# *SR 525/Mukilteo Multimodal Project: Phase 2*

# 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 |

# EXECUTIVE SUMMARY

This technical report describes the data collected during impact pile driving and monitoring of underwater sound levels from driving 30-inch steel piles for the Washington State Department of Transportation (WSDOT) at the Mukilteo Multimodal Project, Phase 2 between October and December of 2017. Data collected included both in-water and upland pile driving. Data was first collected for one, 30-inch pile during the test pile phase of the project in October of 2017. Then two production piles were monitored in December of 2017 (Table 1). A fourth upland pile was monitored during impact pile driving (Table 2). Unconfined bubble curtains were deployed for all piles impact driven to attenuate potential underwater noise effects. Measurements were collected between 12 and 14 meters from the in water piles and at 22 meters from the upland pile.

None of the attenuated piles monitored exceeded the 206 $dB_{peak}$ threshold for fish at the measured distances. The peak attenuated sound levels measured ranged between 185 $dB_{peak}$ and 196 $dB_{peak}$ while monitoring the impact pile driving operation as shown in Table 1. The daily Cumulative Sound Exposure Level (cSEL) for all four piles monitored exceeded the threshold of 187 $dB_{cSEL}$ at 10 meters. They also exceeded the cSEL for all marine mammals except for the Non-harbor seal pinnipeds. All four piles had broadband exceedences for the 150 $dB_{RMS}$ for Murrelet and 160 $dB_{RMS}$ for Marine Mammal behavioral disturbances.

*Table 1: Summary of 30-inch Pile Attenuated Impact Driving Underwater Sound Levels.*

| Pile # | Date | Hydro-Phone Range (m) | Lower Frequency Range (Hz) | Absolute Highest Peak (dB) | $RMS_{90\%}$ (dB) | Single Strike $SEL_{90\%}$ (dB) | Cumulative SEL (dB) |
|---|---|---|---|---|---|---|---|
| 1 | 10/25/17 | 12 | Broadband | 190 | 180 | 170 | 193 |
| | | | 7 | 196 | 179 | 170 | 192 |
| | | | 50 | 194 | 179 | 169 | 192 |
| | | | 60 | 195 | 178 | 168 | 191 |
| | | | 150 | 192 | 172 | 162 | 186 |
| | | | 275 | 191 | 170 | 160 | 184 |
| 2 | 12/19/17 | 12 | Broadband | 195 | 185 | 170 | 193 |
| | | | 7 | 194 | 180 | 170 | 193 |
| | | | 50 | 194 | 179 | 169 | 192 |
| | | | 60 | 193 | 179 | 169 | 191 |
| | | | 150 | 192 | 174 | 165 | 187 |
| | | | 275 | 191 | 173 | 160 | 185 |
| 3 | 12/19/17 | 14 | Broadband | 190 | 179 | 167 | 189 |
| | | | 7 | 190 | 177 | 167 | 189 |
| | | | 50 | 191 | 176 | 167 | 189 |
| | | | 60 | 190 | 176 | 166 | 188 |
| | | | 150 | 186 | 169 | 156 | 181 |

| Pile # | Date | Hydro-Phone Range (m) | Lower Frequency Range (Hz) | Absolute Highest Peak (dB) | $RMS_{90\%}$ (dB) | Single Strike $SEL_{90\%}$ (dB) | Cumulative SEL (dB) |
|---|---|---|---|---|---|---|---|
| | | | 275 | 185 | 167 | 157 | 179 |

*Table 2: Summary of 30-inch Pile Attenuated Upland Impact Driving Underwater Sound Levels.*

| Pile # | Date | Hydro-Phone Range (m) | Lower Frequency Range (Hz) | Absolute Highest Peak (dB) | $RMS_{90\%}$ (dB) | Single Strike $SEL_{90\%}$ (dB) | Cumulative SEL (dB) |
|---|---|---|---|---|---|---|---|
| 4 | 10/25/17 | 22 | Broadband | 192 | 180 | 167 | 189 |
| | | | 7 | 193 | 176 | 166 | 189 |
| | | | 50 | 192 | 175 | 165 | 189 |
| | | | 60 | 192 | 175 | 165 | 188 |
| | | | 150 | 192 | 168 | 158 | 183 |
| | | | 275 | 192 | 166 | 156 | 180 |

# 1 INTRODUCTION

The Washington State Ferries (WSF) proposes to construct the new Mukilteo Multimodal ferry terminal in Phase II and completely remove the existing berthing structures at the existing Mukilteo Ferry Terminal. Construction activities will consist of earthwork, retaining wall construction, soil contamination remediation, surveying, installing signals at two intersections, roadway construction, utility work, the construction of berthing structures, an overhead walkway and a terminal building. The work includes permanent landscaping and architectural elements, constructing all four of the planned toll booths, constructing seven of the planned holding lanes, constructing a transit station, the installation of the supervisor's office, and a fishing pier. See vicinity map (Figure 1).

This report summarizes the impact pile driving results measured at the Mukilteo Multimodal Phase 2 project in an effort to collect site-specific data on underwater noise levels during the months of October and December 2017. Three 30-inch diameter steel piles were monitored on two separate days as they were driven with an impact hammer. A fourth 30-inch steel pile was monitored during impact driving at an upland location. This report applies high-pass frequency filters to the underwater acoustic measurements to determine the sound levels for the marine mammal functional hearing groups.

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

The intrusive sounds that frequently occurred for a period associated with the use of impact the 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 3.

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 Marbled Murrelet.

*Figure 1: Vicinity map of the Mukilteo Multimodal Ferry Terminal*

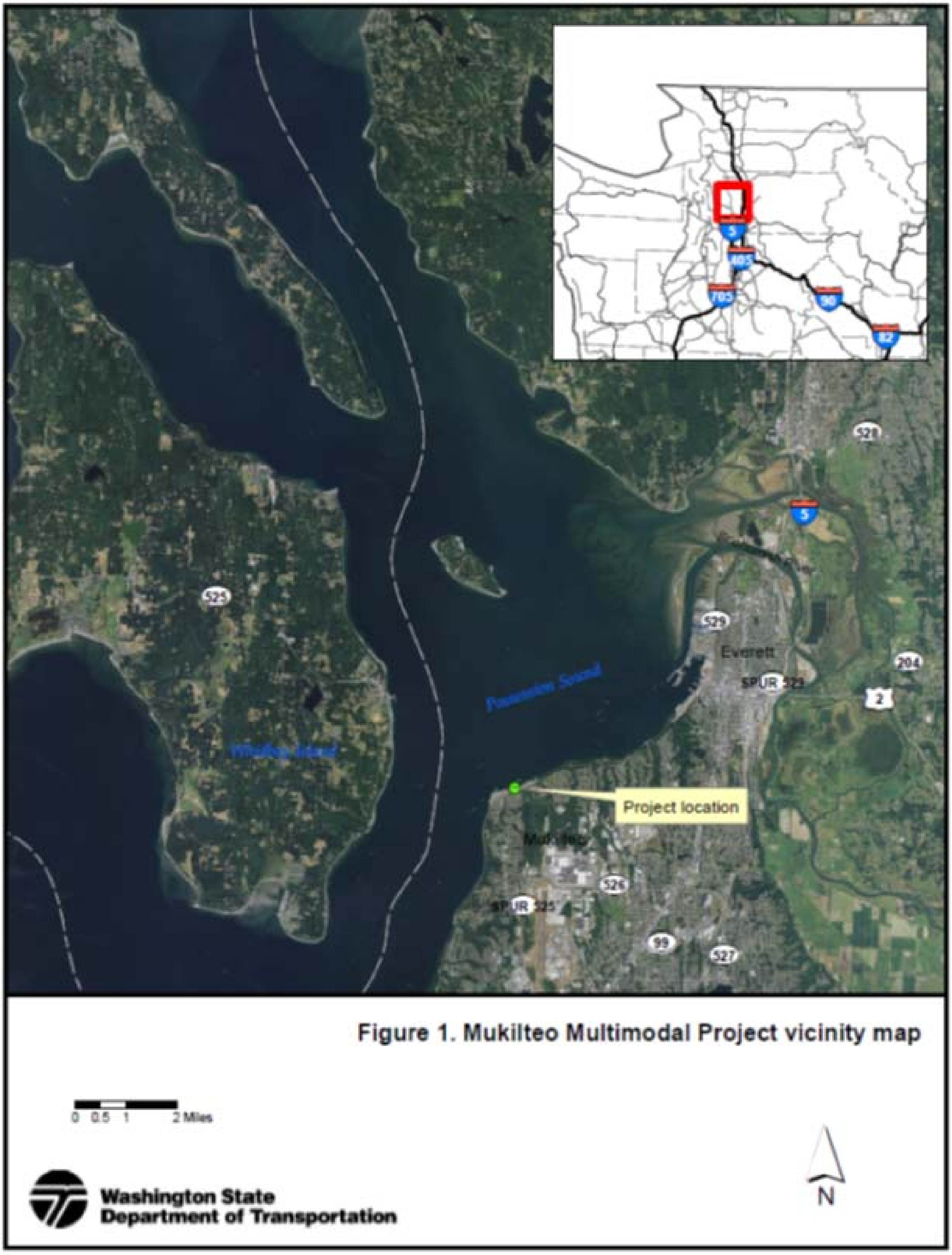



Figure 1. Mukilteo Multimodal Project vicinity map

*Table 3: 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)

# 2 PROJECT AREA

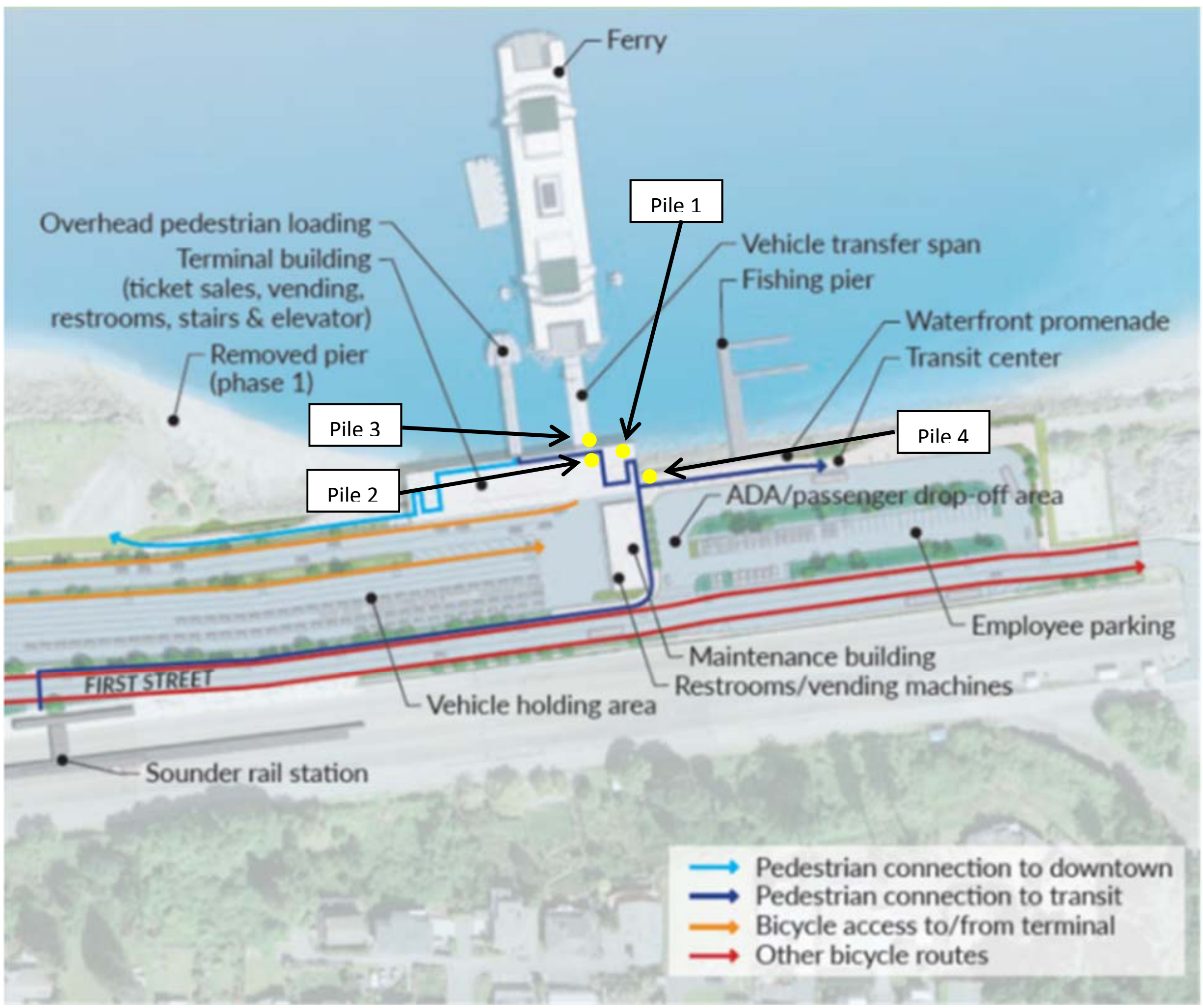
The Mukilteo Multimodal Ferry Terminal project is located in the city of Mukilteo. Washington State Ferries (WSF) proposes to construct the new Mukilteo Multimodal ferry terminal in Phase II and completely remove the existing berthing structures at the existing Mukilteo Ferry Terminal. Construction activities will consist of earthwork, retaining wall construction, soil contamination remediation, surveying, installing signals at two intersections, roadway construction, utility work, the construction of berthing structures, an overhead walkway and a terminal building. The work includes permanent landscaping and architectural elements, constructing all four of the planned toll booths, constructing seven of the planned holding lanes, constructing a transit station, the installation of the supervisor's office, and a fishing pier.

# 3 PILE INSTALLATION LOCATION

Three hollow steel piles installed during the initial impact pile driving activity at the Mukilteo Multimodal Ferry Terminal (Phase 2) were monitored. Figure 2 indicates the approximate location of the Mukilteo Multimodal Ferry Terminal project and the location of the three, 30-inch steel piles driven in water and one 30-inch steel pile driven in an upland location (Pile 4).

The hydrophone was located at 12 or 14 meters from each in water pile monitored and 22 meters from the upland pile and placed at mid-water depth. The depth of the water where the hydrophone was deployed was approximately 15 feet deep, depending on tidal influence, for the in water piles and 10.5 feet deep for the upland pile measurement.

*Figure 2: Approximate Location of the Mukilteo Multimodal Ferry Terminal Monitored Piles*



# 4 UNDERWATER SOUND LEVELS

## 4.1 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 (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.

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:

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

Where $\tau$ 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.

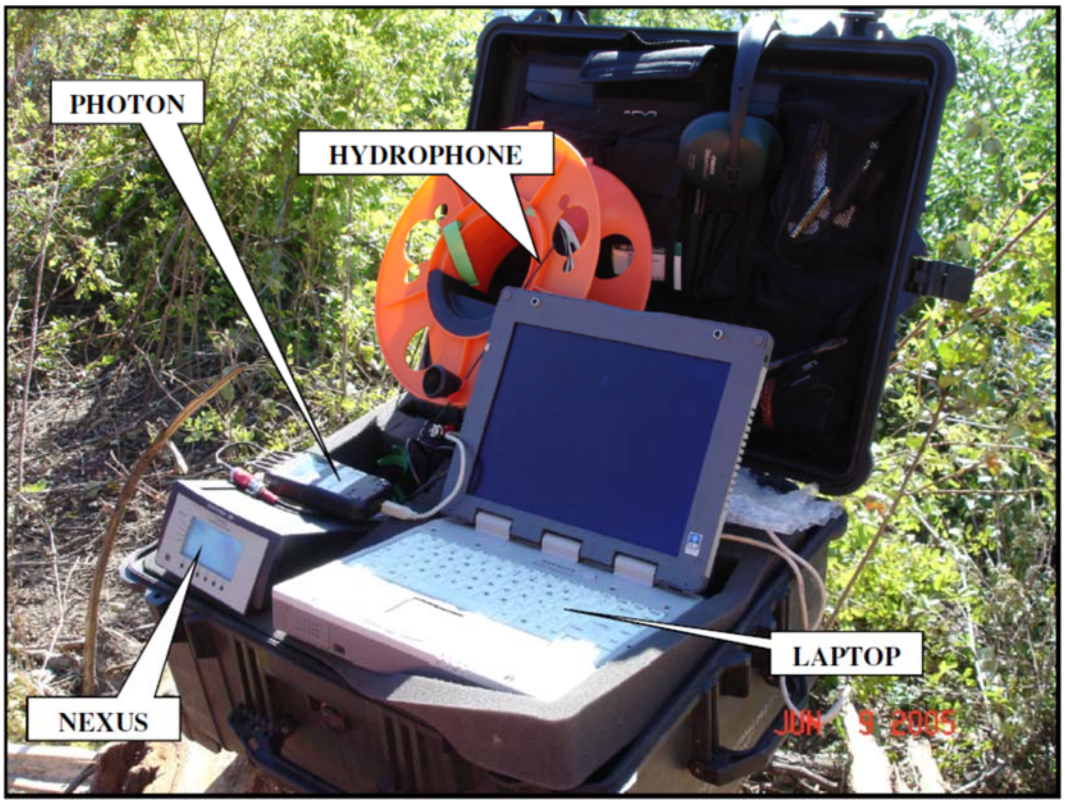
$$cSEL = SEL_{90\%} + 10 \text{ LOG (total number of pile strikes)} \qquad \text{(eq. 3)}$$

# 5 METHODOLOGY

## 5.1 TYPICAL EQUIPMENT DEPLOYMENT

The hydrophone was deployed from the crane barge. 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 12 to 14 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*




Underwater sound levels were measured near the piles using one Reson TC 4013 hydrophone deployed on a weighted nylon cord. 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 recording 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.

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 (RMS90%). The single strike SEL for each pile 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 $\mu Pa^2 \bullet sec$.

Due to the variability between the absolute peaks for each pile impact strike, a $50^{th}$ percentile or L50 peak, RMS90% and SEL90% value is computed.

For purposes of characterizing pile driving source levels relevant to marine mammals, Matlab software was used for the analysis of collected data and was filtered through a high-pass filter with the cutoff frequency corresponding to the lower frequency of the functional hearing group (described in NMFS 2016, Southall et al. 2007). 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, harbor seals, and northern elephant seals
- Harbor Seals

# 6 PILE INSTALLATION RESULTS

## 6.1 UNDERWATER SOUND LEVELS

WSDOT conducted hydroacoustic monitoring for 3, 30-inch steel piles struck with an impact hammer in water and a fourth 30-inch steel pile driven in an upland position. Data from all piles analyzed in the paragraphs below are also summarized in Table 4.

*Pile 1*

Pile 1 is located immediately adjacent to the rip rap on the shoreline at the new terminal location (Figure 2). The results for Pile 1 can be found in Table 4. Figure 4 shows the time history plot for Pile 1 for each pile strike of the peak, RMS90%, SEL90% and cumulative SEL (cSEL) levels. There is some variability in the peak strike levels and the RMS90% and SEL90% values are relatively stable but indicate a slight rise towards the end of the pile driving. Pile 1 has exceeded the auditory injury threshold for all marine mammal thresholds, except the 185 $dB_{cSEL}$ and 203 $dB_{cSEL}$ for the Harbor Seals and Non-harbor seals pinnipeds respectively and the disturbance threshold of 160 $dB_{RMS}$ for all marine mammals.

*Figure 4: Time history plot of individual impact strikes for Pile 1*

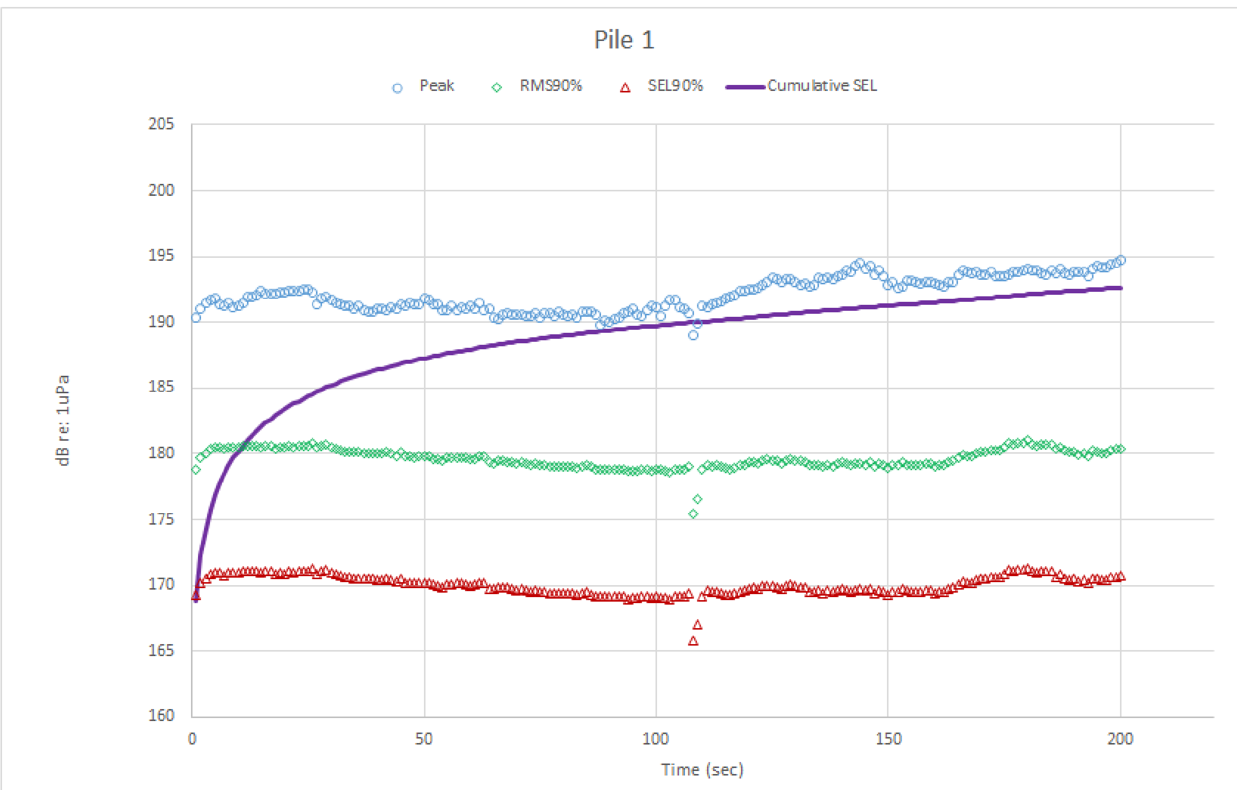


Figure 5 shows the Power Spectral Density (PSD) plot (sound pressure level as a function of frequency) for the pile drive. The plot indicates that most of the energy is below 1000 Hz.

*Figure 5: Power Spectral Density Plot for Pile 1*

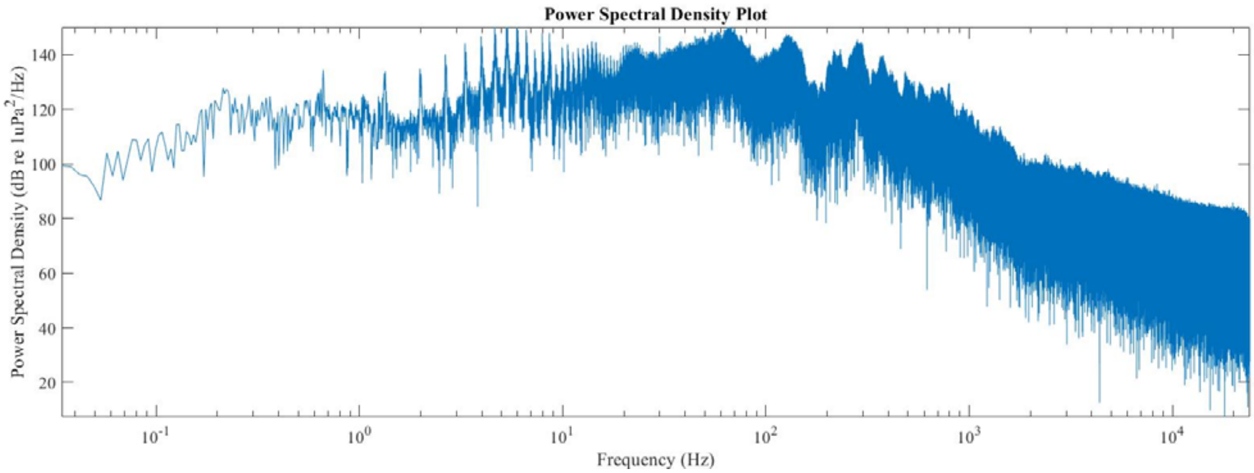
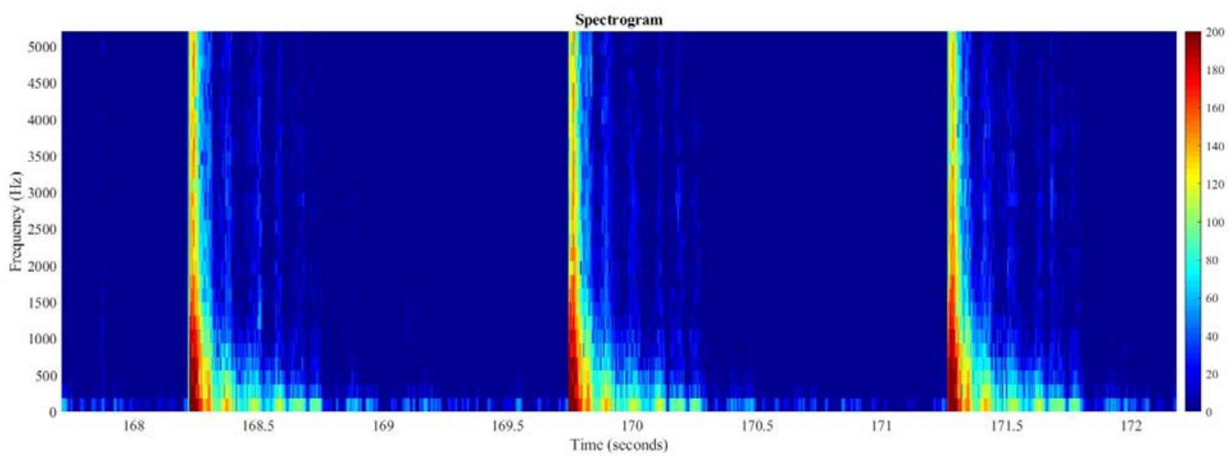



Figure 6 shows the spectrogram plot (sound intensity as a function of time and frequency) of three consecutive pile strikes. The color bar to the right indicates the decibel level. The plot indicates that most of the energy is in the initial part of the pile strike and is less than 1000 Hz.

*Figure 6: Spectrogram Plot for Pile 1*




## *Pile 2*

Pile 2 is located immediately adjacent to the rip rap on the shoreline and approximately 10 meters west of Pile 1 (Figure 2). The results for Pile 2 are in Table 4. Pile 2 exceeded the auditory injury threshold for all marine mammals except for the Non-harbor seal pinnipeds. It has exceeded disturbance threshold for all marine mammal species at the distance measured.

Figures 7, 8 and 9 show the time history plot, PSD plot and spectrogram plot respectively. The peak, RMS90% and SEL90% values are relatively stable throughout the pile driving period. The PSD and spectrogram plots indicate that most of the energy in each pile strike is below about 1000 Hz.

*Figure 7: Time history plot of individual pile strikes for Pile 2*

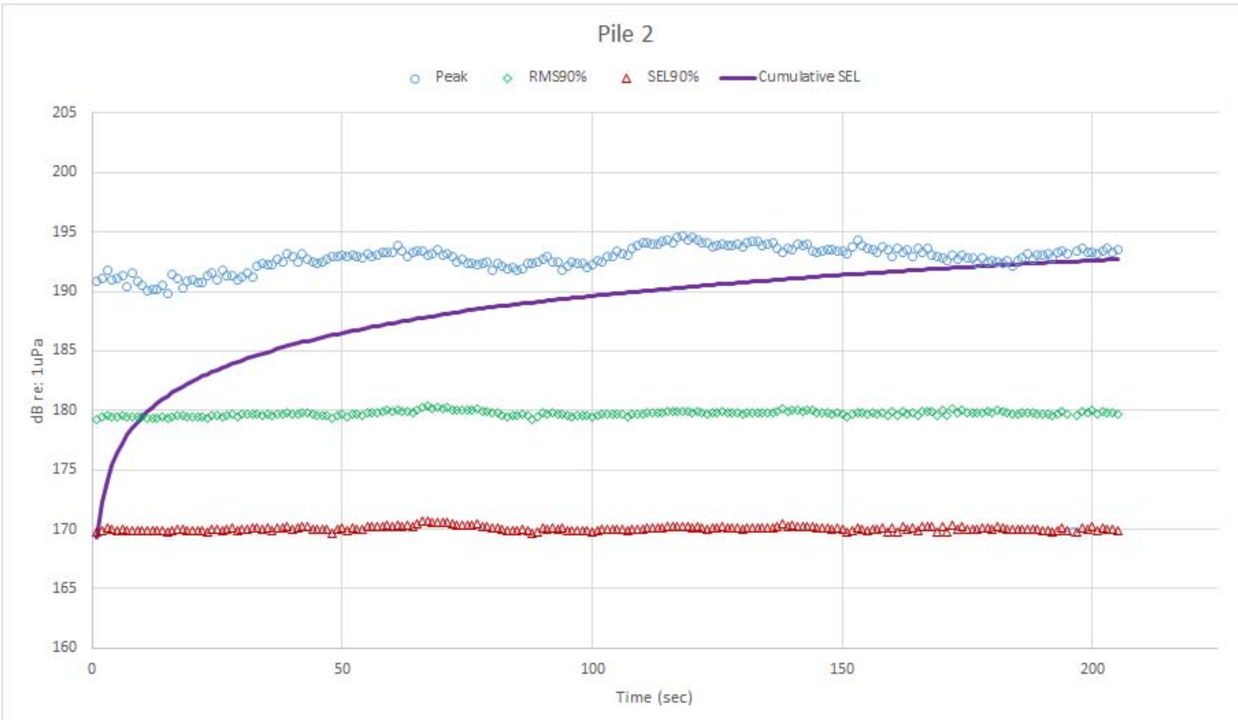



*Figure 8: Power Spectral Density Plot for Pile 2*

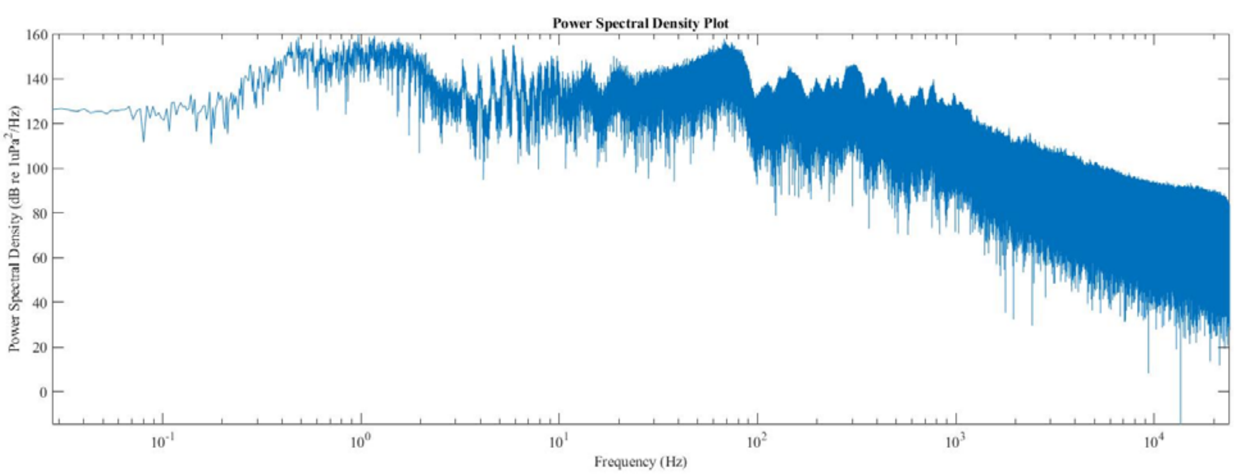
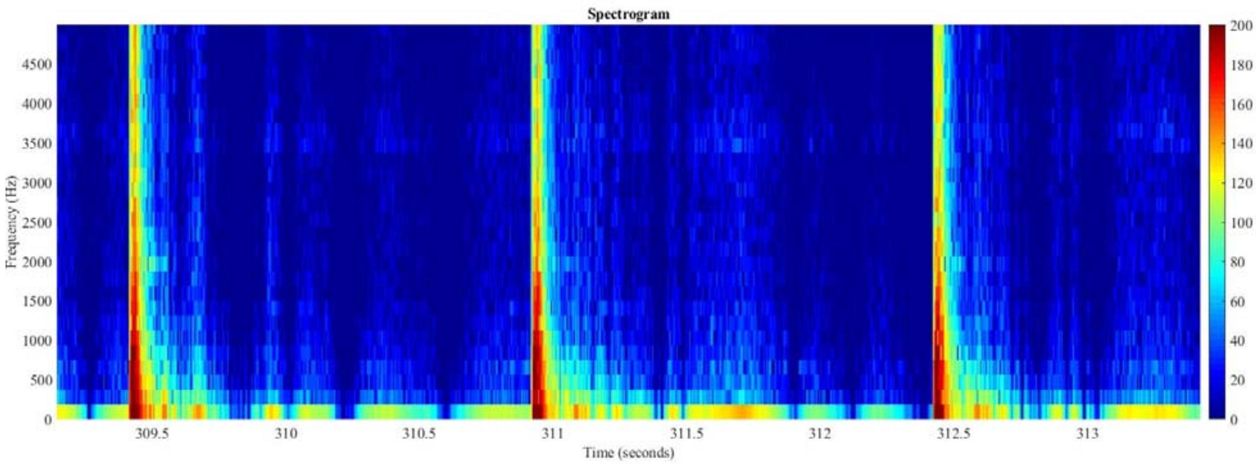


*Figure 9: Spectrogram Plot for Pile 2*




### *Pile 3*

Pile 3 is located approximately 10 meters north of Pile 2. The results for Pile 3 are in Table 4. Pile 3 has exceeded the auditory thresholds for all marine mammals except for Non-harbor seal pinnipeds and the mid-frequency cetaceans and the disturbance threshold for all marine mammals.

Figures 10, 11 and 12 show the time history plot, the PSD plot and the spectrogram respectively. The time history plots in Figure 10 show that the values for the peak, RMS90% and SEL90% are relatively stable throughout the pile driving. The PSD and spectrogram plots show similar results seen for Piles 1 and 2.

*Figure 10:   Time history plot of individual pile strikes for pile 3*

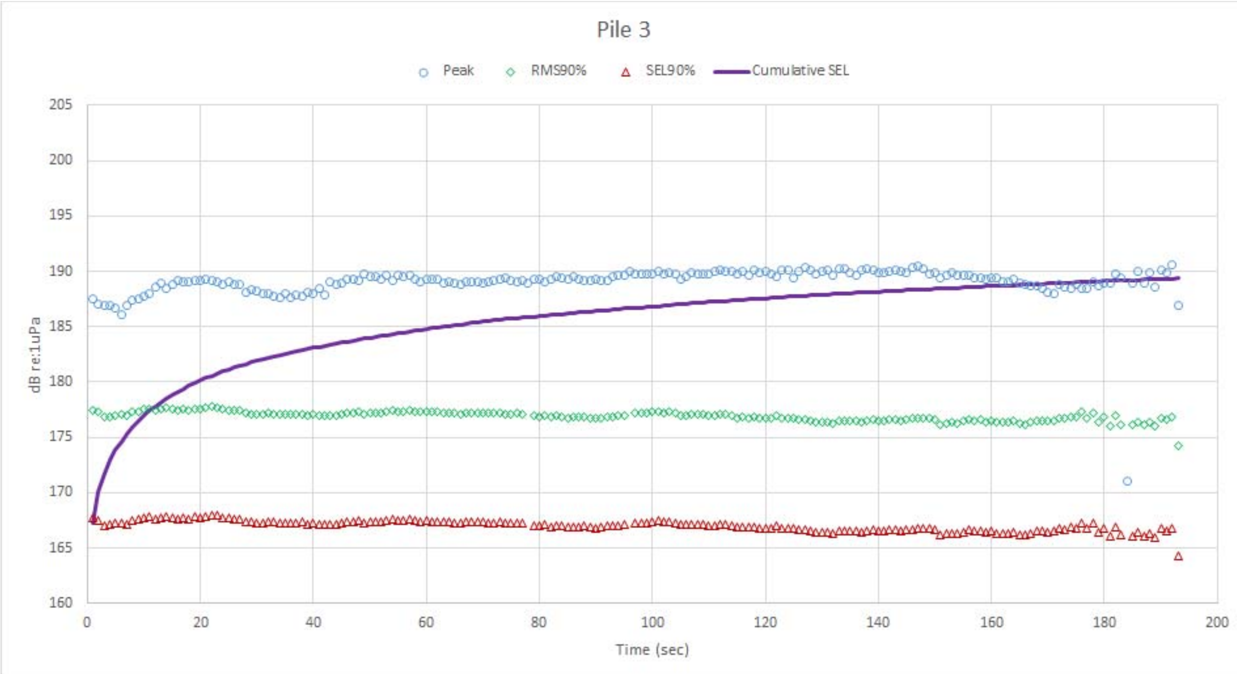



*Figure 11:   Power Spectral Density Plot for Pile 3*

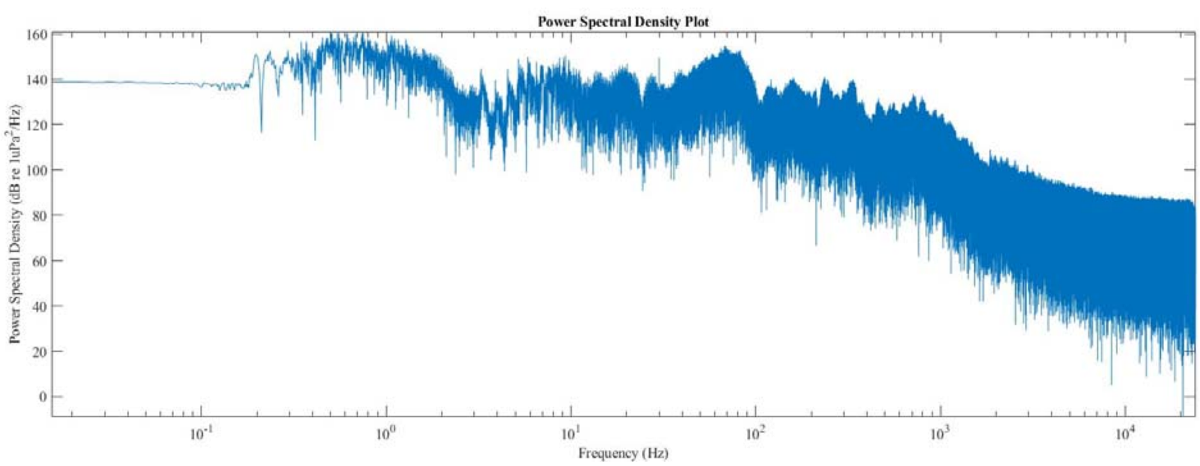
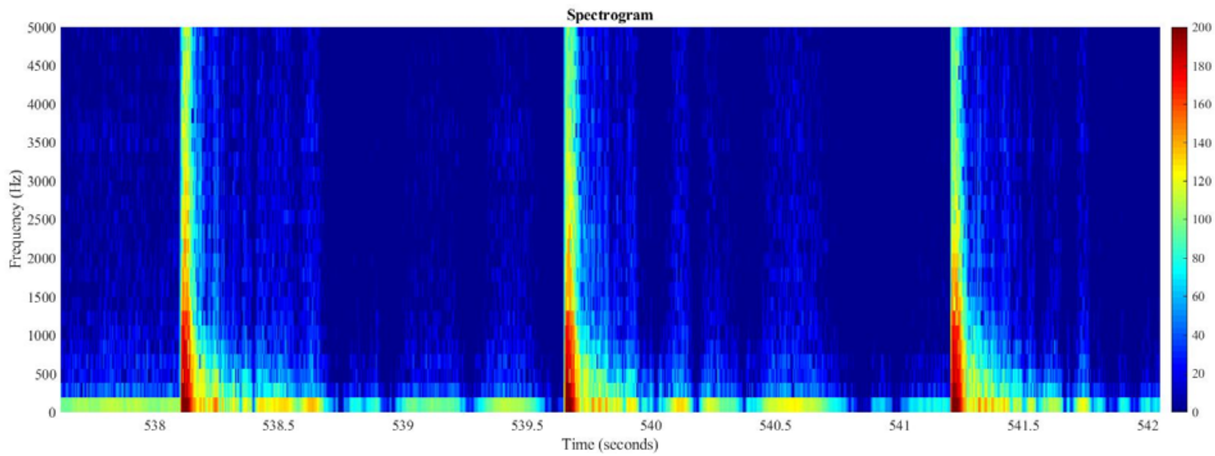


*Figure 12: Spectrogram Plot for Pile 3*




All the three monitored piles exceeded the behavior effects threshold RMS of 160 dB$_{RMS}$ for all marine mammals, fish and marbled Murrelets of 160 dB$_{RMS}$.

### 6.1.1 Upland Impact Driving

*Pile 4*

Pile 4 is located south of Pile 1 on the existing paved pathway along the shoreline. The results for Pile 4 can be found in Table 4. Pile 4 has exceeded the auditory thresholds for all marine mammals except for Non-harbor seal pinnipeds and mid-frequency cetaceans and the disturbance threshold for all marine mammals.

*Figure 13: Time history plot of individual pile strikes for Pile 4 (upland)*

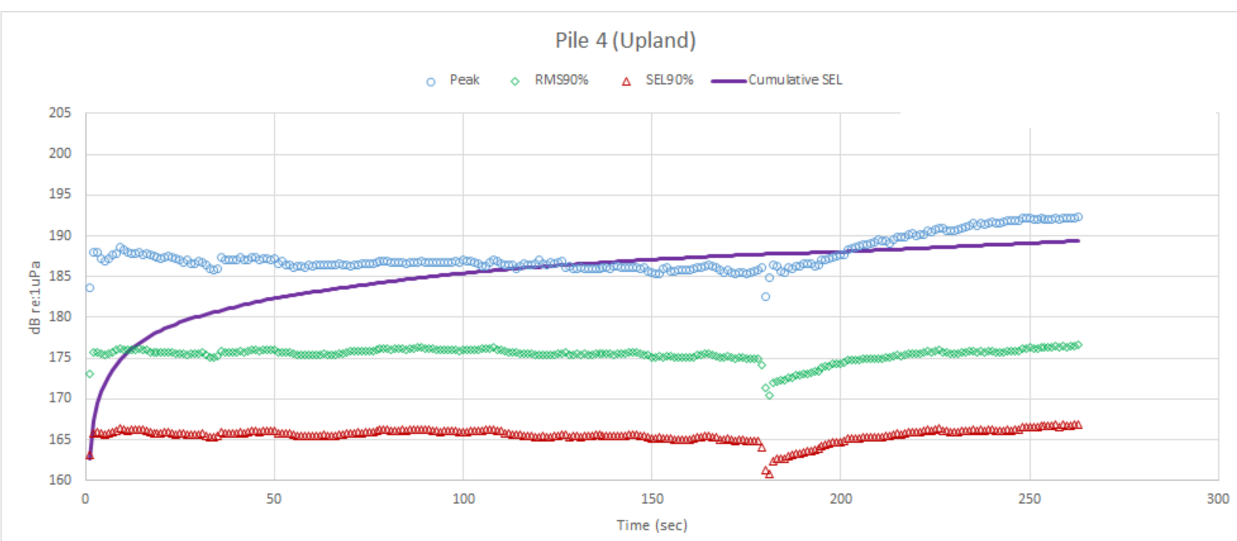


*Figure 14: Power Spectral Density Plot for Pile 4 (upland)*

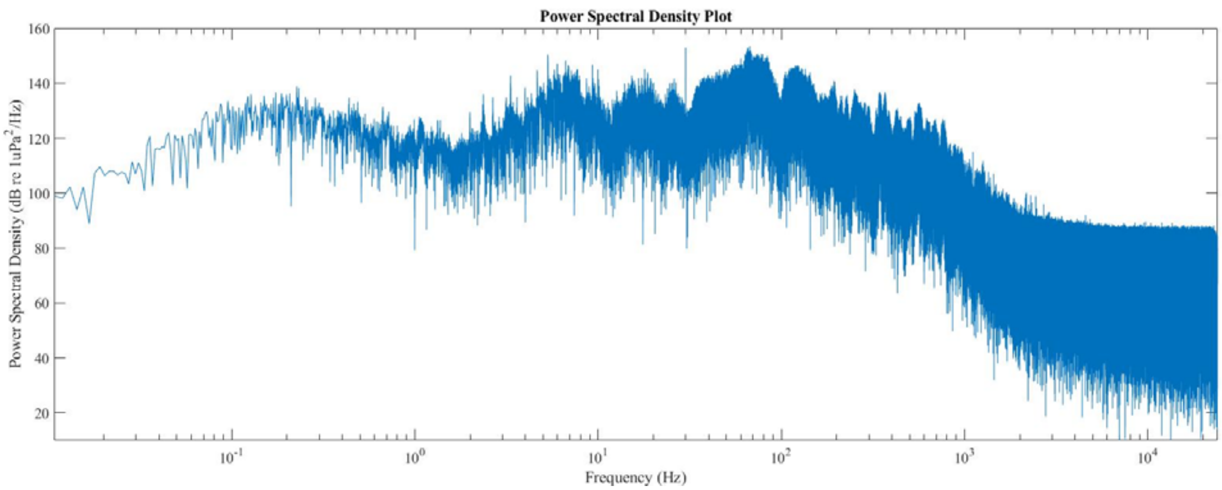



Figure 15 shows the PSD plots for Pile 3 (in water) and Pile 4 (upland). There are some slight differences in the very low frequencies below approximately 4 Hz but at frequencies that are higher there is little difference.

Figure 15: Combined PSD Plot for Pile 3 (blue, in water) and Pile 4 (red, upland)

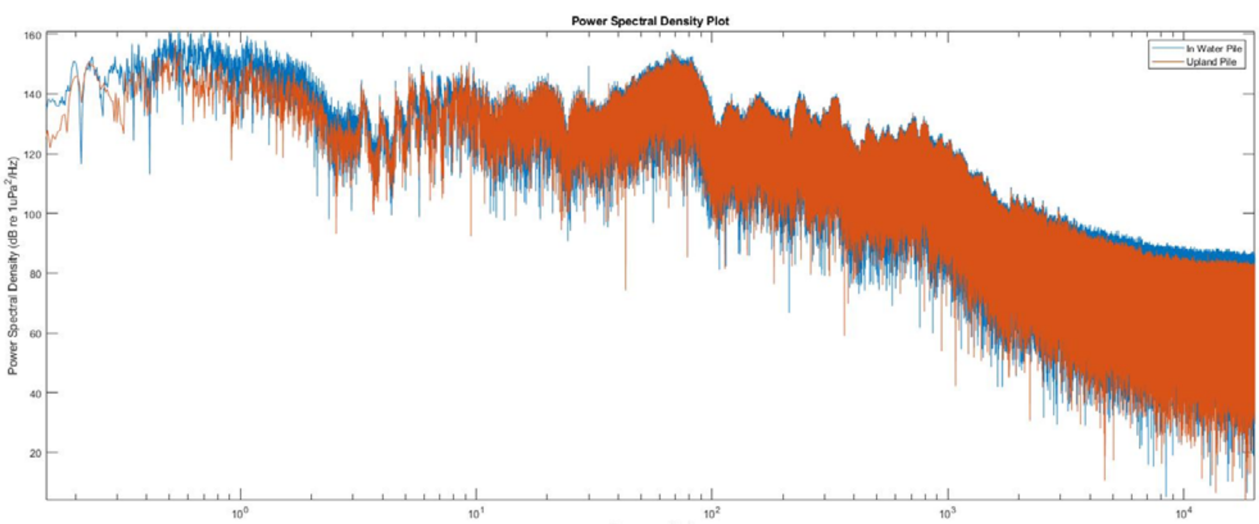


Figure 16: Spectrogram Plot for Pile 4 (upland)

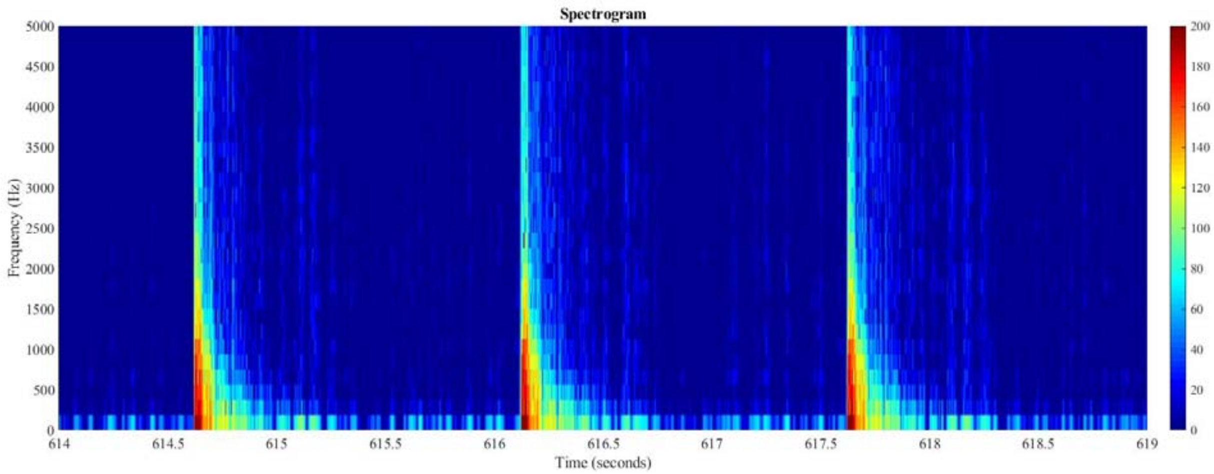



Table 4: Summary of Underwater Attenuated Sound Levels for 30-in Piles for the Mukilteo Multimodal Terminal Project

| Pile # | Date & Time | Hydro -phone Depth (feet) | Total Number Of Strikes | Lower Frequency Range (Hz) | Absolute Highest Peak (dB) | Peak $L_{50}$ (dB) | $RMS_{90\%}$ $L_{50}$ (dB) | Single Strike $SEL_{90\%}$ (dB) | cSEL (dB) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 10/25/17 9:45 AM | 15 | 200 | Broadband | 195 | 190 | 179 | 169 | 203 |
| | | | | 7 | 196 | 191 | 179 | 169 | 194 |
| | | | | 50 | 192 | 187 | 176 | 166 | 191 |
| | | | | 60 | 192 | 186 | 175 | 165 | 190 |
| | | | | 150 | 191 | 181 | 168 | 158 | 183 |
| | | | | 275 | 191 | 179 | 166 | 156 | 181 |
| 2 | 12/19/17 9:33 AM | 15 | 205 | Broadband | 195 | 193 | 185 | 170 | 193 |
| | | | | 7 | 194 | 193 | 180 | 170 | 193 |
| | | | | 50 | 194 | 192 | 179 | 169 | 192 |
| | | | | 60 | 193 | 191 | 179 | 169 | 191 |
| | | | | 150 | 192 | 189 | 174 | 165 | 187 |
| | | | | 275 | 191 | 187 | 173 | 160 | 185 |
| 3 | 12/19/17 9:46 AM | 15 | 193 | Broadband | 190 | 189 | 179 | 167 | 189 |
| | | | | 7 | 190 | 189 | 177 | 167 | 189 |
| | | | | 50 | 191 | 188 | 176 | 167 | 189 |
| | | | | 60 | 190 | 187 | 176 | 166 | 188 |
| | | | | 150 | 186 | 183 | 169 | 156 | 181 |
| | | | | 275 | 185 | 181 | 167 | 157 | 179 |

Table 5: Summary of Underwater Attenuated Sound Levels for 30-in Upland Pile for the Mukilteo Multimodal Terminal Project

| Pile # | Date & Time | Hydro -phone Depth (feet) | Total Number Of Strikes | Lower Frequency Range (Hz) | Absolute Highest Peak (dB) | Peak $L_{50}$ (dB) | $RMS_{90\%}$ $L_{50}$ (dB) | Single Strike $SEL_{90\%}$ (dB) | cSEL (dB) |
|---|---|---|---|---|---|---|---|---|---|
| 4 | 10/25/17 9:45 AM | 10.5 | 263 | Broadband | 192 | 187 | 180 | 167 | 189 |
| | | | | 7 | 193 | 187 | 176 | 166 | 189 |
| | | | | 50 | 192 | 187 | 175 | 165 | 189 |
| | | | | 60 | 192 | 186 | 175 | 165 | 188 |
| | | | | 150 | 192 | 180 | 168 | 158 | 183 |
| | | | | 275 | 192 | 179 | 166 | 156 | 180 |

## 6.2 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 6: Summary of daily broadband cumulative SEL's

| Day | Daily cSEL (dB) | Distance (m) |
|---|---|---|
| 10/25/2017 | 203 | 12 |
| 12/19/2017 | 194 | 12-14 |

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# 7 SUMMARY

A total of 4, 30-inch steel piles were monitored for the construction of the new Mukilteo Multimodal Ferry Terminal project. The underwater sound levels analyzed, produced the following results.

- Peak broadband underwater attenuated sound levels at 12 to 14 meters varied in a range between 190 $dB_{Peak}$ and 195 $dB_{Peak}$ with the peak $L_{50}$ ranging between 189 $dB_{peak}$ to 190 $dB_{peak}$.
- The measured $RMS_{90\%}$ $L_{50}$ levels ranged between 179 $dB_{RMS90\%}$ and 185 $dB_{RMS90\%}$.
- Cumulative Sound Exposure Levels (cSEL) for all piles driven on a particular day, ranged between 194 $dB_{cSEL}$ and 203 $dB_{cSEL}$.
- For the upland pile (Pile 4) the peak levels were approximately 2 to 3 dB lower than the piles driven in the water, the RMS 90% was about the same as for Piles 1 and 3 but 5 dB lower than Pile 2. The cumulative SEL for Pile 4 was 0 dB to 14 dB lower than the piles in water. The reason the upland pile was not that different from those driven in water is likely due to the upland pile being relatively close to the water's edge.

# 8 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.

NMFS- National Marine Fisheries Service. 2016. *Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Threshold Levels for Onset Permanent and Temporary Threshold Shifts*. U.S. Department of Commerce, NOAA. NOAA Technical Memorandum NMFS-OPR-55. 178 pp.

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# 9 APPENDIX A: WAVEFORM ANALYSIS FIGURES

Figure 17: Waveform Analysis of attenuated Pile 1 impact driven

**Mukilteo Test Pile 1 2017**

**Figure a. Waveform**

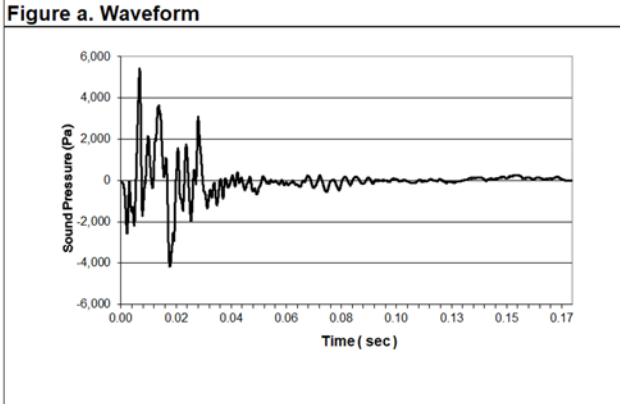


**Figure b. Narrow Band Frequency Spectra**

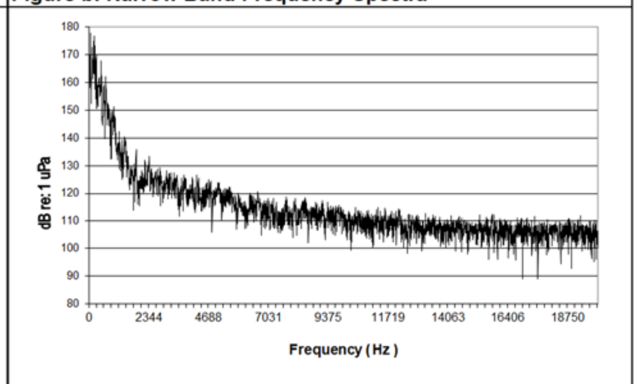


**Figure c. Accumulation of Sound Energy**

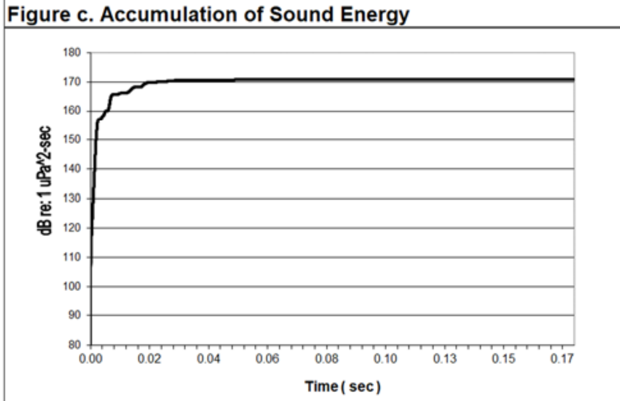


**Figure d. Sound Pressure and Sound Energy Levels**

Signal Analysis Sound Pressure / Energy Levels

| Sensor Depth | Peak | RMS90%* | SEL |
|---|---|---|---|
| 15-feet | 195 | 186 | 171 |

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

Figure 18: Waveform Analysis of attenuated Pile 2 impact driven

**Mukilteo Test Pile 2 2017**

**Figure a. Waveform**

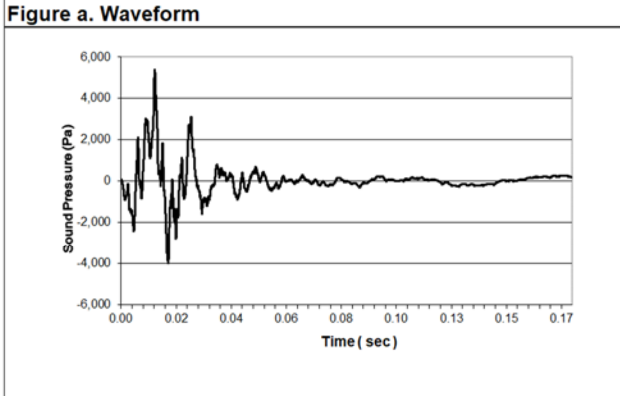


**Figure b. Narrow Band Frequency Spectra**

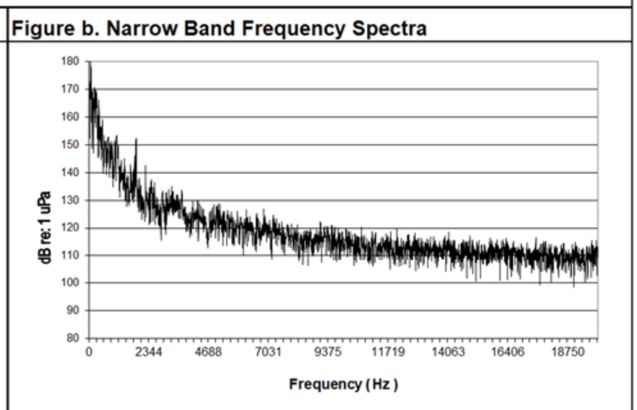


**Figure c. Accumulation of Sound Energy**

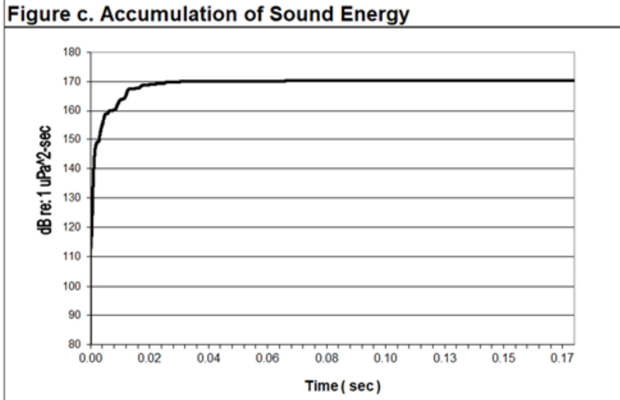


**Figure d. Sound Pressure and Sound Energy Levels**

Signal Analysis Sound Pressure / Energy Levels

| Sensor Depth | Peak | RMS90%* | SEL |
|---|---|---|---|
| 15-feet | 195 | 185 | 170 |

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

Figure 19: Waveform Analysis of attenuated Pile 3 impact driven

**Mukilteo Test Pile 3 2017**

**Figure a. Waveform**

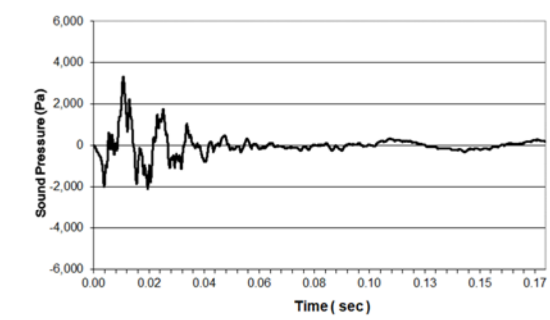


**Figure b. Narrow Band Frequency Spectra**

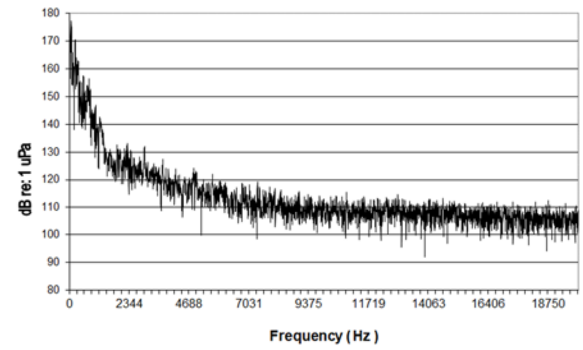


**Figure c. Accumulation of Sound Energy**

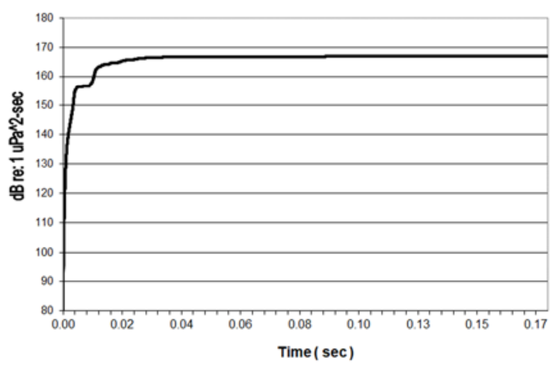


**Figure d. Sound Pressure and Sound Energy Levels**

Signal Analysis Sound Pressure / Energy Levels

| Sensor Depth | Peak | RMS90%* | SEL |
|---|---|---|---|
| 15-feet | 190 | 179 | 167 |

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

Figure 20: Waveform Analysis of upland Pile 1 impact driven

**Mukilteo Test Upland Pile 1 2017**

**Figure a. Waveform**

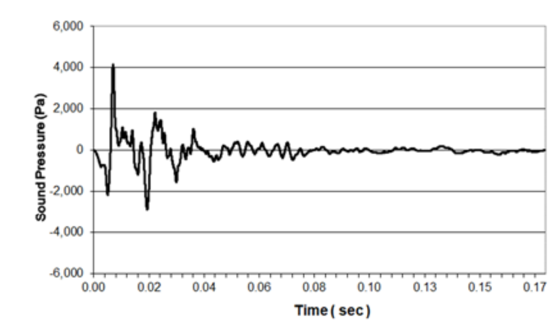


**Figure b. Narrow Band Frequency Spectra**

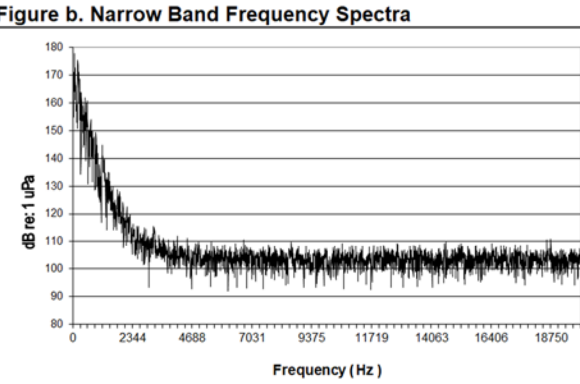


**Figure c. Accumulation of Sound Energy**

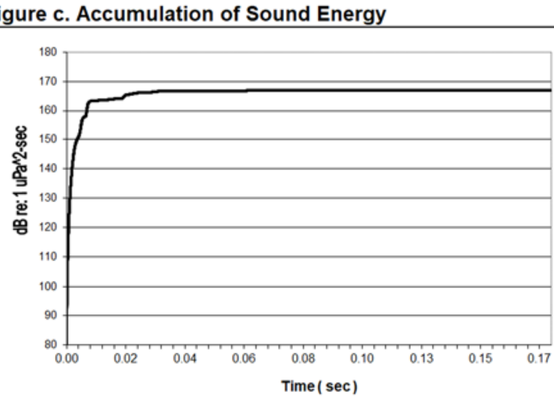


**Figure d. Sound Pressure and Sound Energy Levels**

Signal Analysis Sound Pressure / Energy Levels

| Sensor Depth | Peak | RMS90%* | SEL |
|---|---|---|---|
| 10-feet | 192 | 180 | 167 |

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

# 10 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).

$$SEL = 10 \log \left( \int_0^T \frac{p^2(t)}{p_0^2} dt \right) \quad dB \qquad \text{(eq. 1)}$$

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, $10\text{Log}_{10}(N)$. 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 $uPa^2 \bullet s$). Next compute the sum of the linear units and convert this sum back into dB by taking $10\text{Log}_{10}$ of the value. This was the cumulative SEL for all of the pile strikes.