SR 525/ Mukilteo Ferry Terminal (Phase 3) Marine Structures 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
NMFS	National Marine Fisheries Service
Pa	Pascal
RMS	Root Mean Squared
SEL	Sound Exposure Level
SPL	Sound Pressure Level
WSDOT	Washington State Department of Transportation
WSF	Washington State Ferries
USFW	United States Fish and Wildlife

EXECUTIVE SUMMARY

This technical report describes the data collected during impact pile driving and monitoring of underwater sound levels from driving two 24-inch steel piles for the Washington State Department of Transportation (WSDOT) Ferries Division (WSF) at the SR 525/ Mukilteo Ferry Terminal (Phase 3) Marine Structures Project, on January 29, 2020. The piles were monitored in the Possession Sound in the City of Mukilteo, Snohomish County, Washington. A confined bubble curtain was deployed for all piles impact driven to attenuate potential underwater noise effects. Piles were vibratory driven initially and then impacted during these measurements. Measurements were collected at 10 meters from each pile.

As shown in Table 1, both Piles 1 and 2 exceeded the Root Mean Square (RMS) dB Behavioral Threshold for broadband, low frequency, Phocids, and Otariid hearing groups. Both Piles 1 and 2 exceeded the Peak dB Auditory Injury Threshold for the low frequency hearing group. The Cumulative Sound Exposure Level (cSEL) dB Auditory Injury Threshold (183 dB_{cSEL}) was exceeded for fish for Piles 1 and 2, as well as the low frequency hearing group for Pile 2. A combined total of 264 strikes for Piles 1 and 2 resulted in a daily cSEL dB Auditory Injury Threshold exceedances for fish (broadband) and two marine mammal hearing groups: low frequency and high frequency.

Table 1: Summary of 24-inch Pile Impact Driving Broadband and Weighted Underwater Sound Levels

Pile #	Hearing Group	Peak L_{50} (dB)	Single Strike $SEL_{90\%}$ L_{50} (dB)	$RMS_{90\%}$ L_{50} (dB)	Exceed dB RMS Behavioral Threshold? (Y/N)	Absolute Highest Peak (dB)	Exceed Peak dB Auditory Injury Threshold? (Y/N)	cSEL (dB)	Exceed dB cSEL Auditory Injury Threshold? (Y/N)
1	Broadband	190	166	177	Y	193	N	185	Y
	Low Freq.	189	163	174	Y	192	Y	182	N
	Mid. Freq.	164	135	146	N	171	N	155	N
	High Freq.	163	135	145	N	171	N	153	N
	Phocids	181	154	165	Y	185	N	173	N
	Otariids	181	154	164	Y	184	N	173	N
2	Broadband	191	166	176	Y	194	N	188	Y
	Low Freq.	189	163	173	Y	193	Y	185	Y
	Mid. Freq.	167	136	146	N	175	N	158	N
	High Freq.	164	131	141	N	171	N	154	N
	Phocids	182	154	164	Y	188	N	177	N
	Otariids	181	154	164	Y	187	N	176	N
Combined Piles	Broadband	-	-	-	-	-	-	190	Y
	Low Freq.	-	-	-	-	-	-	187	Y
	Mid. Freq.	-	-	-	-	-	-	160	N
	High Freq.	-	-	-	-	-	-	157	Y
	Phocids	-	-	-	-	-	-	178	N
	Otariids	-	-	-	-	-	-	178	N

1 INTRODUCTION

The Washington State Department of Transportation (WSDOT) Ferries Division (WSF) operates and maintains 19 ferry terminals and one maintenance facility, all of which are located in either Puget Sound or the San Juan Islands (Georgia Basin). Since its creation in 1951, WSF has become the largest ferry system in the United States, operating 28 vessels on 10 routes with over 500 sailings each day.

To improve, maintain, and preserve the terminals, WSF conducts construction, repair and maintenance activities as part of its regular operations. One of these projects is the relocation of the Mukilteo ferry terminal, located in the Possession Sound. See vicinity map (Figure 1). The Mukilteo ferry terminal has not had significant improvements for almost 30 years and needs key repairs. The existing facility is deficient in a number of aspects, such as safety, multimodal connectivity, capacity, and the ability to support the goals of local and regional long-range transportation and comprehensive plans. The project is intended to:

- Reduce conflicts, congestion, and safety concerns for pedestrians, bicyclists, and motorists by improving local traffic and safety at the terminal and the surrounding area that serves these transportation needs.
- Provide a terminal and supporting facilities with the infrastructure and operating characteristics needed to improve the safety, security, quality, reliability, efficiency, and effectiveness of multimodal transportation.
- Accommodate future demand projected for transit, HOV, pedestrian, bicycle, and general purpose traffic.

Construction would require the installation of permanent and temporary piles in the Possession Sound to support the new ferry terminal.

This report summarizes the impact pile driving results measured in the Possession Sound in an effort to collect site-specific data on underwater noise levels during the month of January 2020. Two 24-inch diameter steel piles were monitored (Figure 2).

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

The results are compared against the auditory injury and behavioral disturbance thresholds that the National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife (USFW) have determined for fish and marine mammals.

Figure 1: Vicinity Map of SR 525/ Mukilteo Ferry Terminal (Phase 3) Marine Structures Project

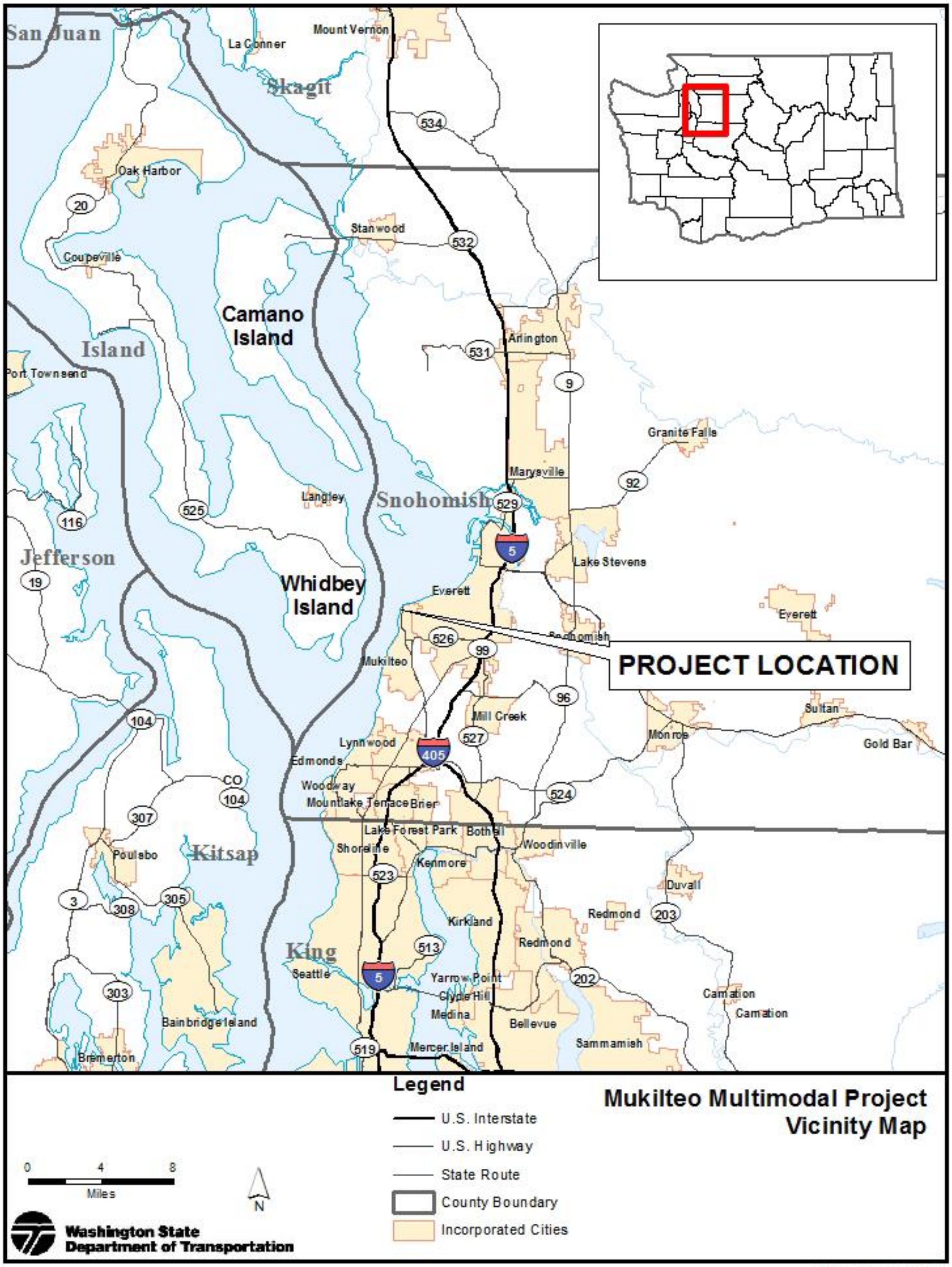
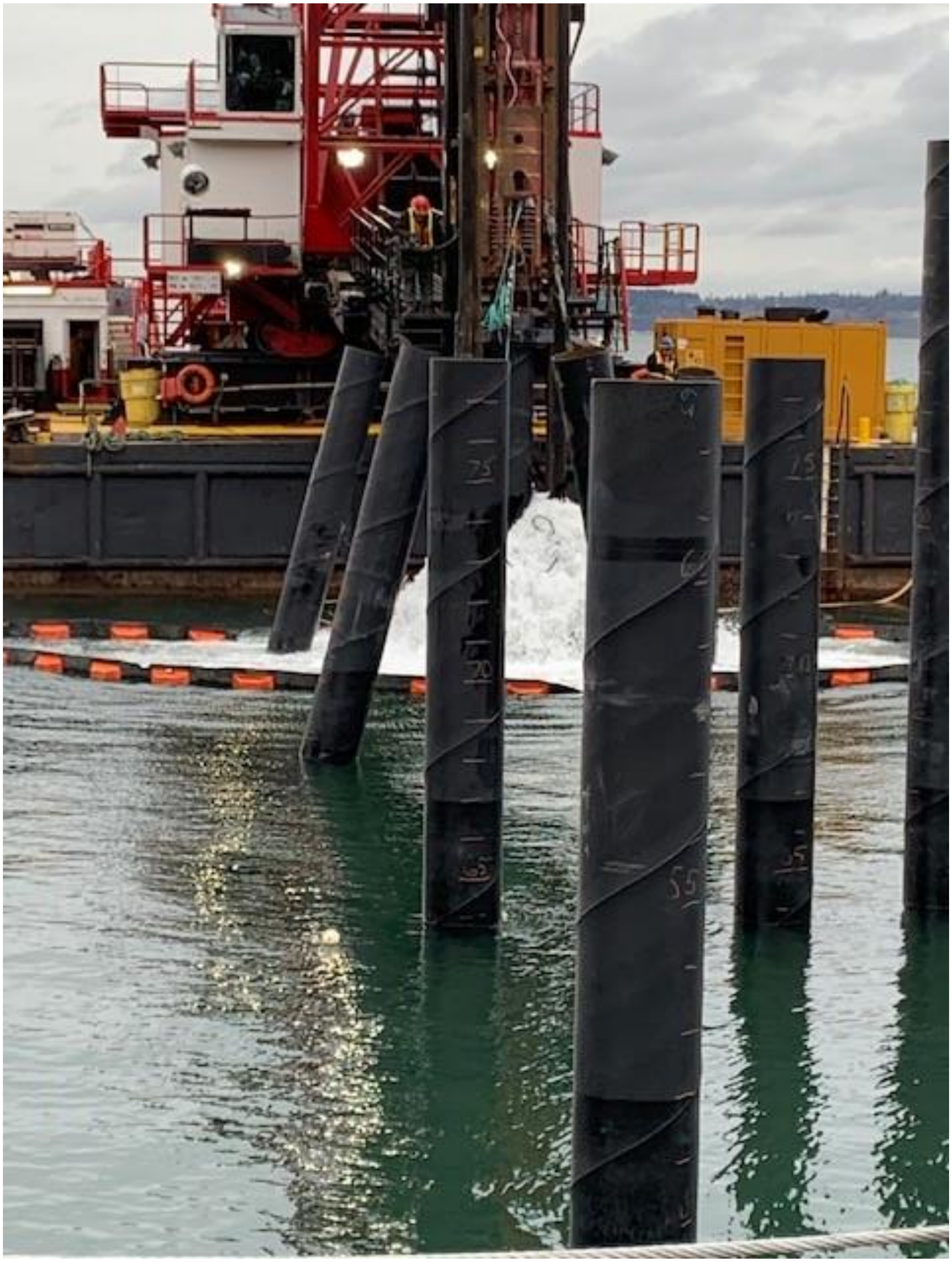


Figure 2: 24-in Piles at Mukilteo Ferry Terminal (Phase 3) Project



2 PROJECT AREA

The Mukilteo Ferry Terminal is located in the City of Mukilteo, Snohomish County, Washington. The terminal is located in Township 28 North, Range 4 East, Section 3, in Possession Sound. The new terminal would be approximately 1,700 feet (ft.) east of the existing terminal in Township 28N, Range 4E, Section 33. Land use in the Mukilteo area is a mix of residential, commercial, industrial, and open space and/or undeveloped lands.

3 PILE INSTALLATION LOCATION

Two 24-inch steel piles were monitored during impact pile driving activity in the Possession Sound in the City of Mukilteo, Snohomish County, Washington. Figure 3 indicates the approximate location of the piles monitored.

The hydrophone was located at 10 meters from each in water pile monitored and placed at mid-water depth. The depth of the water where the hydrophone was deployed was approximately 30 to 35 feet deep depending on location and tidal influence.

Figure 3: Approximate Locations of Piles 1 and 2 at Mukilteo Ferry Terminal (Phase 3) Project

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.

The L_{50} or 50th 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.

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

5 METHODOLOGY

5.1 TYPICAL EQUIPMENT DEPLOYMENT

For each pile monitored, the hydrophone was deployed from the shore. The monitoring equipment is outlined below and shown in Figure 4. The hydrophone was stationed and fixed with an anchor and the line held taught by suspending the line from a surface float. The hydrophone was placed at a distance of 10 meters from each pile being monitored. A confined bubble curtain was deployed for all piles impact driven in water depths greater than 2 feet to mitigate potential underwater noise effects with one bubble ring inside at the bottom (See Figure 5).

Figure 4: Near Field Acoustical Monitoring Equipment

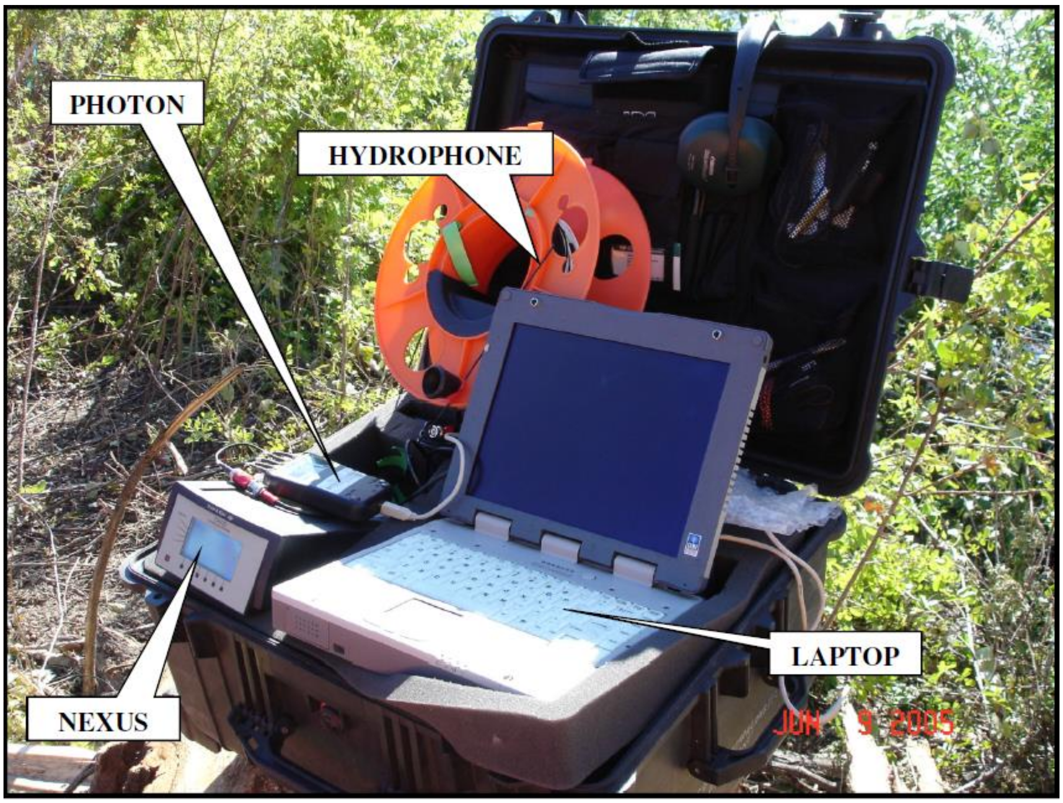


Figure 5: Confined Bubble Curtain Used at Mukilteo Ferry Terminal Project

Underwater sound levels were measured using one Reson TC 4013 hydrophone. 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 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. WSDOT has the system and software calibration checked annually against National Institute of Standards and Technology (NIST) traceable standard.

Signal recording 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.

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 50th percentile or L_{50} peak, RMS90% and SEL90% value is computed. MatLab software was used for the analysis of collected data.

The underwater noise thresholds are displayed below in Table 2.

Table 2: Impact Driving Underwater Sound Level Thresholds

Hearing Group	Peak Threshold (dB)	Behavioral Threshold (dB RMS)	Auditory Injury Threshold (dB cSEL)
Broadband	206	150	183
Low Freq.	183	160	183
Mid. Freq.	230	160	185
High Freq	202	160	155
Phocids	218	160	185
Otariids	232	160	203

6 PILE INSTALLATION RESULTS

6.1 UNDERWATER SOUND LEVELS

WSDOT conducted hydroacoustic monitoring for two 24-inch steel piles struck with an impact hammer in water depths of 30 to 35 feet in the Possession Sound. Data from all piles analyzed in the paragraphs below and summarized in Table 3.

Pile 1

Pile 1 is located approximately 100 feet from the shoreline in approximately 35 feet of water on the northeast side of the new ferry terminal (See Figure 3).

As shown in Table 3, Pile 1 exceeded the Root Mean Square (RMS) dB Behavioral Threshold for broadband (fish) and low frequency, Phocids, and Otariid marine mammal hearing groups. The distance from the pile to the RMS dB Behavioral Threshold for the exceeded hearing groups is 631 meters (2070 feet) for broadband, 86 meters (281 feet) for low frequency, 22 meters (71 feet) for Phocids, and 18 meters (61 feet) for Otariid (See Table 3).

Pile 1 also exceeded the Peak dB Auditory Injury Threshold for the low frequency hearing group. The distance from the pile to the Peak dB Auditory Injury Threshold for the low frequency hearing group is 40 meters (See Table 3).

The Cumulative Sound Exposure Level (cSEL) dB Auditory Injury Threshold was exceeded for the fish for Pile 1. Approximately 32 strikes out of 87 strikes exceeded the 183 dB cSEL threshold for fish. The distance from the pile to the cSEL dB Auditory Injury Threshold for fish is 14 meters (See Table 3).

Figures 6, 7, 8, 9, and 10 show the time history plot, 1/3rd Octave band plot, Power Spectral Density (PSD) plot, peak pile strike spectrogram, and full drive spectrogram plot respectively.

Figure 6 shows the peak, RMS90%, SEL90%, and cumulative SEL values for each attenuated pile strike. The pile strikes appeared to be relatively stable throughout the entire drive.

Figure 6: Time History Plot of Individual Pile Strikes for Monitored Pile 1

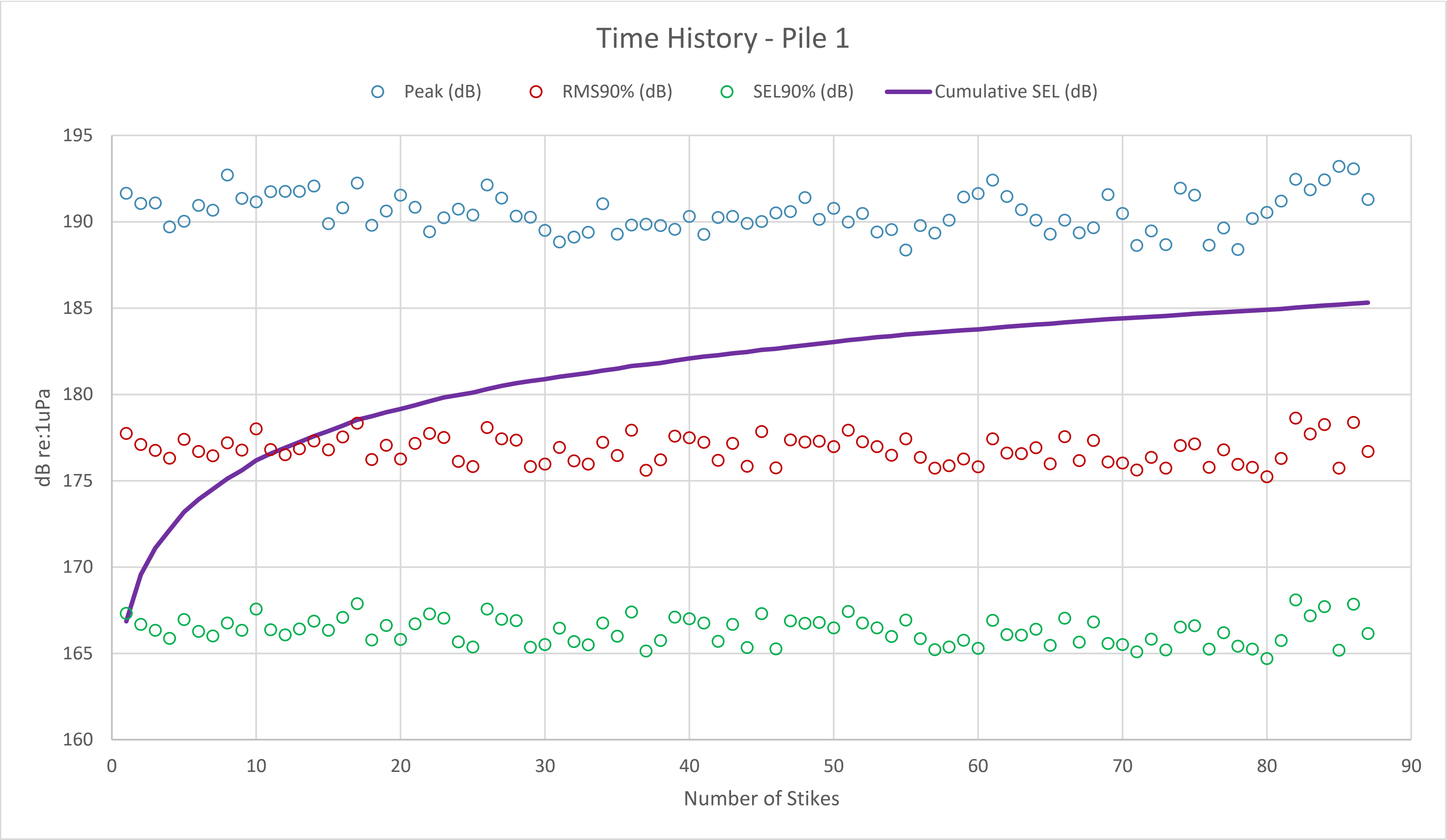


Figure 7 shows the 1/3rd Octave band plot for Pile 1. The plot indicates that the dominant frequency band is at about 400 Hz with possible harmonics seen at 200 and 400 Hz.

Figure 7: 1/3rd Octave Band Plot for Monitored Pile 1

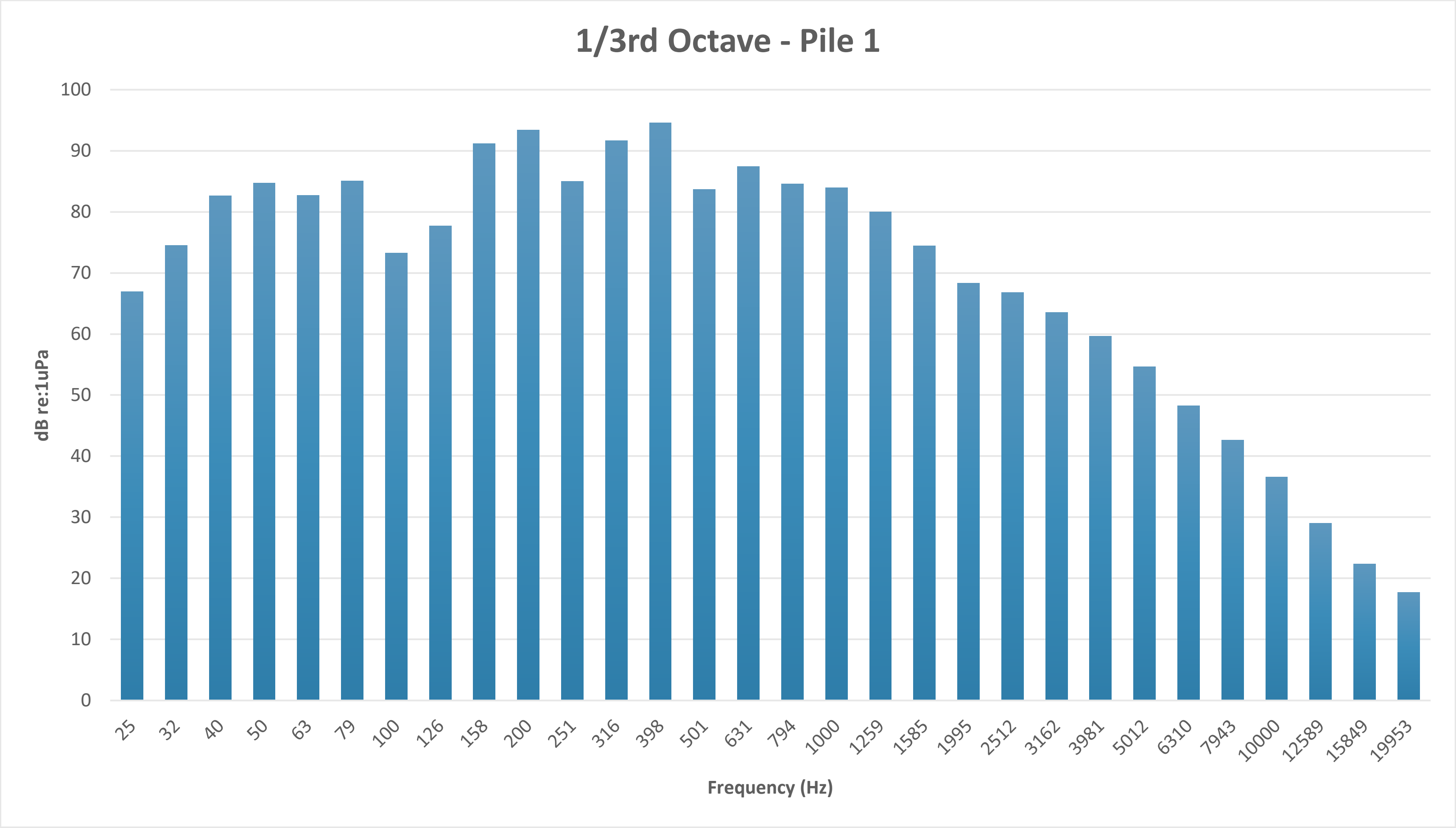


Figure 8 shows the Power Spectral Density (PSD) plot (sound pressure level as a function of frequency) for the peak pile strike and two additional strikes adjacent to the peak which shows a finer detail for each frequency compared to the 1/3rd Octave plot. The plot indicates that most of the energy in each pile strike is below about 1000 Hz with the dominant frequencies slightly at 20 Hz and 200 Hz.

Figure 8: Power Spectral Density Plot for Monitored Pile 1

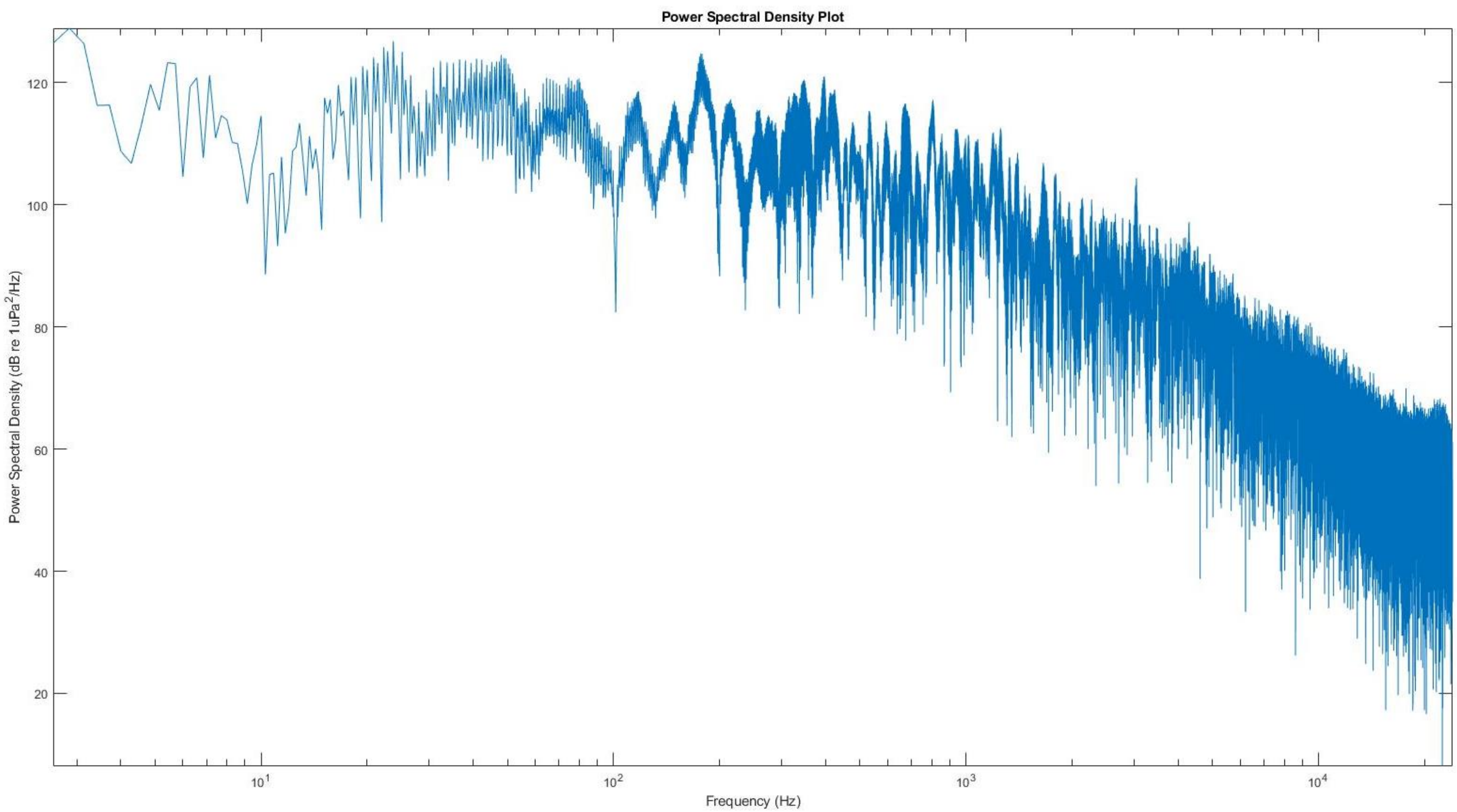
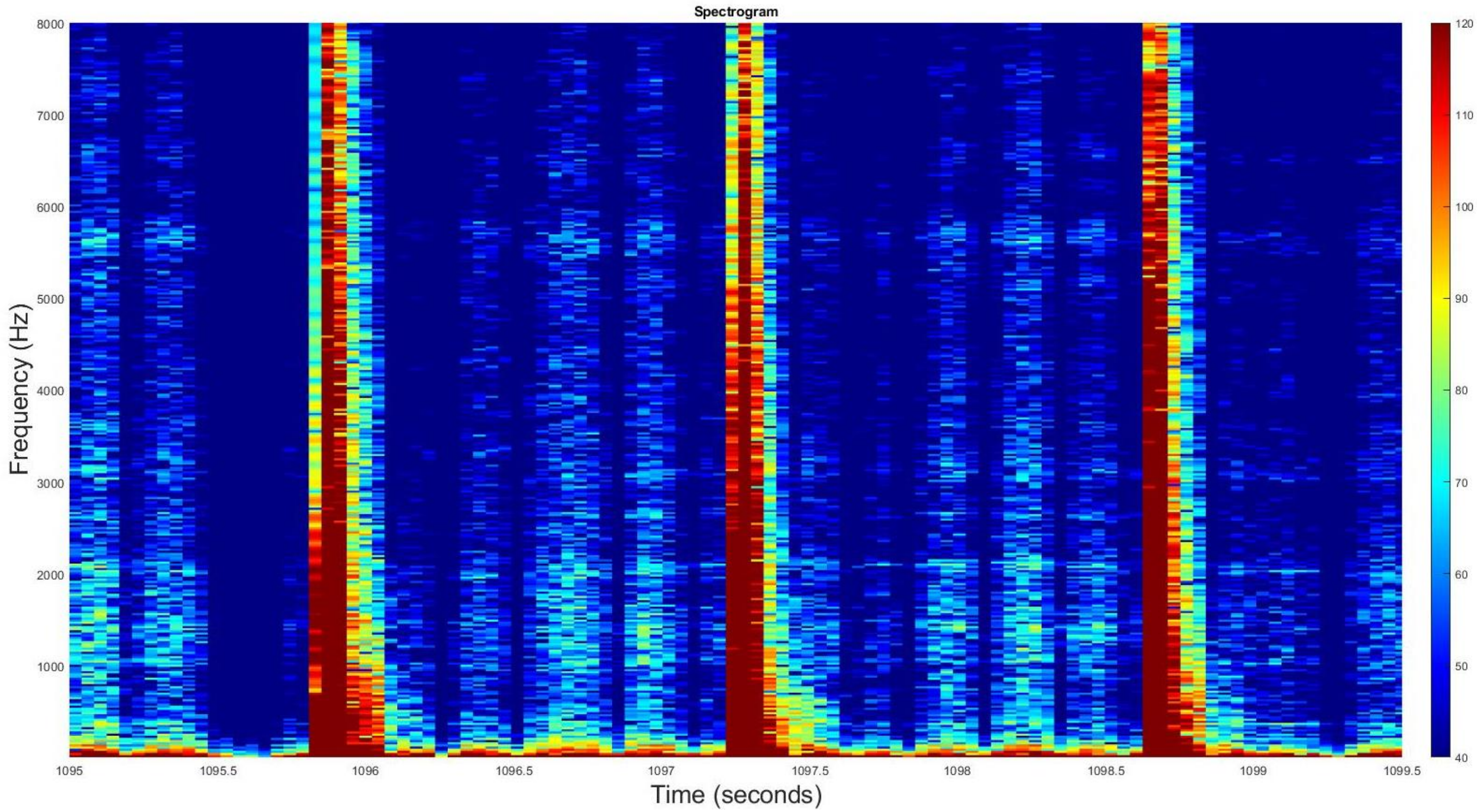


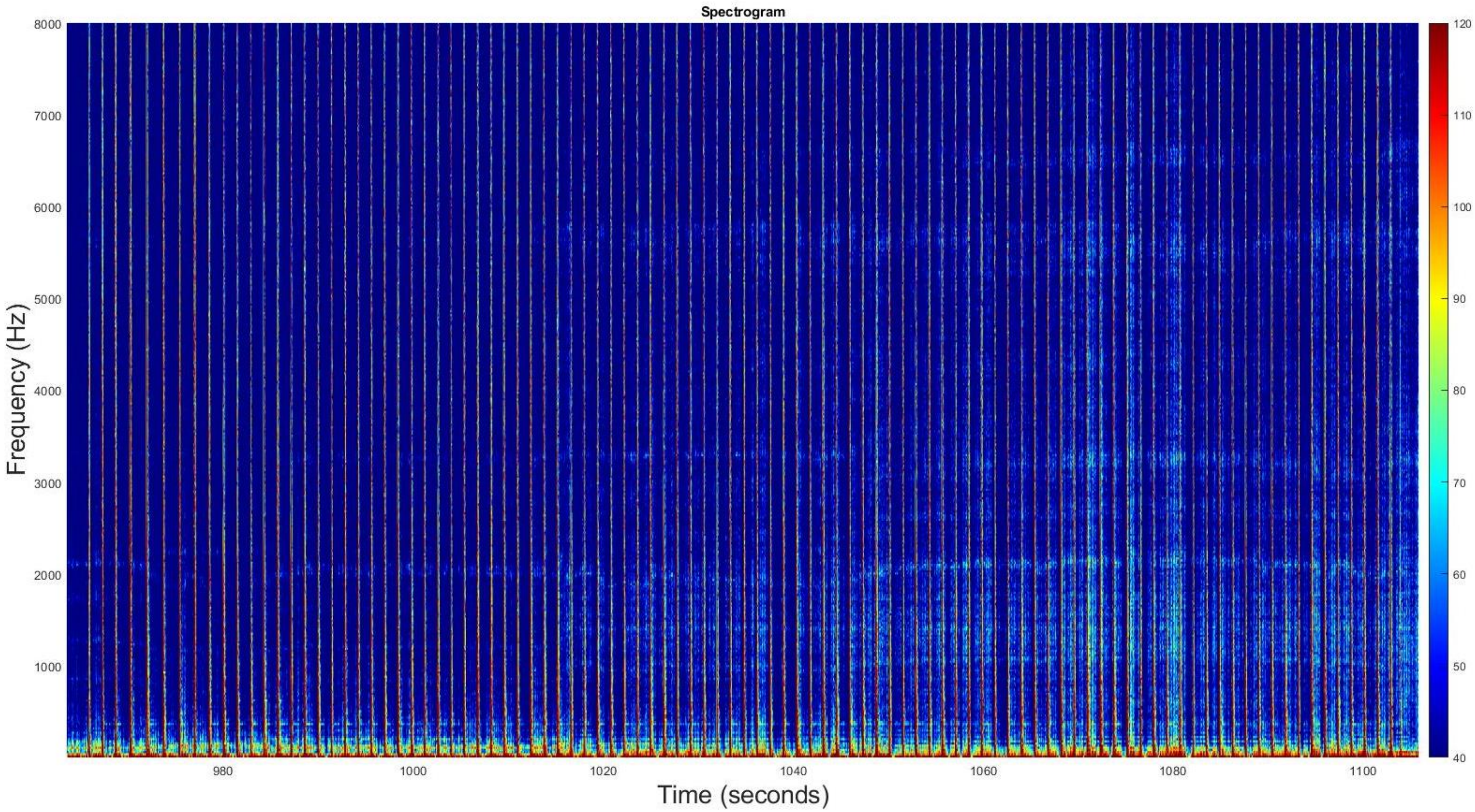
Figure 9 shows the spectrogram plot (sound intensity as a function of time and frequency) which is a visual representation of an acoustic signal with degrees of amplitude represented by color. The plot represents the peak pile strike and two adjacent pile strikes. The color bar to the right indicates the decibel level. The individual pile strikes are distinguished from background by the presence of spectral peaks concentrated in the 20 Hz to 10000 Hz range. The spectrogram shows that there is substantially more energy (red color) in the pile strikes for this pile below approximately 5000 Hz. There are also a couple of horizontal bands at approximately 2000 and 6000 Hz, which could relate to a nearby outboard motor operating during the pile driving activity.

Figure 9: Peak Strike Spectrogram Plot for Monitored Pile 1



The spectrogram plot in Figure 10 represents the entire pile drive run for Pile 1. The plot indicates that there are a couple of horizontal bands at approximately 2000 and 6000 Hz, which become more intense in the second half of the drive. This could relate to a nearby outboard motor operating during the pile driving activity, or a change in substrate.

Figure 10: Full Spectogram Plot for Monitored Pile 1



Pile 2

Pile 2 is located approximately 100 feet from the shoreline and approximately 50 feet northeast of Pile 1 (Figure 3). Since there was a 10 minute break between during the drive for Pile 2, two separate recordings were collected. The first section was between 1:08 PM and 1:11 PM and the second section was between 1:21 PM and 1:23 PM.

As shown in Table 3, Pile 2 exceeded the Root Mean Square (RMS) dB Behavioral Threshold for fish and low frequency, Phocids, and Otariid marine mammal hearing groups. The distance from the pile to the RMS dB Behavioral Threshold for the exceeded groups is 541 meters (1775 feet) for fish, 74 meters (241 feet) for low frequency cetaceans, 18 meters (61 feet) for Phocids, and 18 meters (61 feet) for Otariid (See Table 3).

Pile 2 also exceeded the Peak dB Auditory Injury Threshold for the low frequency hearing group. The distance from the pile to the Peak dB Auditory Injury Threshold for the low frequency hearing group is 46 meters (152 feet) (See Table 3).

The Cumulative Sound Exposure Level (cSEL) dB Auditory Injury Threshold was exceeded for the fish and the low frequency marine mammal hearing group for Pile 2. Approximately 120 strikes out of 177 strikes exceeded the 183 dB cSEL threshold for fish. Approximately 67 strikes out of 177 strikes exceeded the 183 dB cSEL threshold for the low frequency cetaceans. The distance from the pile to the cSEL dB Auditory Injury Threshold for the exceeded groups is 22 meters (71 feet) for fish and 14 meters (45 feet) for the low frequency cetaceans (See Table 3).

Figures 11, 12, 13, 14 and 15 show the time history plot, 1/3rd Octave plot, PSD plot, peak pile strike spectrogram, and full drive spectrogram plot respectively.

In Figure 11 the peak, RMS90%, and SEL90% values are relatively stable until the second half of the drive. After that point, they show some slight variability for the remainder of the pile driving. This corresponds to the break and subsequent restart of driving for Pile 2.

Figure 11: Time History Plot of Individual Pile Strikes for Monitored Pile 2

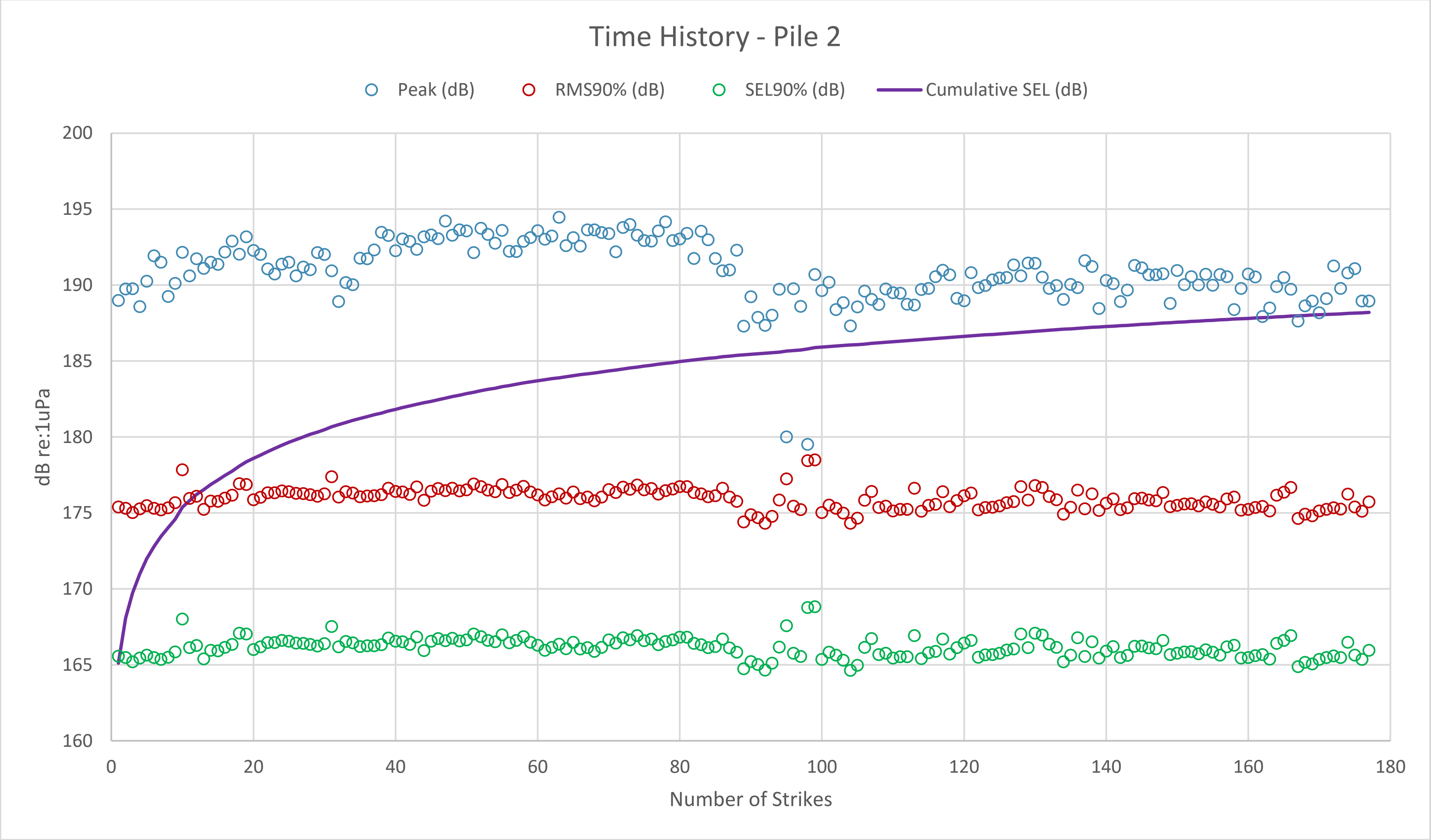
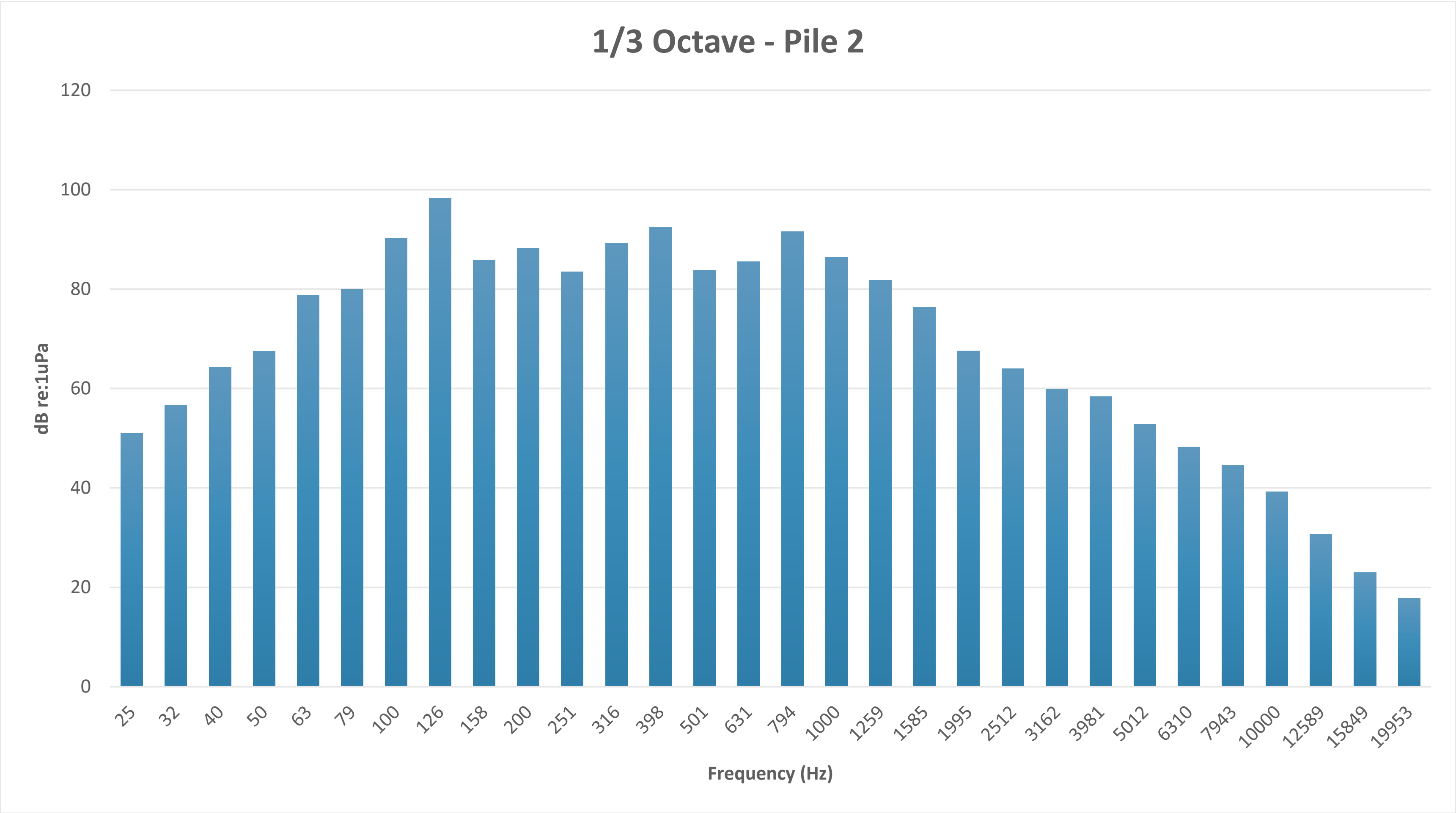


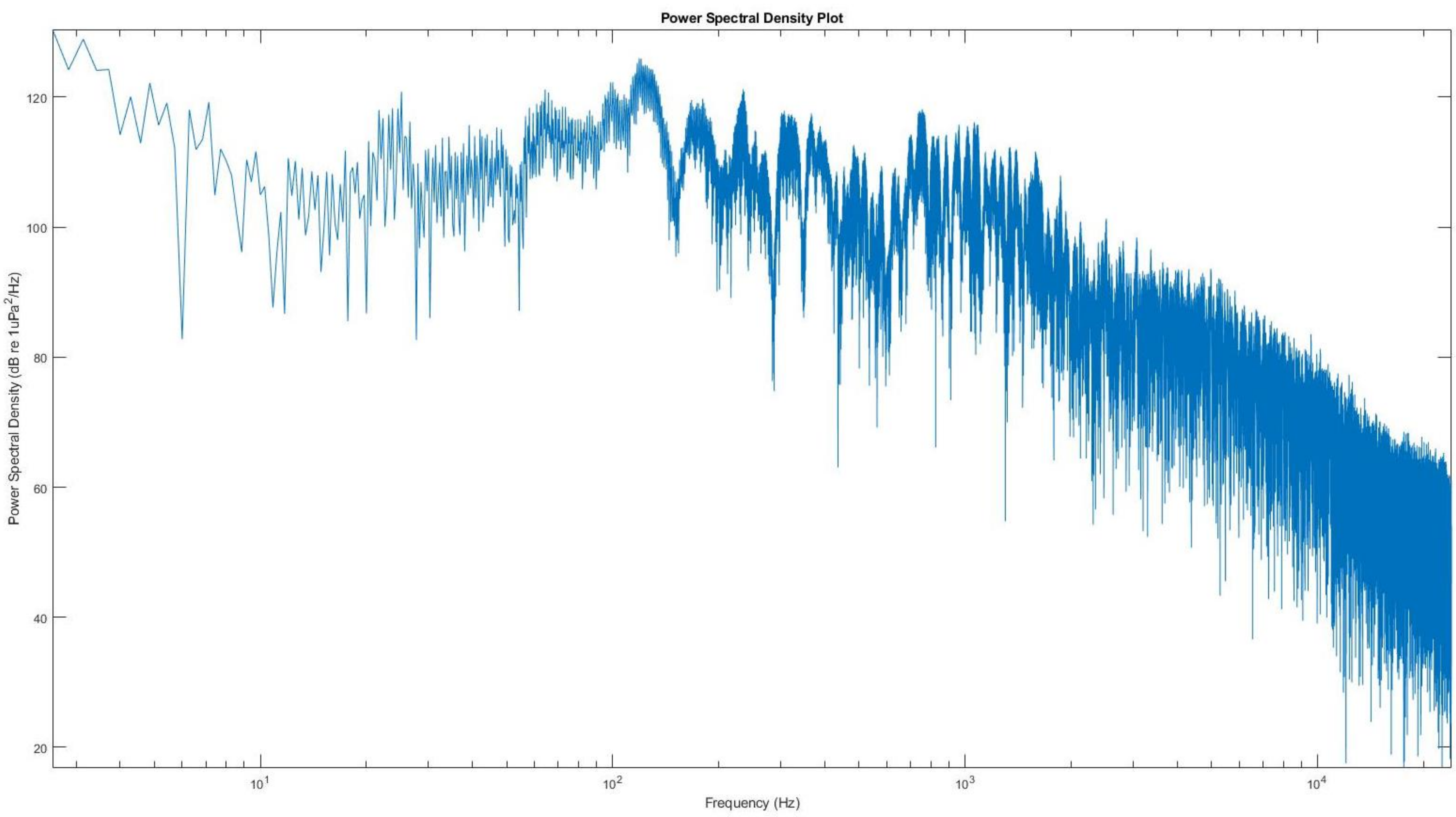
Figure 12 shows the 1/3rd Octave band plot for Pile 2. The plot indicates that the dominant frequency band is at about 125 Hz with a secondary peak at 400 Hz and possible harmonic 800 Hz.

Figure 12: 1/3rd Octave Band Plot for Monitored Pile 2



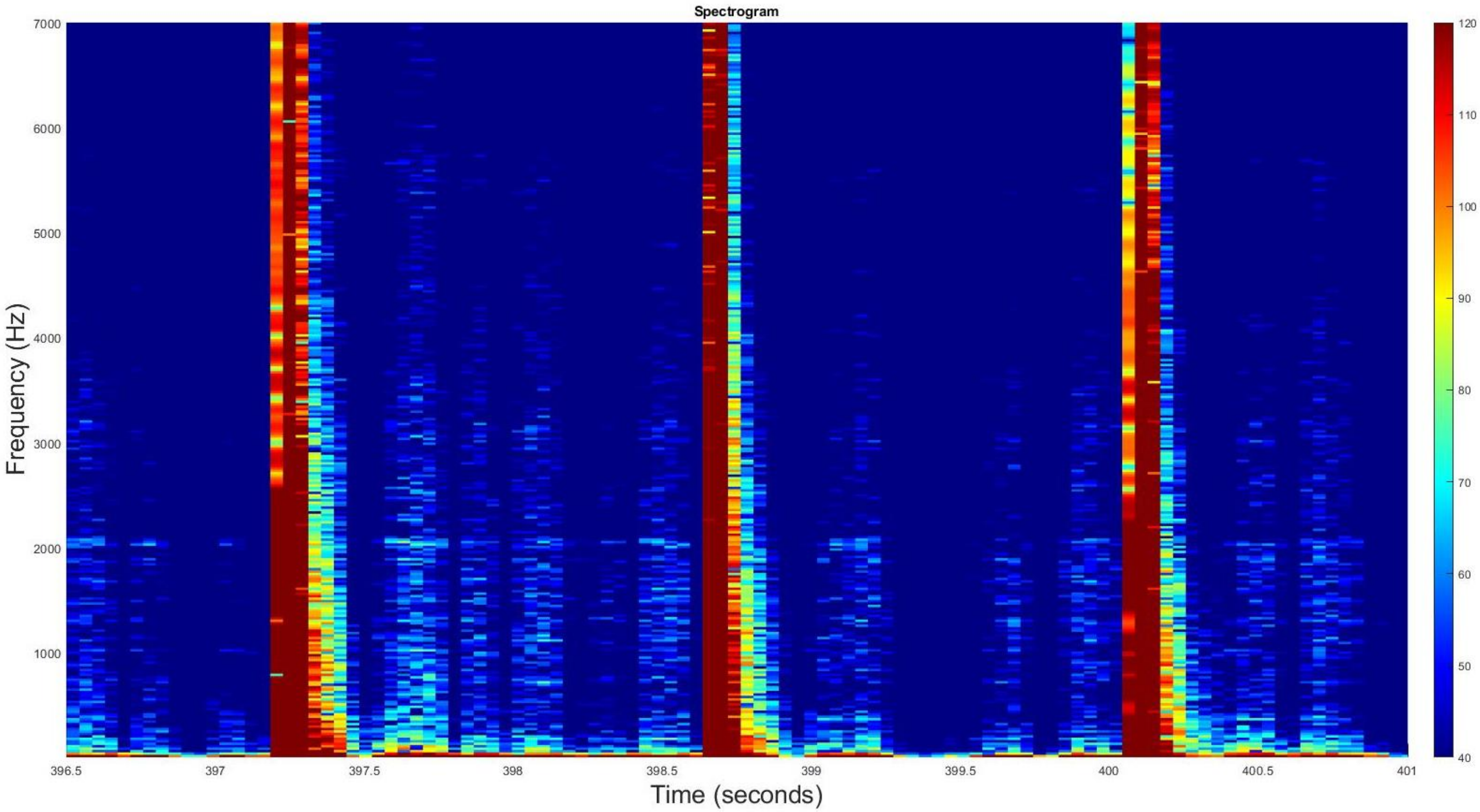
The PSD plot shown in Figure 13 represents the absolute peak pile strike and two adjacent strikes indicates that most of the energy in each pile strike is below about 1000 Hz with the dominant frequencies slightly above 100 Hz.

Figure 13: Power Spectral Density Plot for Monitored Pile 2



The spectrogram plot in Figure 14 represents the peak pile strike and two adjacent pile strikes. The plot indicates that most of the energy is concentrated in the 20 Hz to 3000 Hz range. There is a band around 2000 Hz, possibly relating to a nearby outboard motor operating during the pile driving activity.

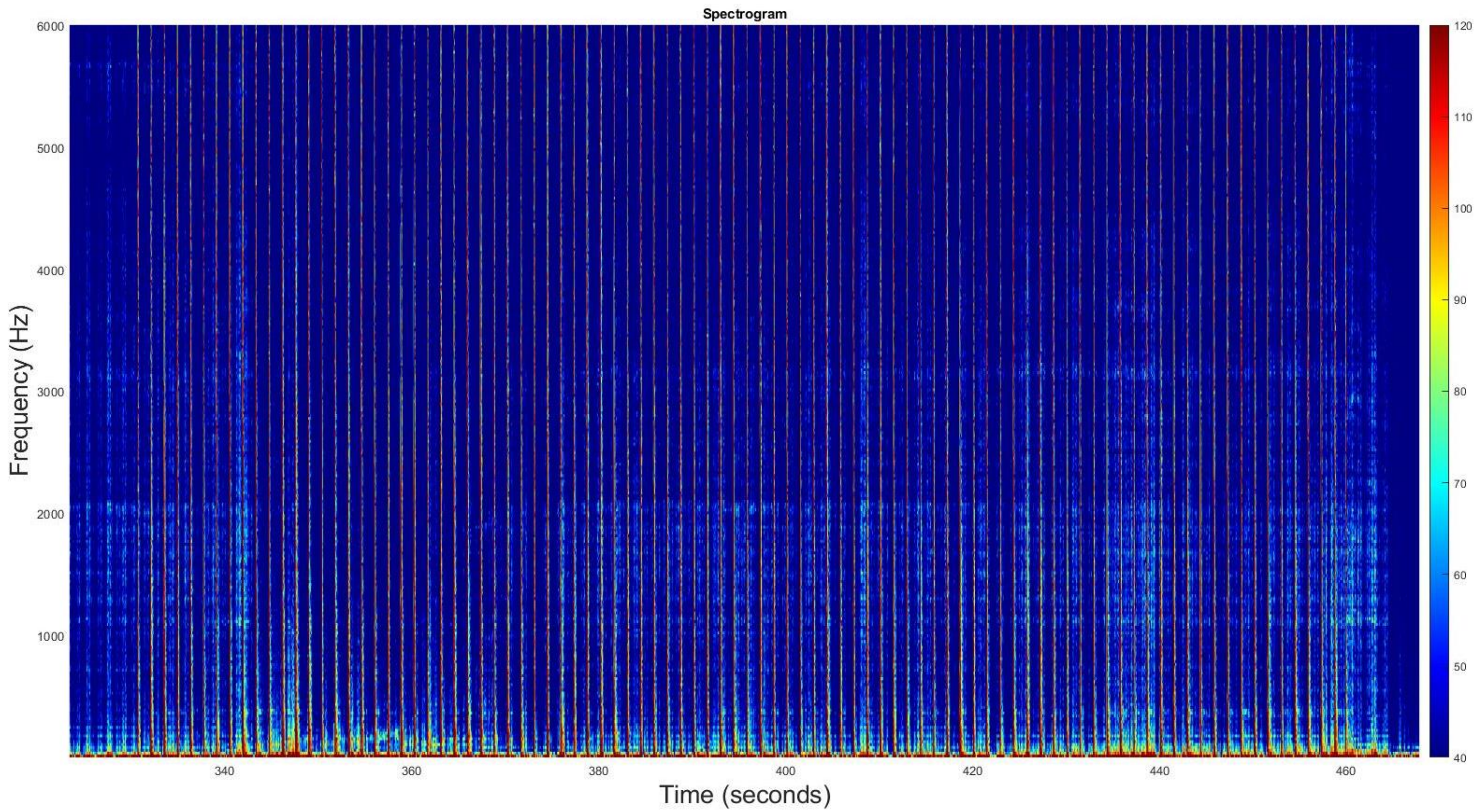
Figure 14: Peak Strike Spectrogram Plot for Monitored Pile 2



The spectrogram plots in Figure 15 (a) and (b) represent the entire pile drive run for Pile 2. The plots indicate that there is more noise between the strikes in the second segment when compared to the first, particularly in the frequencies around 3000 Hz below 2000 Hz. The bands around 3000 Hz, 2000 Hz, and 1000 Hz are more pronounced in the second segment. This could possibly be caused by a change in substrate during the pile driving.

Figure 15: Full Spectogram Plots for Monitored Pile 2 between (a) 1:08 PM and 1:11 PM and (b) 1:21 PM and 1:23 PM

(a)



(b)

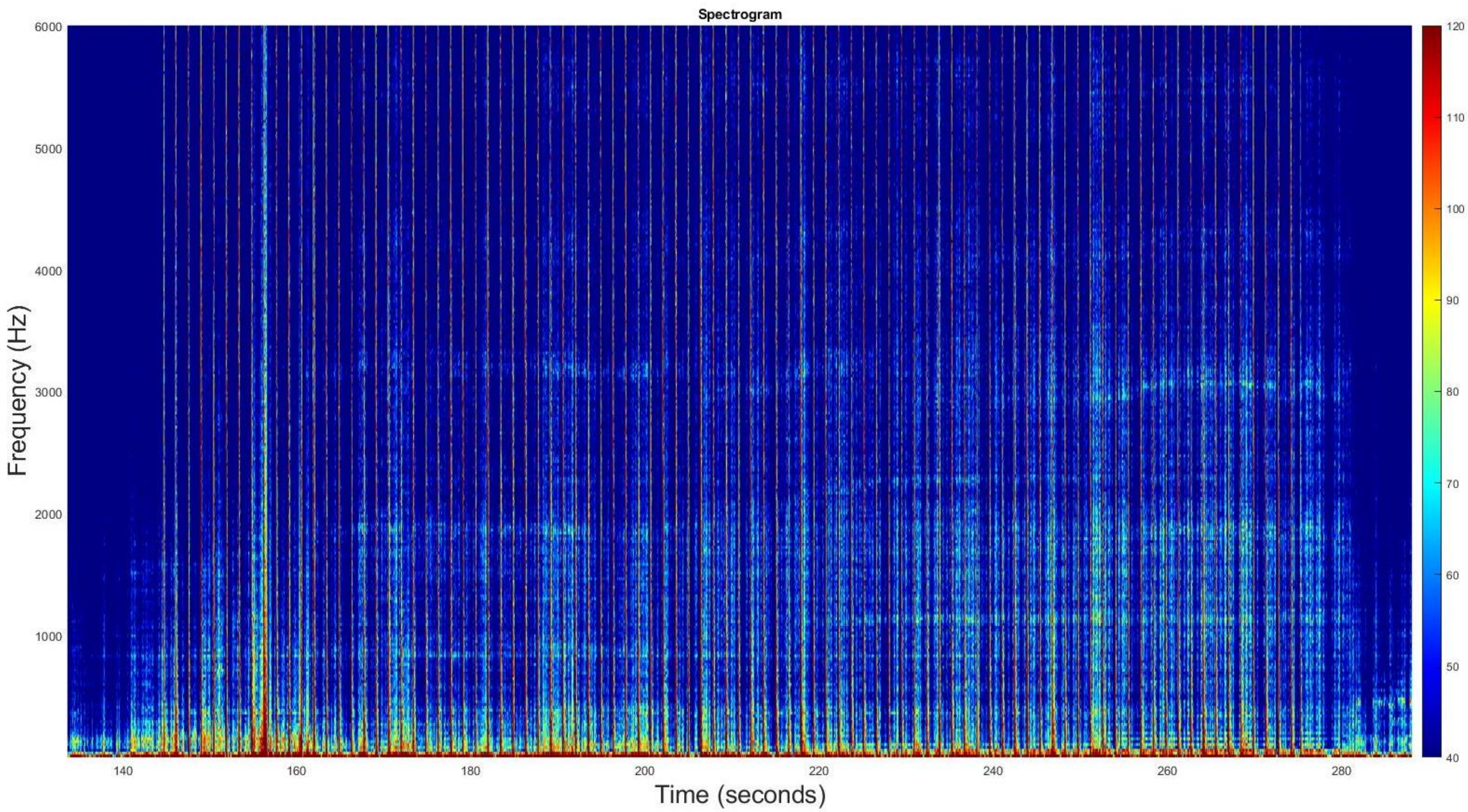

Spectrogram
Frequency (Hz)
6000
5000
4000
3000
2000
1000
140
160
180
200
220
240
260
280
Time (seconds)
120
110
100
90
80
70
60
50
40

Table 3: Summary of Underwater Attenuated Sound Levels for 24-in Piles at Mukilteo Ferry Terminal

Pile #	Date & Time	Water Depth (feet)	Hydro-phone Depth (feet)	Total Number Of Strikes	Hearing Group	Peak L_{50} (dB)	Single Strike $SEL_{90\%}$ L_{50} (dB)	$RMS_{90\%}$ L_{50} (dB)	Behavioral Threshold (dB RMS)	Exceed dB RMS Threshold? (Y/N)	Distance To dB RMS Threshold (meters)	Absolute Highest Peak (dB)	Auditory Injury Threshold (Peak dB)	Exceed Peak dB Threshold? (Y/N)	Distance To Peak dB Threshold (meters)	cSEL (dB)	Auditory Injury Threshold (dB cSEL)	Exceed dB cSEL Threshold? (Y/N)	Distance to dB cSEL Threshold (meters)
1	1-29-2020 11:32 AM-11:35 AM	35	15	87	Broadband	190	166	177	150	Y	631	193	206	N	1	185	183	Y	14
					Low Freq.	189	163	174	160	Y	86	192	183	Y	40	182	183	N	9
					Mid. Freq.	164	135	146	160	N	1	171	230	N	0	155	185	N	0
					High Freq.	163	135	145	160	N	1	171	202	N	0	153	155	N	7
					Phocids	181	154	165	160	Y	22	185	218	N	0	173	185	N	2
					Otariids	181	154	164	160	Y	18	184	232	N	0	173	203	N	0
2	1-29-2020 1:08 PM-1:11 PM & 1:21 PM-1:23 PM	30	15	177	Broadband	191	166	176	150	Y	541	194	206	N	2	188	183	Y	22
					Low Freq.	189	163	173	160	Y	74	193	183	Y	46	185	183	Y	14
					Mid. Freq.	167	136	146	160	N	1	175	230	N	0	158	185	N	0
					High Freq.	164	131	141	160	N	1	171	202	N	0	154	155	N	9
					Phocids	182	154	164	160	Y	18	188	218	N	0	177	185	N	3
					Otariids	181	154	164	160	Y	18	187	232	N	0	176	203	N	0
Combined Piles	1-29-2020	-	-	264	Broadband	-	-	-	-	-	-	-	-	-	-	190	183	Y	29
					Low Freq.	-	-	-	-	-	-	-	-	-	-	187	183	Y	18
					Mid. Freq.	-	-	-	-	-	-	-	-	-	-	160	185	N	0
					High Freq.	-	-	-	-	-	-	-	-	-	-	157	155	Y	14
					Phocids	-	-	-	-	-	-	-	-	-	-	178	185	N	3
					Otariids	-	-	-	-	-	-	-	-	-	-	178	203	N	0

6.2 DAILY CUMULATIVE SEL

Piles 1 and 2 resulted in daily cSEL threshold exceedances of three groups: fish, low frequency cetaceans, and high frequency cetaceans. Approximately 209 strikes out of a total of 264 strikes exceeded the 183 dB cSEL threshold for fish. Approximately 148 strikes out of a total of 264 strikes exceeded the 183 dB cSEL threshold for low frequency cetaceans. Approximately 66 strikes out of a total of 264 strikes exceeded the 155 dB cSEL threshold for high frequency cetaceans.

The distance from the piles to the daily cSEL threshold for the exceeded groups is 29 meters (96 feet) for fish, 18 meters (61 feet) for low frequency cetaceans, and 14 meters (45 feet) for high frequency cetaceans (See Table 3).

7 SUMMARY

Two 24-inch steel piles were monitored for the SR 525/ Mukilteo Ferry Terminal (Phase 3) Marine Structures Project. The underwater sound levels analyzed, produced the following results:

- Pile 1 exceeded the RMS dB Behavioral Threshold for fish and low frequency cetaceans, Phocids, and Otariid hearing groups.

- Pile 1 exceeded the Peak dB Auditory Injury Threshold for the low frequency hearing group and the cSEL dB Auditory Injury Threshold for fish.

- Pile 2 exceeded the RMS dB Behavioral Threshold for fish and low frequency cetaceans, Phocids, and Otariid hearing groups.

- Pile 2 exceeded the Peak dB Auditory Injury Threshold for the low frequency hearing group and the cSEL dB Auditory Injury Threshold for the fish and low frequency cetaceans.

- A combined 264 strikes for Piles 1 and 2 resulted in daily cSEL threshold exceedances of three groups: fish and low frequency and high frequency cetaceans.

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.

9 APPENDIX A: 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, $10Log_{10}(N)$. 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.