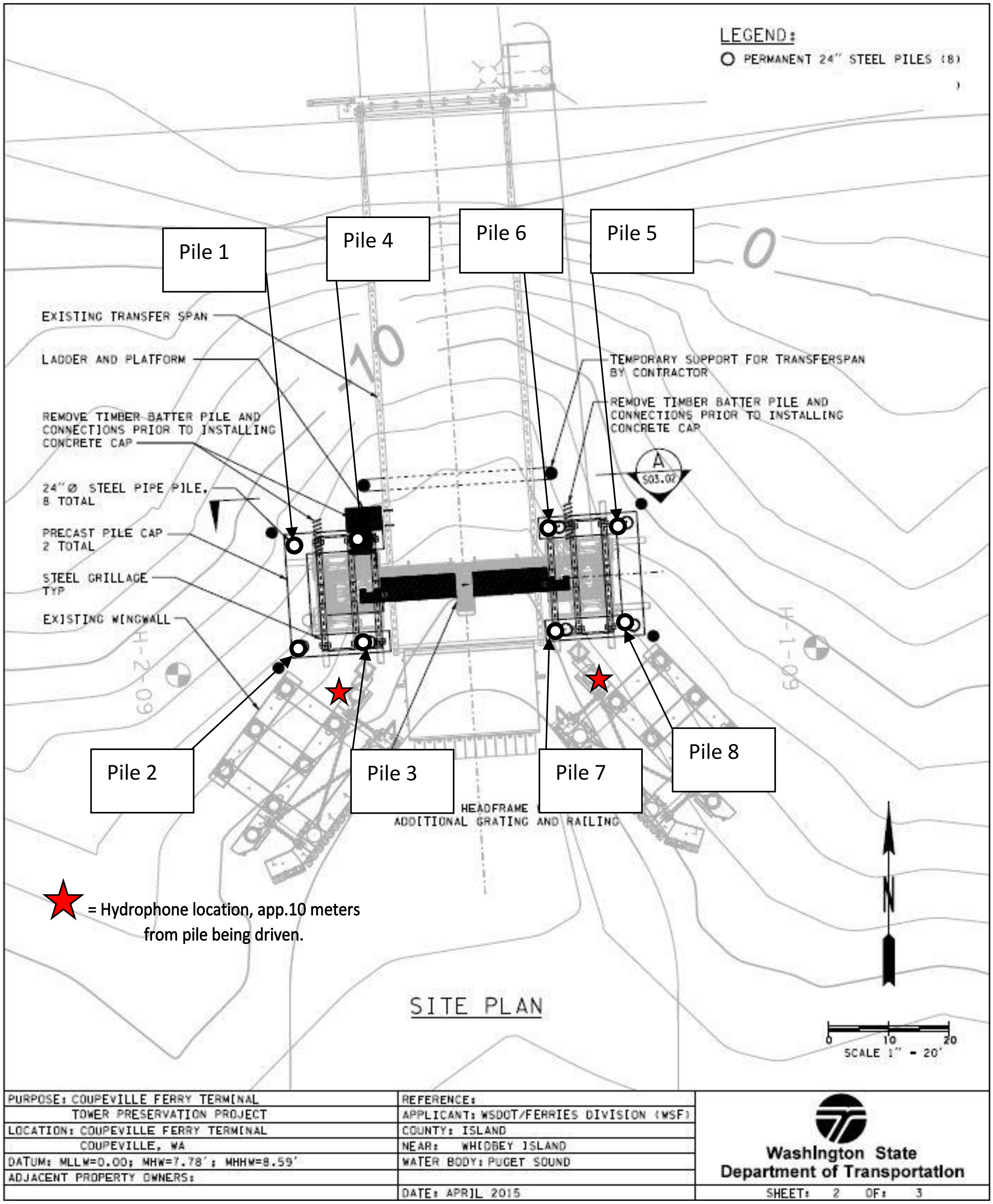
Pile 3 is located east of Pile 2, on the southeast corner of the west terminal timber tower. The pile had an absolute attenuated peak value of 197 dB_{peak} at 10 meters. The attenuated RMS90% was calculated at 180 $dB_{RMS90\%}$ and the attenuated cSEL was calculated to be 194 dB_{cSEL}. Pile 3 has exceeded cSEL threshold for all marine mammals, except the 203 dB_{cSEL} at 275 Hz for the Non-harbor seal pinnipeds, the behavior effects threshold RMS of 160 dB_{RMS} for all marine mammals, as well as the auditory injury threshold for all Cetaceans and Harbor Seals. The distance to the 160 dB_{RMS} threshold using the practical spreading model from the pile location is 707 feet.

Pile 4

Pile 4 is located east of Pile 1 and north of Pile 2, on the northeast corner of the west terminal timber tower. The pile had an absolute attenuated peak value of 201 dB_{peak} at 10 meters. The attenuated RMS90% was calculated at 187 $dB_{RMS90\%}$ and the attenuated cSEL was calculated to be 198 dB_{cSEL}. Pile 4 has exceeded cSEL threshold for all marine mammals, except the 203 dB_{cSEL} at 275 Hz for the Non-harbor seal pinnipeds, the behavior effects threshold RMS of 160 dB_{RMS} for all marine mammals, as well as the auditory injury threshold for all Cetaceans and Harbor Seals. The distance to the 160 dB_{RMS} threshold using the practical spreading model from the pile location is 2,070 feet.

Figure 4 indicates the location of the piles to be monitored and the approximate hydrophone locations for each pile being monitored. Of the eight piles being driven, Piles 1, 2, 3, and 4 were monitored. The hydrophone was located with a clear acoustic line-of-sight between the pile and the hydrophone.

Figure 4. Location of the piles monitored on the Coupeville Ferry Terminal



None of the monitored piles were tested with the sound attenuation off (or absence) to test its effectiveness.   All piles are analyzed in the paragraphs below and summarized in Table 3. Threshold for Marine Mammals and Marble Murrelet as well as fish can be found in Table 2.

Table 3 lists the Coupeville Ferry Terminal Tower piles to be installed, the water depth, and the number and size of piles that was installed.

Table 3: Summary of Underwater Attenuated Broadband Sound Levels for 24 in Pile for the Coupeville Ferry Terminal Project

Pile #	Date & Time	Hydro -phone Depth (feet)	Total Number Of Strikes	Peak L_{50} (dB)	RMS90% L_{50} (dB)	Lower Frequency Range (Hz)	Peak Threshold (dB)	Absolute Highest Peak (dB)	SEL_{cum} Threshold (dB)	SEL_{cum} (dB)	RMS Disturbance Threshold (dB)	RMS 90% (dB)	Single Strike SEL90% (dB)
1	9/15/16 3:07 PM	9.3	392	190	177	Broadband	206	204	**187**	198	160	**190**	175
						7	219	204	**183**		160	**190**	175
						50	230	204	**185**		160	**190**	175
						60	202	**204**	**155**		160	**190**	175
						150	218	204	**185**		160	**190**	175
						275	232	203	203		160	**188**	173
2	9/16/16 12:33 PM	7.5	354	182	175	Broadband	206	206	**187**	200	160	**193**	178
						7	219	206	**183**		160	**193**	178
						50	230	206	**185**		160	**193**	178
						60	202	**206**	**155**		160	**193**	178
						150	218	206	**185**		160	**193**	178
						275	232	204	203		160	**192**	176
3	9/17/16 1:00 PM	7.5	502	185	172	Broadband	206	197	**187**	194	160	**180**	170
						7	219	197	**183**		160	**185**	170
						50	230	197	**185**		160	**186**	170
						60	202	197	**155**		160	**186**	170
						150	218	197	**185**		160	**186**	170
						275	232	195	203		160	**185**	169
4	9/17/16 8:18 AM	7.5	479	190	177	Broadband	206	201	**187**	198	160	**187**	174
						7	219	201	**183**		160	**190**	173
						50	230	201	**185**		160	**190**	173

Pile #	Date & Time	Hydro-phone Depth (feet)	Total Number Of Strikes	Peak L_{50} (dB)	RMS90% L_{50} (dB)	Lower Frequency Range (Hz)	Peak Threshold (dB)	Absolute Highest Peak (dB)	SEL_{cum} Threshold (dB)	SEL_{cum} (dB)	RMS Disturbance Threshold (dB)	RMS 90% (dB)	Single Strike SEL90% (dB)
						60	219	201	**155**		160	**190**	173
						150	230	201	**185**		160	**189**	173
						275	202	200	203		160	**184**	171
Bold numbers are exceedences.													

7.2 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 3).

Table 4 : Summary of daily broadband cumulative SEL's

Day	Daily cSEL (dB)	Distance (ft)
09/15/2017	198	32.8
09/16/2017	200	32.8
09/17/2017	198	32.8

7.3 Airborne Sound Levels

Both A-weighted and un-weighted airborne sound level measurements were collected from the shore, about 100 feet to the pile on the ferry trestle. Pile 1 and 2 data was lost and not retrieved. Also due to rain, no airborne measurements were taken during Pile 3 driving. Airborne measurement during pile 4 driving are reported in this section at 100 feet (A weighed) and 103 feet (un- weighed). Three 5- 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 completely and were eliminated from the data below. Notes were made regarding any anomalous noise events such as boats and low flying commercial aircraft.

For the Coupeville Ferry Terminal the airborne noise levels are measured in terms of the 5-minute average continuous sound level (5-minute Leq):

$$\text{(5 min)} \quad L_{eq} = 10\log\left(\frac{1}{T}\int_T p(t)^2\,dt\right)$$

Where p(t) is the acoustic overpressure, T = 5 minutes and 0 < t < T.

RMS values are calculated by integrating the sound pressure averaged over some time period, in this case 5-minutes in a similar way that the Leq values are calculated. Therefore, in this instance the 5-minute Leq is the same as the RMS sound pressure level over a 5-minute period.

Table 4: summarizes the A-weighted and un-weighted L_{eq} , and L_{Max} values for the entire Pile 4 drive averaging the three 5- minute readings recorded. The measured levels are all standardized to a distance of 50 feet, which is the standard distance for reporting construction noise levels.

Table 5: Summary of Airborne Sound Level Collected in September 2016

Pile #	Pile Type	Distance from Pile (m)	Measured L_{Aeq}/RMS (dBA)	L_{Aeq}/RMS at 50 feet (dBA)	Measured L_{max}/RMS (dBA)	L_{max} at 50 feet (dBA)
A-Weighted (dBA)						
1	24-inch Steel	*	*	*	*	*
2	24-inch Steel	*	*	*	*	*
3	24-inch Steel	N/A	N/A	N/A	N/A	N/A
4	24-inch Steel	100	91	97	101	95
Un-weighted (dB)						
1	24-inch Steel	*	*	*	*	*
2	24-inch Steel	*	*	*	*	*
3	24-inch Steel	N/A	N/A	N/A	N/A	N/A
4	24-inch Steel	103	94	101	104	98

(*) Data lost

The A-weighted 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 L_{Aeq} sound levels for each pile strike for Pile 4 ranged between approximately 98 dBA and 102 dBA.

A-weighted Results

The time history plot of A-weighted airborne sound levels for each individual pile strike measured for the 24-inch Steel piles is shown in Figure 1. The L_{Aeq} sound levels for each pile strike for the 24-inch steel Pile 4 ranged between approximately 89 dBA and 96 dBA. The dB levels for each pile strike are shown in Figure 5 below.

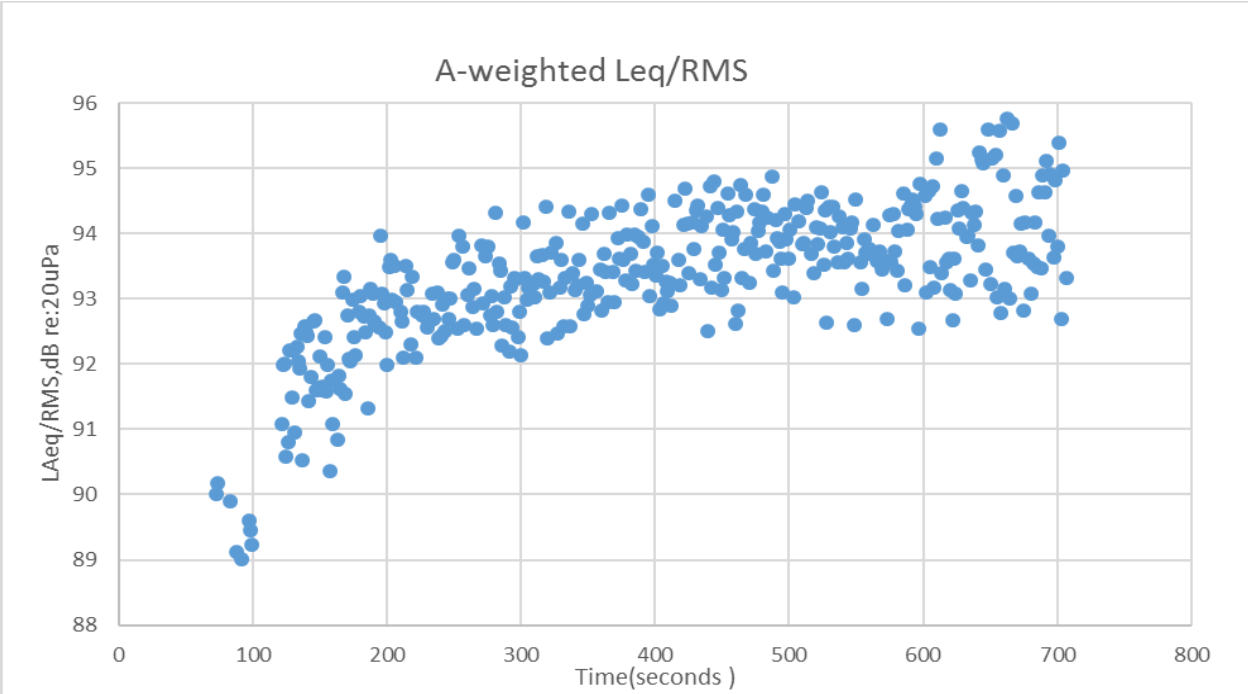


Figure 5: Time history of LAeq airborne sound levels for each pile strike for the 24-inch Steel Pile 4

Un-weighted Results

The time history plot of un-weighted airborne sound levels for each individual pile strike measured for the 24-inch Steel pile is shown in Figure 6. The un-weighted L_{eq} sound levels for pile strike for the 24-inch Steel pile 4 ranged between approximately 89 dB and 101 dB.

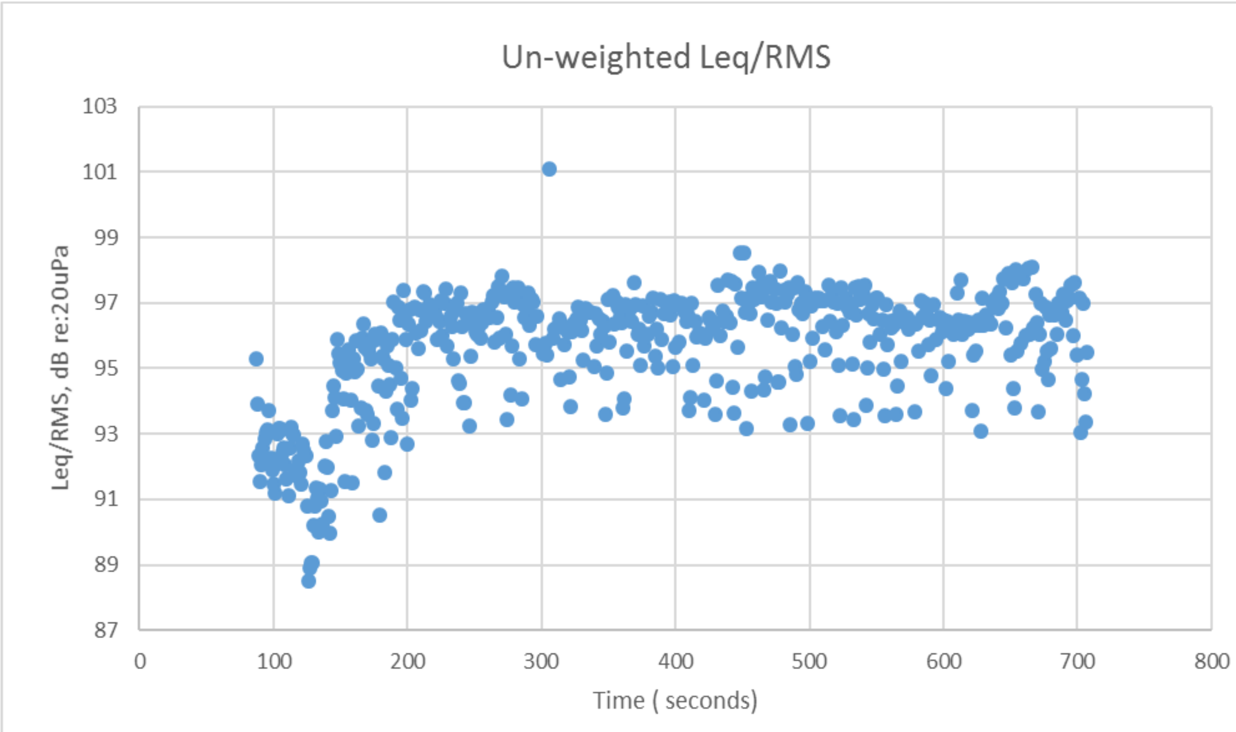


Figure 6: Time history of Leq/RMS airborne sound levels for each pile strike for the 24-inch Steel Pile 4.

Figures 7 and 8 show the overall 1/3rd octave band frequencies for both A-weighted and un-weighted sound level averaged using three, 5-minute measurements for Pile 4. Figure 7 shows a typical distribution of sound levels between 40 Hz and 20 kHz with the dominant frequency at approximately 400 Hz for impact driving 24-inch Steel Pile, which are usually dominant in the 400 Hz to 800 Hz range.

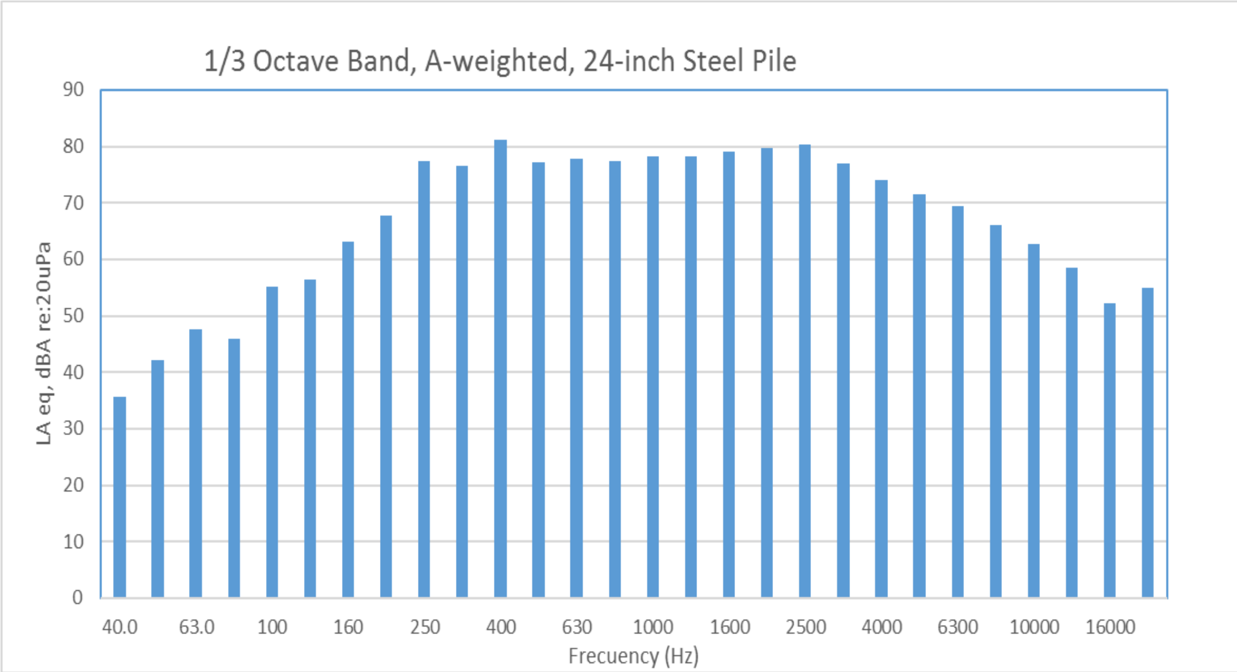


Figure 7: Average A-weighted overall 1/3rd octave band frequencies (LAeq) for impact pile driving of the 24-inch Steel Piles.

Figure 8 shows a typical distribution of un-weighted sound levels between 40 Hz and 20 kHz with the dominant frequency at approximately 400 Hz which is typical for impact driving of steel piles. The dominant un-weighted frequencies for each pile type are similar to the dominant A-weighted frequencies.

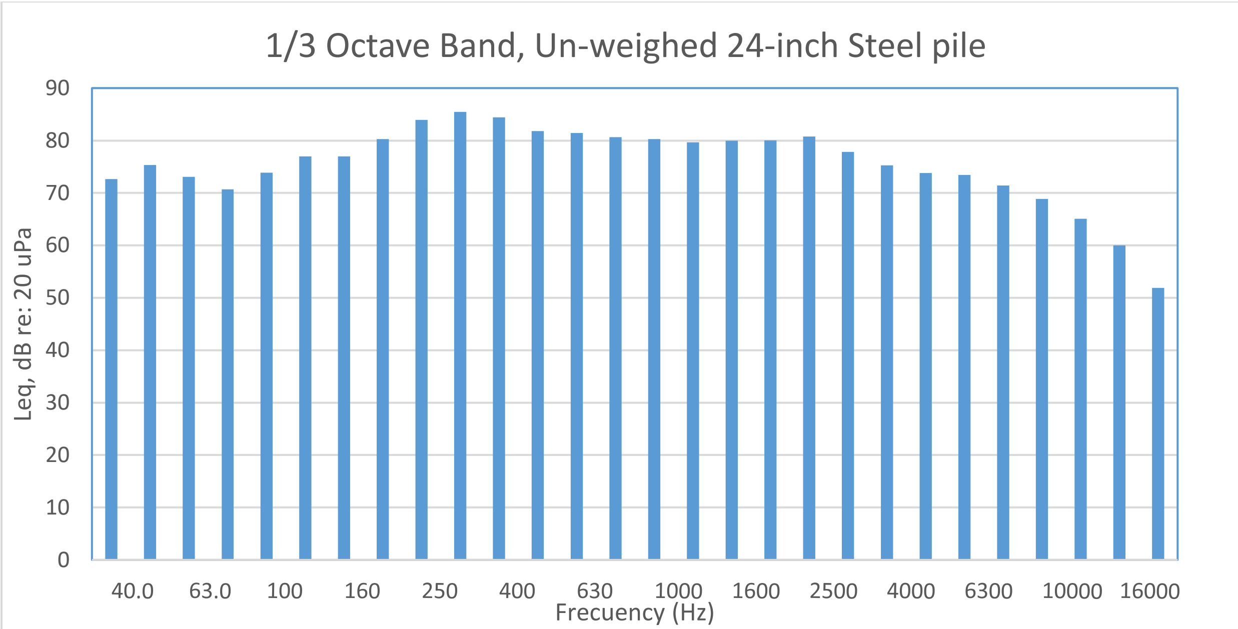


Figure 8: Averaged A-weighted overall 1/3rd octave band frequencies (Leq) for impact driving of the 24-inch Steel Piles

7.4 Impact Pile Driving for Fish and Murrelet Consultations

Analysis of the data from the San Francisco-Oakland Bay Bridge Pile Installation Demonstration project (PIDP) indicated that 90 percent of the acoustic energy for most pile driving impulses occurred over a 50 to 100 millisecond period with most of the energy concentrated in the first 30 to 50 milliseconds (Illingworth and Rodkin, 2001). The RMS values computed for this project was computed over the duration between where 5% and 95% of the energy of the pulse occurs. The SEL energy plot will assist in interpretation of the single strike waveform. The single strike SEL associated with the highest absolute peak strike along with the total number of strikes per pile and per day was used to calculate the cumulative SEL for each pile.

Units of underwater sound pressure levels was dB (re:1 μPa) and units of SEL was re:1 μPa^{2}•sec. In addition to a full broadband analysis the data was analyzed for the 1/3 octave band.

8 CONCULUSION

A total of 4, 24-inch steel piles were monitored for the construction of the SR 20 Coupeville Ferry Terminal project. The underwater sound levels analyzed, produced the following results.

- Peak underwater attenuated sound levels at 10 meters varied in a range between 197 dB_{Peak} and 206 dB_{Peak} with the peak L_{50} ranging between 182 dB_{peak} to 190 dB_{peak}.
- The measured $RMS_{90\%}$ levels ranged between 173 $dB_{RMS90\%}$ and 184 $dB_{RMS90\%}$ with the RMS90% L50 ranging between 172 $dB_{RMS90\%}$ and 177 $dB_{RMS90\%}$.
- Cumulative Sound Exposure Levels (cSEL) for all piles driven on a particular day, ranged between 198 dB_{cSEL} and 200 dB_{cSEL}.

The distance measured from the pile location to the 160 dB_{RMS} threshold for marine mammals as well as the auditory injury threshold for all Cetaceans and Harbor Seals using the practical spreading model from the pile location ranged between 707 feet and 18,274 feet from the pile.

Airborne sound levels were monitored and data was collected for a 24-inch steel pile for A-weighted sound levels and un-weighted sound levels during impact driving. The measurements produced the following results.

- The A-weighted L_{eq} sound level for impact driving a 24-inch steel Pile 4 was 97 dB re: 20 µPa at 50 feet.
- The un-weighted L_{eq} sound level for Pile 4 was 101 dB re: 20 µPa at 50 feet.

For Pile 4, airborne sound levels are within the typical range for impact pile driving at 50 feet distance as well as the 1/3 octave frequency range.

9 REFERENCES

Illingworth and Rodkin, Inc. 2001. Noise and Vibration Measurements Associated with the Pile Installation Demonstration Project for the San Francisco-Oakland Bay Bridge East Span, Final Data Report, Task Order 2, Contract No. 43A0063.

Southall, B.L., A.E. Bowles, W.T. Ellison, J.J. Finneran, R.L. Gentry, C.R. Greene, D. Kastak, D.R. Ketten, J.H. Miller, P.E. Nachtigall, W.J. Richardson, J.A. Thomas, and P.L. Tyack. 2007. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. Aquatic Mammals 33(4): 411-521.

10 APPENDIX A: WAVEFORM ANALYSIS FIGURES

Figure 9: Waveform Analysis of attenuated Pile 1

Coupeville at 10m Broadband

Figure a. Waveform

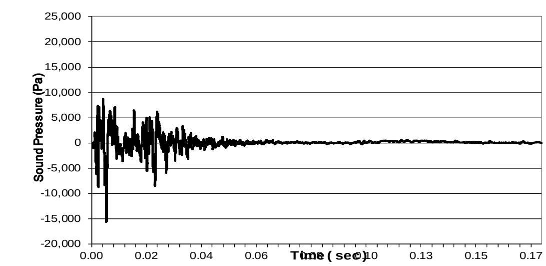


Figure b. Narrow Band Frequency Spectra

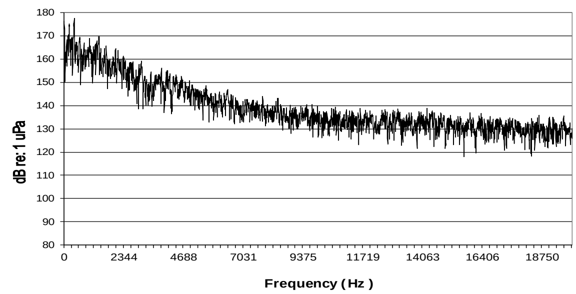


Figure c. Accumulation of Sound Energy

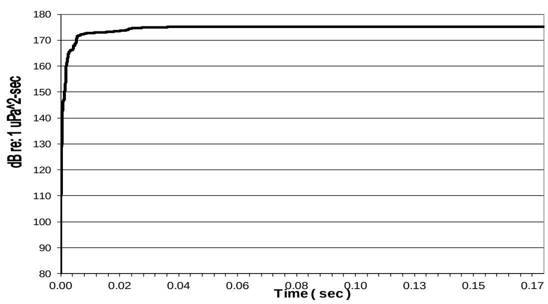


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
9.3-feet	204	190	175

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

Figure 10: Waveform Analysis of attenuated Pile 2

Coupeville at 12m Broadband

Figure a. Waveform

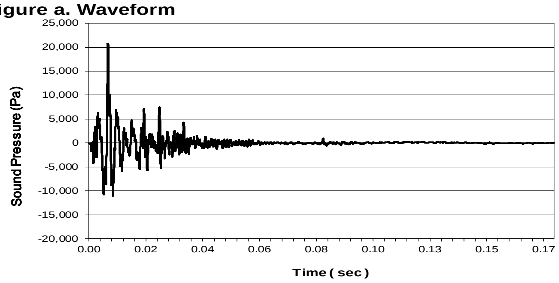


Figure b. Narrow Band Frequency Spectra

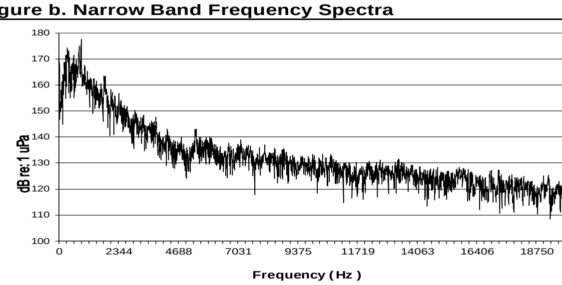


Figure c. Accumulation of Sound Energy

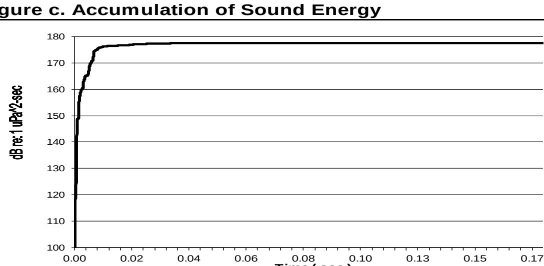


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
7.5-feet	206	193	178

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

Figure 11: Waveform Analysis of attenuated Pile 3

Coupeville at 10m Broadband

Figure a. Waveform

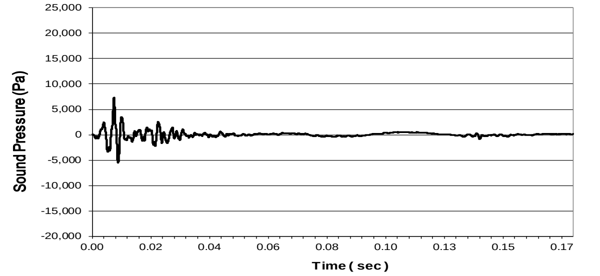


Figure b. Narrow Band Frequency Spectra

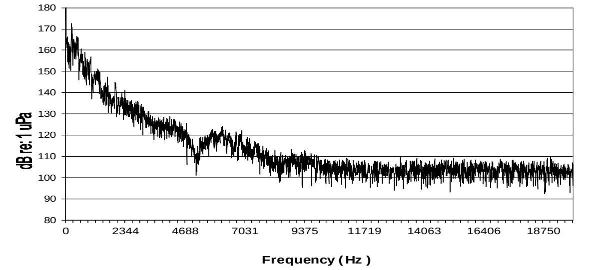


Figure c. Accumulation of Sound Energy

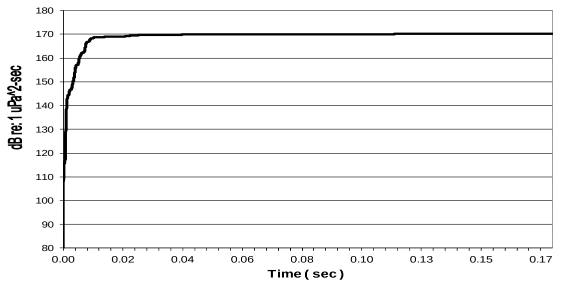


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
7.5-feet	197	180	170

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

Figure 12: Waveform Analysis of attenuated Pile 4

Coupeville at 10m Broadband

Figure a. Waveform

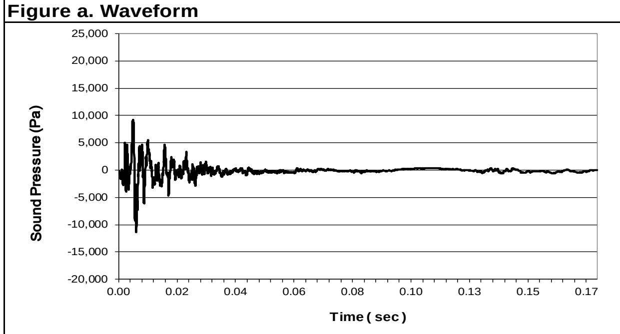


Figure b. Narrow Band Frequency Spectra

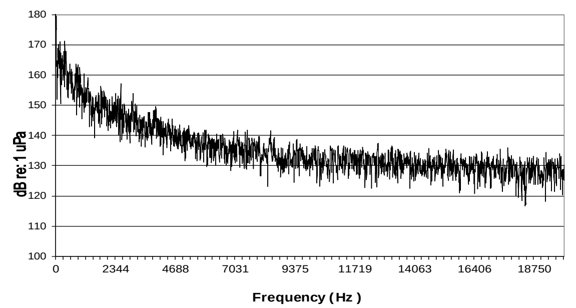


Figure c. Accumulation of Sound Energy

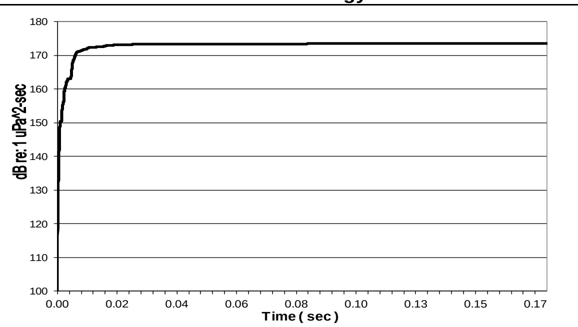


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
7.5-feet	201	188	174

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

11 APPENDIX B – CALUCLATION OF CUMULATIVE SEL

An estimation of individual SEL values can be calculated for each pile strike by calculating the following integral, where T is T_{90}, the period containing 90% of the cumulative energy of the pulse (eq. 1).

$$SEL = 10\log\left(\int_0^T \frac{p^2(t)}{{p_0}^2}\,dt\right) \quad dB$$

(eq. 1)

Calculating a cumulative SEL from individual SEL values cannot be accomplished simply by adding each SEL decibel level arithmetically. Because these values are logarithms they must first be converted to antilogs and then accumulated. Note, first, that if the single strike SEL is very close to a constant value (within 1 dB), then cumulative SEL = single strike SEL + 10 times log base 10 of the number of strikes N, i.e, $10Log_{10}(N)$. However if the single strike SEL varies over the sequence of strikes, then a linear sum of the energies for all the different strikes needs to be computed. This is done as follows: divide each SEL decibel level by 10 and then take the antilog. This will convert the decibels to linear units (or uPa^2●s). Next compute the sum of the linear units and convert this sum back into dB by taking $10Log_{10}$ of the value. This was the cumulative SEL for all of the pile strikes.