I-5 SB Tacoma HOV 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
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 eleven 24-inch steel piles with 14-inch H-pile ‘stingers’ attached to the bottom of the pile. The data was collected for the Washington State Department of Transportation (WSDOT) for the I-5 Tacoma HOV Project, on July 23, July 31, August 6, August 9, and August 10, 2019. The piles were monitored within the Puyallup River under I-5 between MP 134.62 to 136.63 (Table 1). 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.

The data from two of the piles (Piles 6 and 11) monitored were not saved due to equipment malfunction. However, data from field notes was used for these piles to estimate sound levels. The peak attenuated sound levels measured ranged between 193 dB_{peak} and 204 dB_{peak} while monitoring the impact pile driving operation as shown in Table 1. The Cumulative Sound Exposure Level (cSEL) for five piles monitored did exceed the threshold of 197 dB_{cSEL} at 10 meters. The distance to the daily cSEL threshold of 197 dB from the 10 meter location is ranged from 6 meters (21 feet) to 30 meters (97 feet) both up and downstream.

Table 1: SB I-5 Tacoma HOV Project Summary of 24-inch Pile Attenuated Impact Driving Broadband Underwater Sound Levels

Pile #	Date	Hydro-Phone Range (m)	Absolute Highest Peak (dB)	$RMS_{90\%}$ (dB)	Single Strike $SEL_{90\%}$ (dB)	Cumulative SEL (dB)	Exceedance?
1	7-23-19	10	204	184	173	204	Y
2	7-31-19	10	201	180	170	200	Y
3	7-31-19	10	202	182	172	202	Y
4	8-6-19	10	201	177	166	197	N
5	8-6-19	10	200	176	166	195	N
6	8-9-19	10	197	182	172	202	Y
7	8-10-19	10	198	179	169	194	N
8	8-10-19	10	198	177	167	194	N
9	8-10-19	10	196	178	168	196	N
10	8-10-19	10	196	177	167	194	N
11	8-10-19	10	193	178	168	198	Y

1 INTRODUCTION

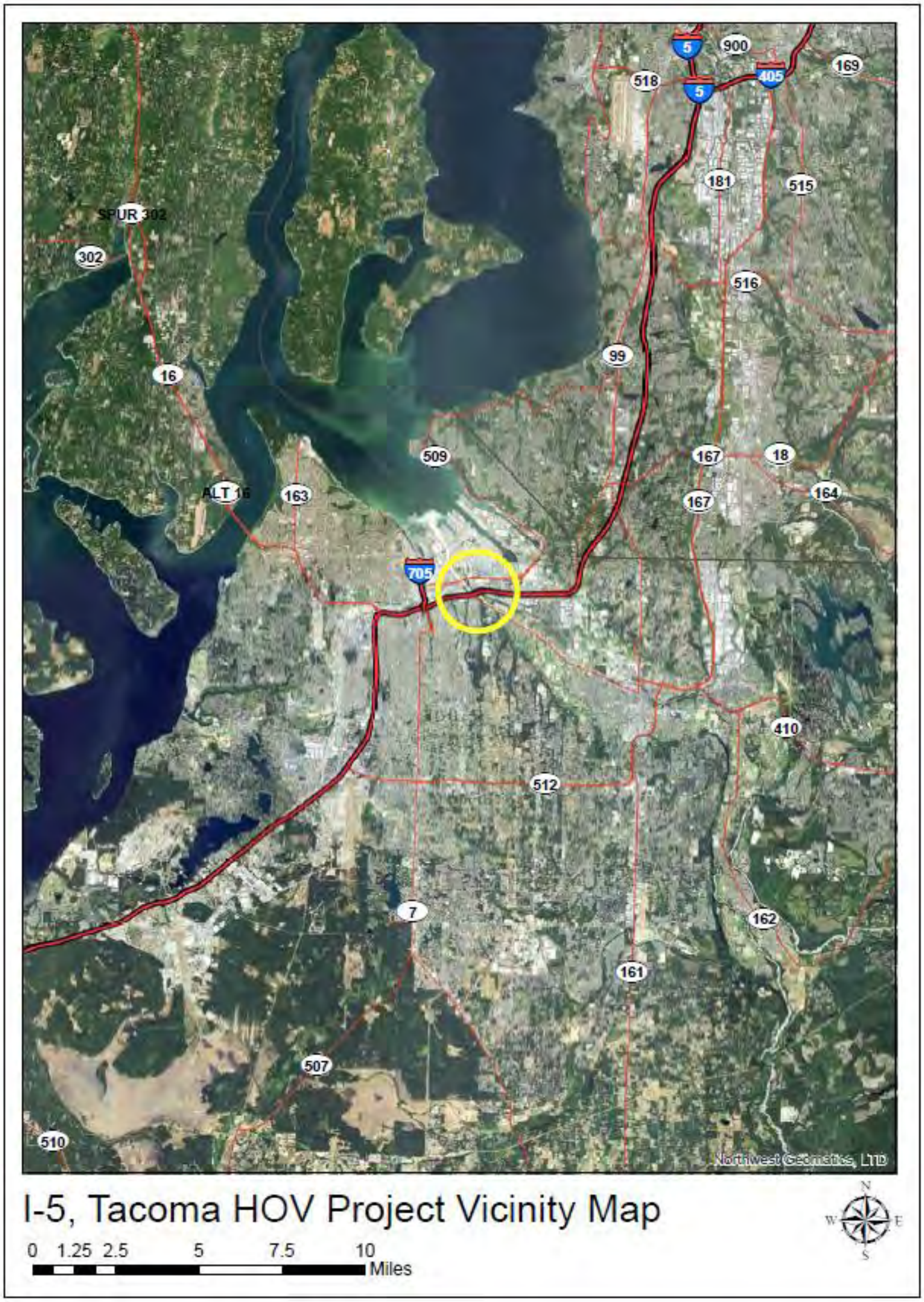
The Washington State Department of Transportation (WSDOT) is creating a new high-occupancy vehicle (HOV) lane on I-5 southbound (SB) between Portland Avenue to Port of Tacoma Road. HOV bypass lanes and ramp metering on existing lanes will be on existing on-ramps at the Port of Tacoma Road/20th Avenue East interchange. The SB project is constructing a new crossing over the Puyallup River with a change in alignment and is removing the existing Puyallup River I-5 bridges. Bridge demolition and a new bridge construction would require the installation of permanent and temporary piles in the Puyallup River to support the new bridge crossing and the temporary work trestles. See vicinity map (Figure 1).

This report summarizes the impact pile driving results measured in the Puyallup River in an effort to collect site-specific data on underwater noise levels during the months of July and August 2019. Eleven 24-inch diameter steel piles with 14-inch H-pile stingers 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 thresholds that the National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife (USFW) has determined would result in auditory injury to fish.

Figure 1: Vicinity map of I-5 Tacoma HOV Project



Stingers are steel pipe or H-piles attached to the bottom of steel or concrete piles to improve impact pile driving. Because the stingers are attached to a metal plate closing off the bottom end of the piles it can actually create more resistance, require more energy to drive the piles and to displace the substrate resulting in higher sound levels underwater.

Figure 2: Photo of 24-inch hollow steel piles with H-pile stingers attached at closed end

2 PROJECT AREA

The SB project limits extend from milepost (MP) 134.62 to 136.63 along the I-5 corridor in Pierce County, beginning at Portland Avenue in Tacoma and end at approximately the I-5/Port of Tacoma Road interchange in Fife, extending across the Puyallup River. They lie within Sections 1 through 4, 8 through 13, 37, and 38, Township 20 North, Range 3 East (USGS 1981).

3 PILE INSTALLATION LOCATION

Eleven 24-inch steel piles with 14-inch H-pile stingers were monitored during impact pile driving activity at the Puyallup River under I-5. 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 6 to 8 feet deep depending on location and tidal influence.

Figure 3: Approximate Locations of Piles 1 through 11 at the Puyallup River under I-5

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 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

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

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:

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

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.

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

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 (Figure 5) with one bubble ring inside at the bottom.

Figure 4: Near Field Acoustical Monitoring Equipment

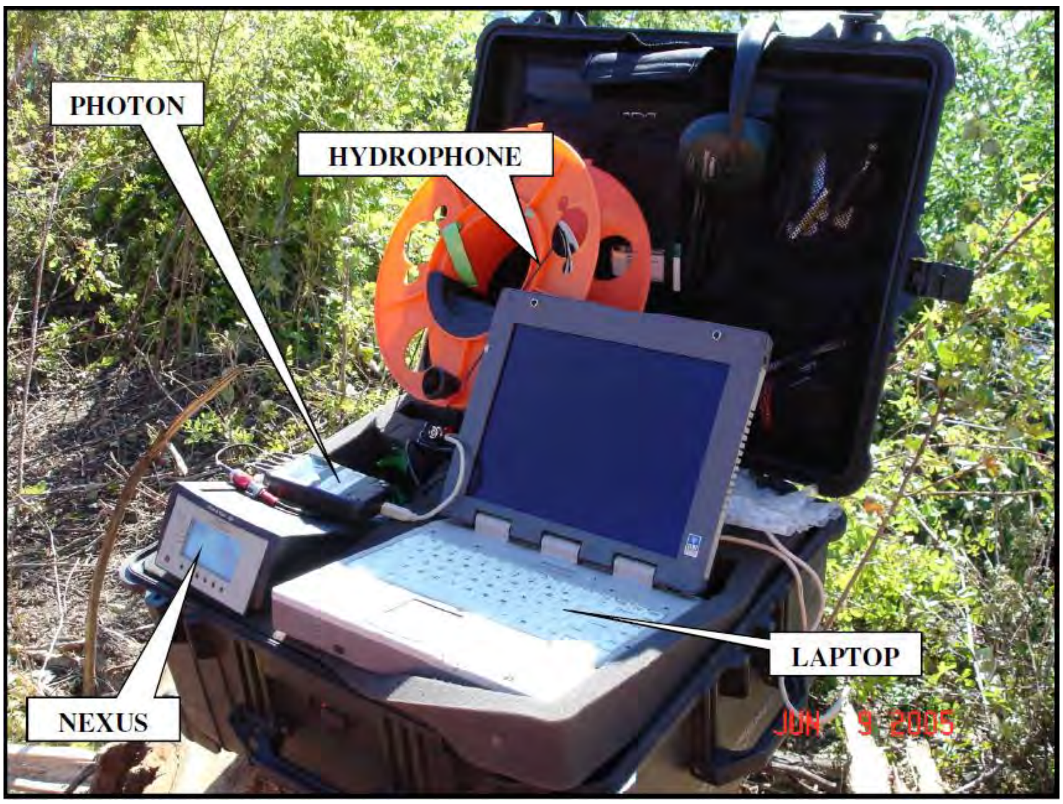


Figure 5: Confined Bubble Curtain Used at Tacoma HOV Project.

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. 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 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 50^{th} 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 applied to this project is a broadband cumulative Sound Exposure Level (cSEL) 197 dB cSEL. The weighted marine mammal auditory thresholds and un-weighted behavioral thresholds are also evaluated.

6 PILE INSTALLATION RESULTS

6.1 UNDERWATER SOUND LEVELS

WSDOT conducted hydroacoustic monitoring for eleven 24-inch steel piles struck with an impact hammer in water depths of 6 to 8 feet at the Puyallup River under I-5. The results of two of the piles were not saved due to equipment malfunction. However, the data collected from field notes during monitoring was used to estimate the sound levels. Data from all piles analyzed in the paragraphs below are also summarized in Table 3.

Pile 1

Pile 1 is located approximately one foot from the waters edge in approximately 4 feet of water on the east side of the river as it passes under I-5 (Figure 2). The results for Pile 1 are in Table 2.

Figures 6, 7, 8 and 9 show the time history plot, 1/3rd Octave band plot, Power Spectral Density (PSD) plot and spectrogram plot respectively. Pile 1 exceeded cSEL threshold of 197 dB_{cSEL} set for this project. Approximately 1,165 strikes exceeded the 197 dB cSEL threshold for this project out of a total of 1,756 pile strikes. The distance to the 197 dB threshold from the pile is 30 meters (97 feet) both up and downstream. Pile 1 exceeded the auditory injury threshold for all marine mammal hearing groups except for the mid frequency cetaceans and non-harbor seal pinnipeds (Table 2). Pile 1 exceeded the behavioral threshold for fish (150 dBRMS) and for all marine mammal hearing groups (160 dBRMS) with the exception of mid and high frequency cetaceans.

Figure 6 shows the peak, RMS and SEL levels for each attenuated pile strike. The pile strikes appeared to be relatively stable up to approximately 320 strikes and then they became more variable over time from that point forward. The peak L50 (peak 50th percentile) was used to statistically differentiate between the bubble curtain being on versus off which allows for a more stable and accurate comparison than the absolute peak. For Pile 1 there was only a 1 dB difference between the bubbles being on versus off. The bubble curtain design used for this pile did not allow the bubble ring inside the containment system to be in contact with the mud bottom allowing some of the sound energy to escape into the water and there may have been some steel to steel contact with the pile and the bubble curtain.

Figure 6: Time history plot of individual pile strikes for monitored Pile 1

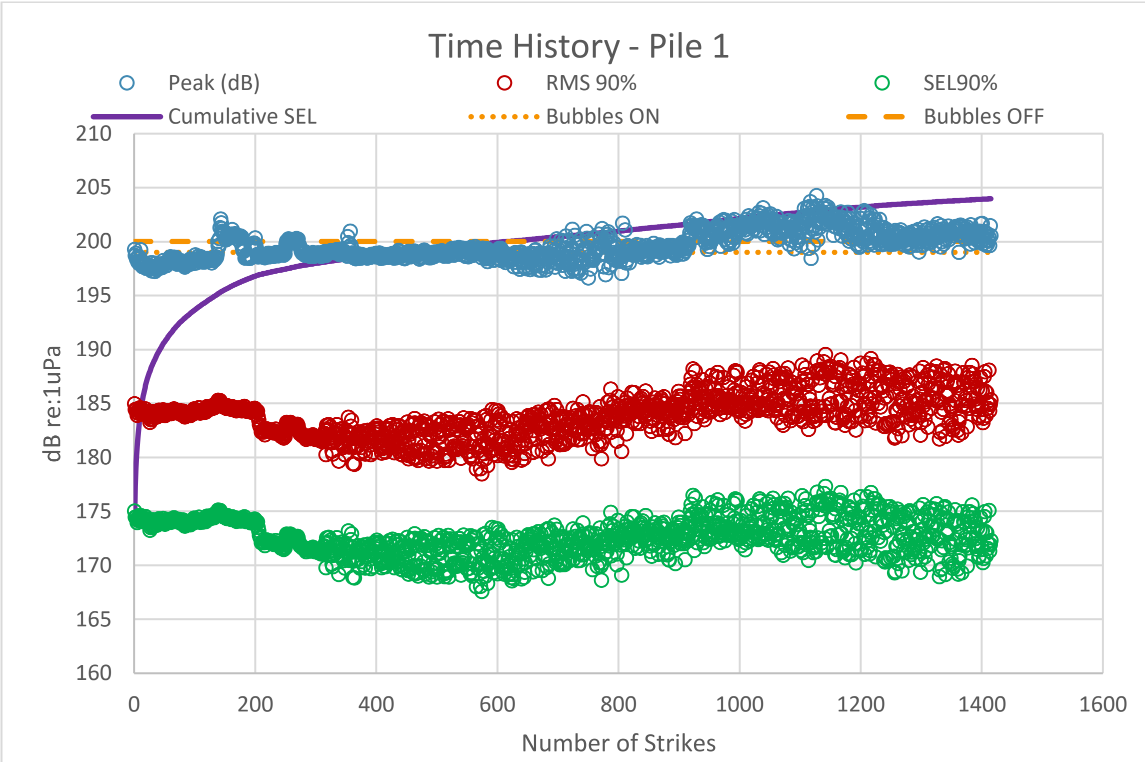


Figure 7 shows the 1/3rd Octave band plot for Pile 1. The plot indicates that the dominant frequency band is at about 500 Hz with possible harmonics seen at 1000 and 2000 Hz.

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

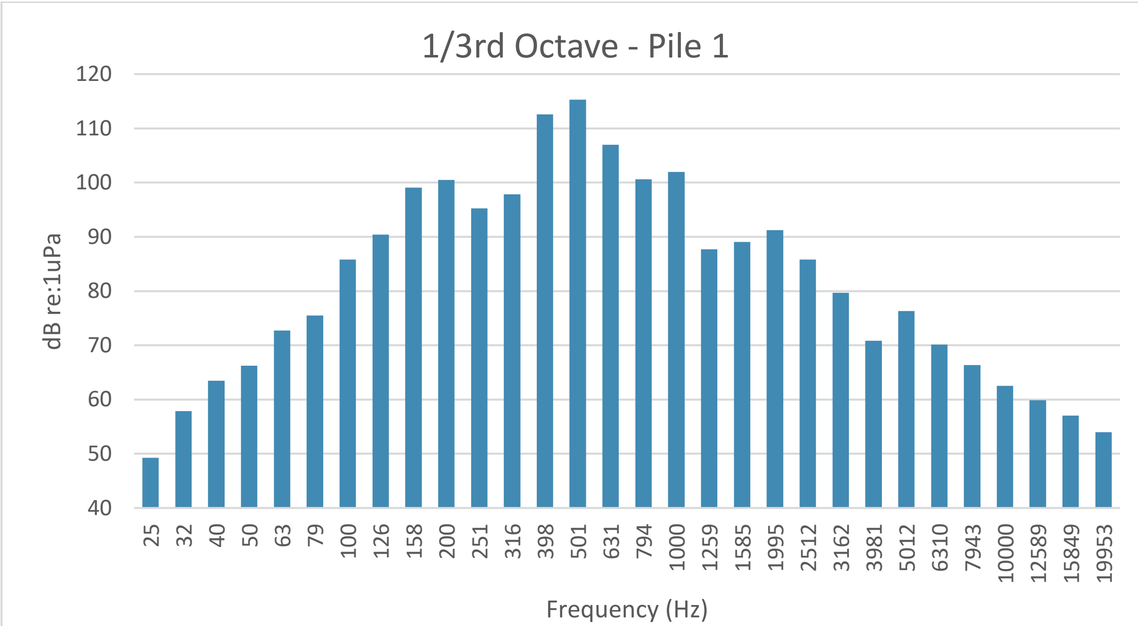


Figure 8 shows the Power Spectral Density (PSD) plot (sound pressure level as a function of frequency) for the peak pile strike and two additional strikes adjacent to the peak which shows a finer detail for each frequency compared to the 1/3rd Octave plot. The plot indicates that the dominant frequency energy is just above 300 Hz with most of the energy of the pile strikes below that frequency and sharply dropping off above.

Figure 8: Power Spectral Density Plot for monitored Pile 1

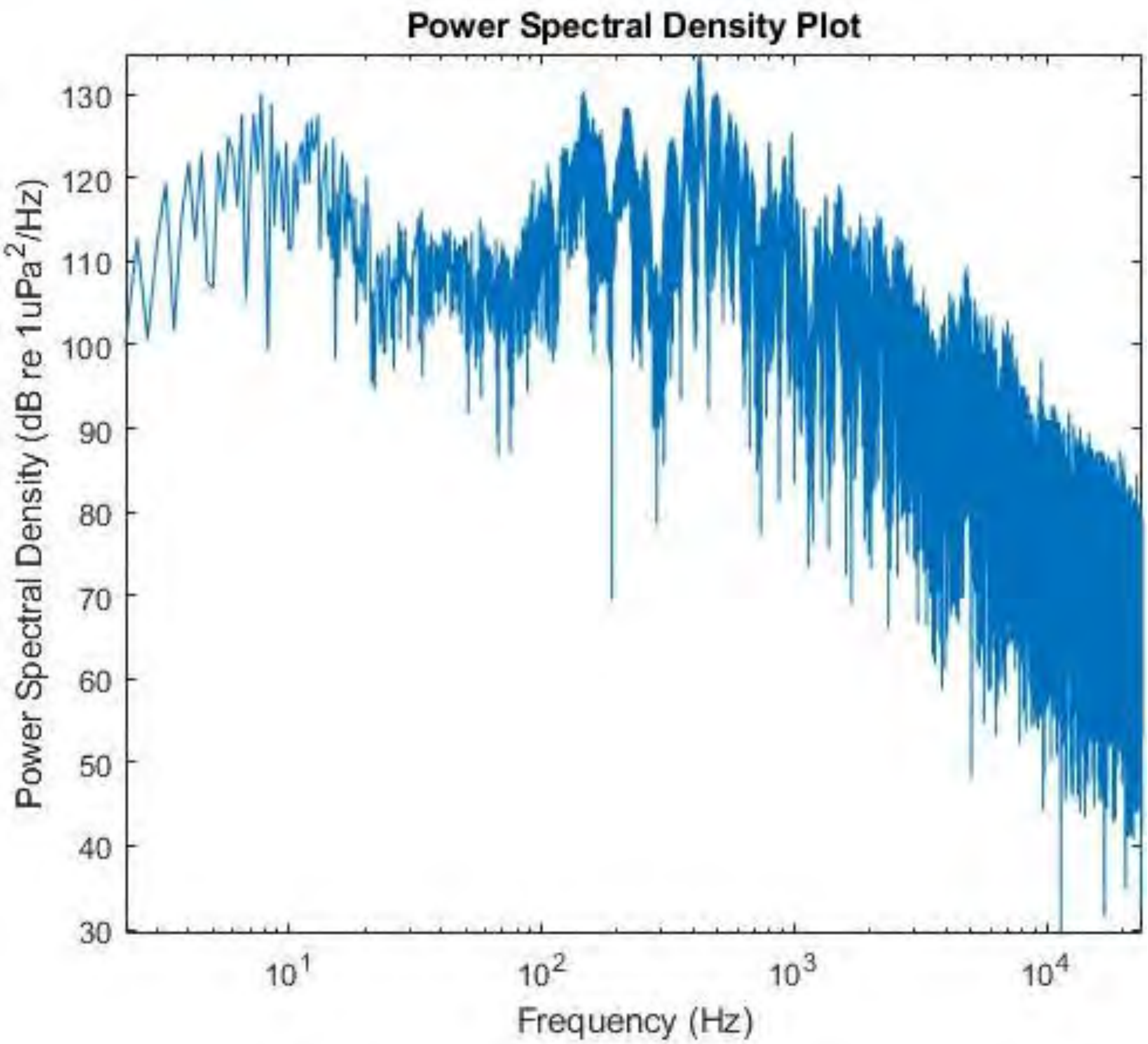
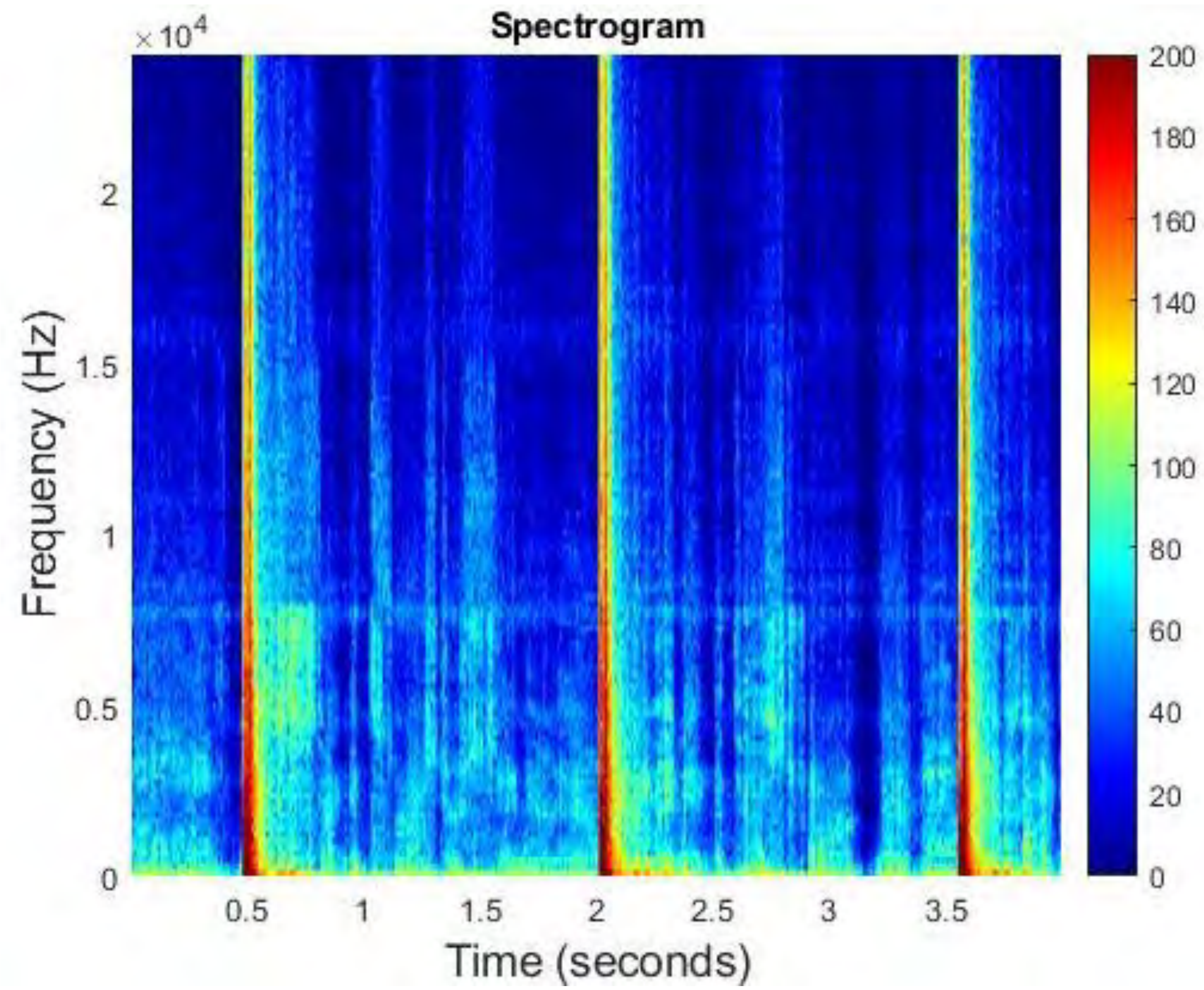


Figure 9 shows the spectrogram plot (sound intensity as a function of time and frequency) which is a visual representation of an acoustic signal with degrees of amplitude represented by color. The plot represents the peak pile strike and two adjacent pile strikes. The color bar to the right indicates the decibel level. The individual pile strikes are distinguished from background by the presence of spectral peaks in the 20 Hz to 20000 Hz range. The spectrogram plot indicates that most of the energy is concentrated in the 20 Hz to 5000 Hz range with maximum levels observed below about 1000 Hz.

Figure 9: Spectrogram Plot for monitored Pile 1



A possible low frequency Scholte wave was observed on some pile strikes in the bubbles off condition. This is shown in Figure 10 as what looks like a second smaller strike after the main pile strike. The Scholte wave results from the substrate rebounding after the initial pile strike.

Figure 10: Plot of peak pile strikes indicating Scholte waves for monitored Pile 1 and bubbles off

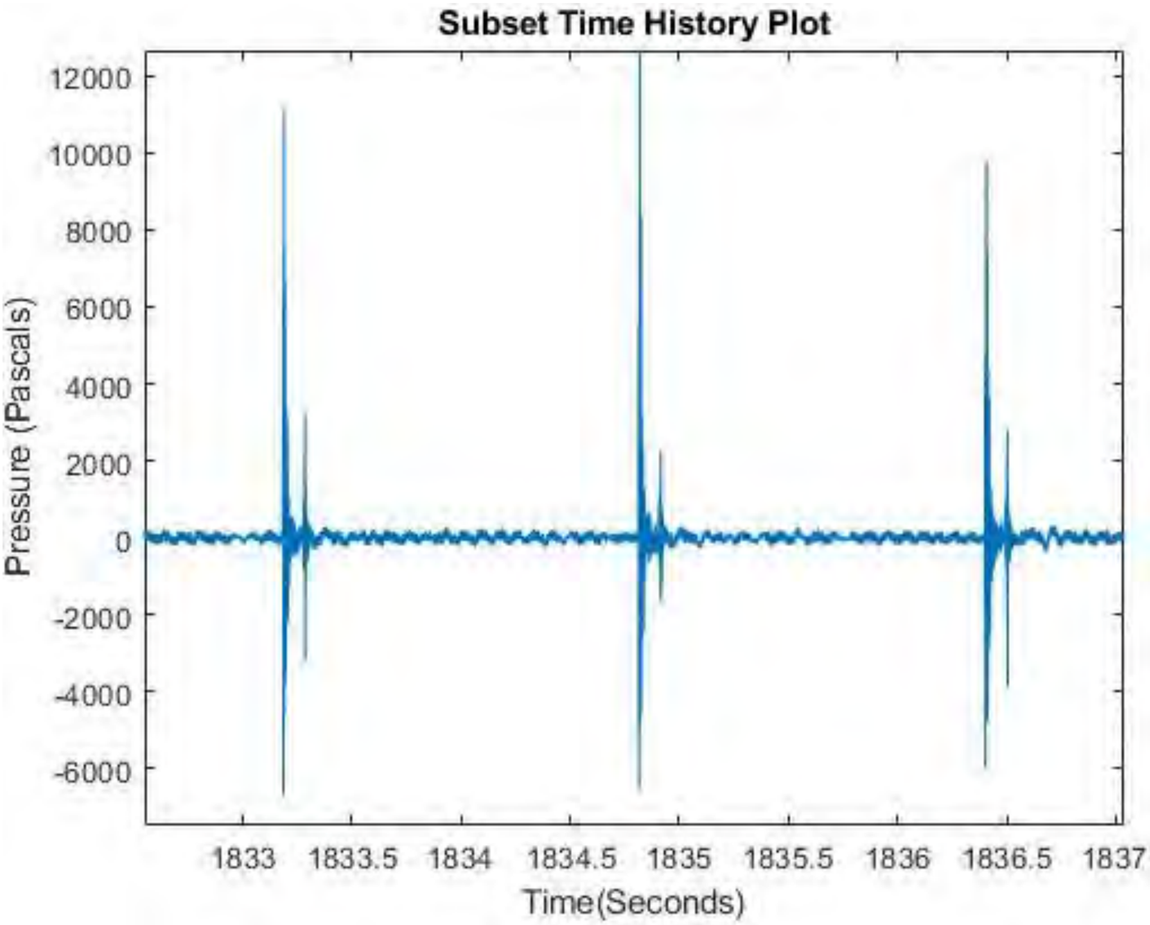
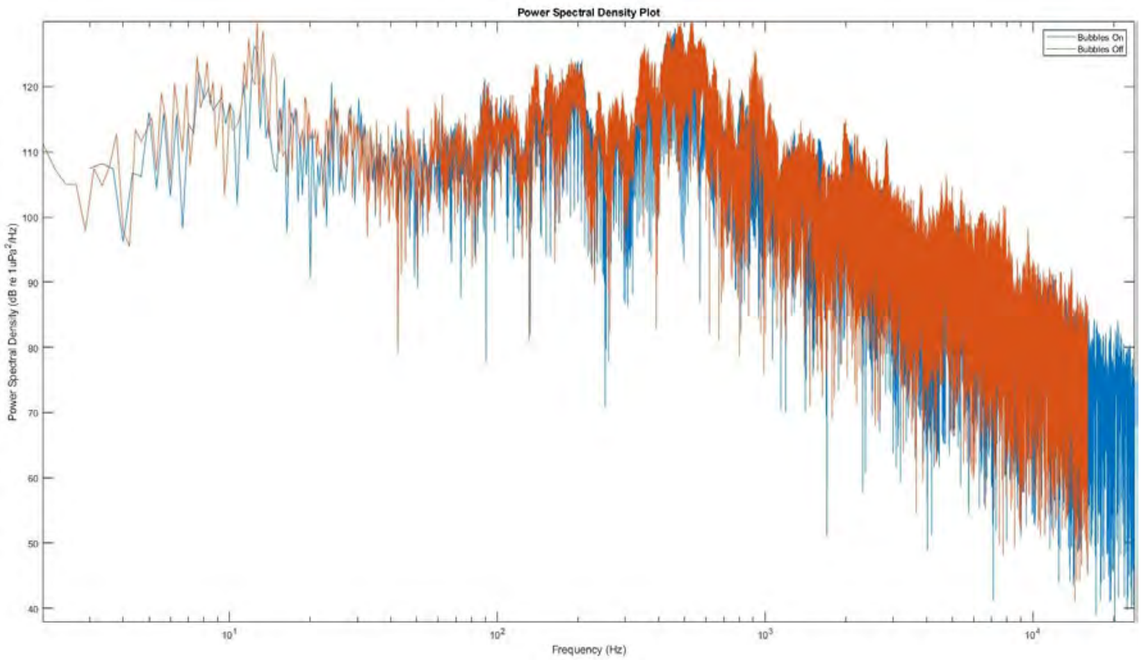


Figure 11 shows the PSD frequency plot for the bubbles on versus the bubbles off. The bubbles on condition shows that there is very little difference in the frequency distribution compared to bubbles off with only slight reductions in the frequencies below about 20 Hz and above about 200 Hz.

Figure 11: PSD plot of bubbles on versus bubbles on for monitored Pile 1



Pile 2

Pile 2 is located approximately one foot from the shoreline and approximately 10 feet southeast of Pile 1 (Figure 2). The results for Pile 2 are in Table 2. Pile 2 exceeded cSEL threshold of 197 dB_{cSEL} set for this project. Approximately 770 strikes exceeded the 197 dB cSEL threshold for this project out of a total of 1,277 pile strikes. The distance to the 197 dB threshold from the pile is 16 meters (52 feet) both up and downstream. Pile 2 exceeded the auditory injury threshold for the mid frequency cetaceans and harbor seal pinnipeds (Table 2). Pile 2 exceeded the behavioral threshold for fish (150 dBRMS) and for marine mammal hearing groups (160 dBRMS) with the exception of mid and high frequency cetaceans.

Figures 12, 13, 14 and 15 show the time history plot, 1/3rd Octave plot, PSD plot and spectrogram plot respectively. In Figure 12 the peak, RMS90% and SEL90% values are relatively stable until the last third of the drive. After that point, they show some slight variability for the remainder of the pile driving. The measured values indicate that although the bubble curtain was modified to bring the bubble ring closer to the substrate and minimize steel to steel contact it was still not performing very well with estimated sound level reductions of approximately 1 dB.

Figure 12: Time history plot of individual pile strikes for monitored Pile 2

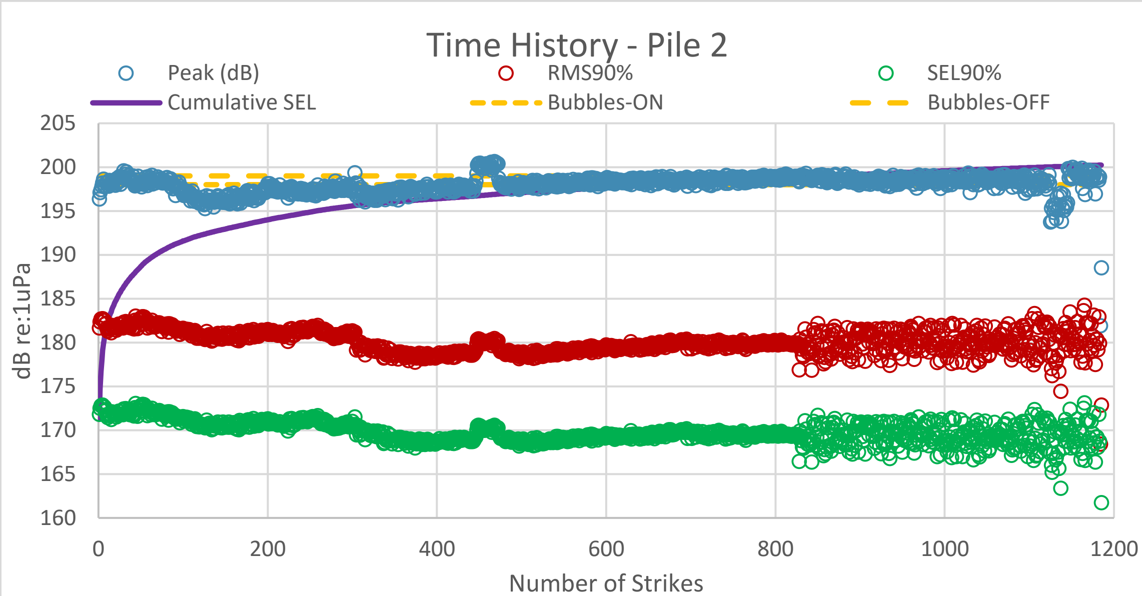
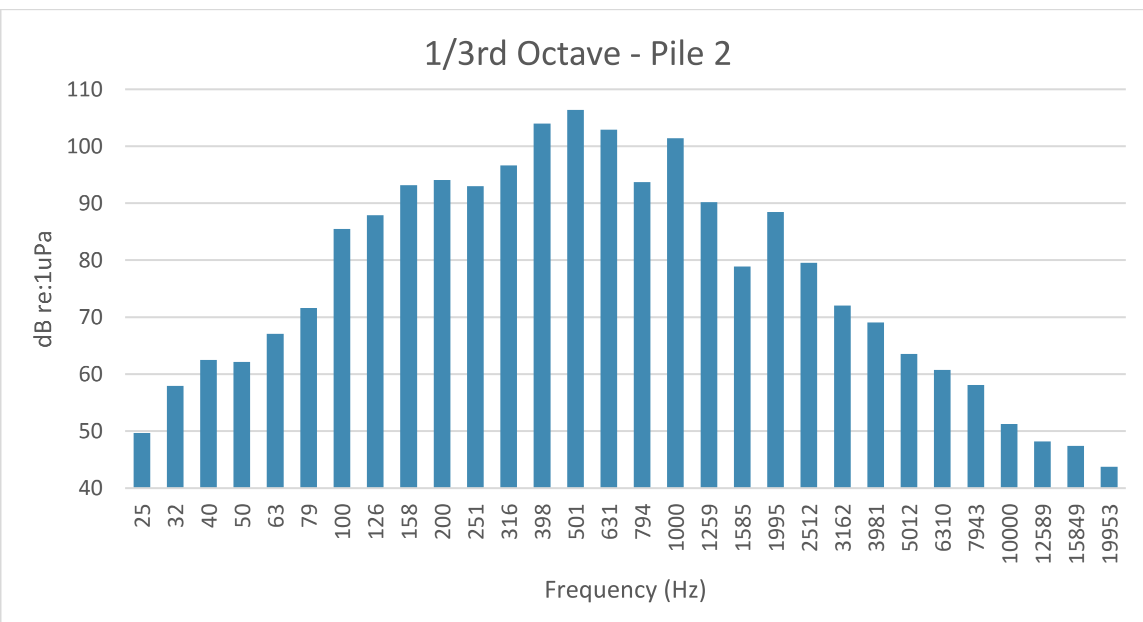


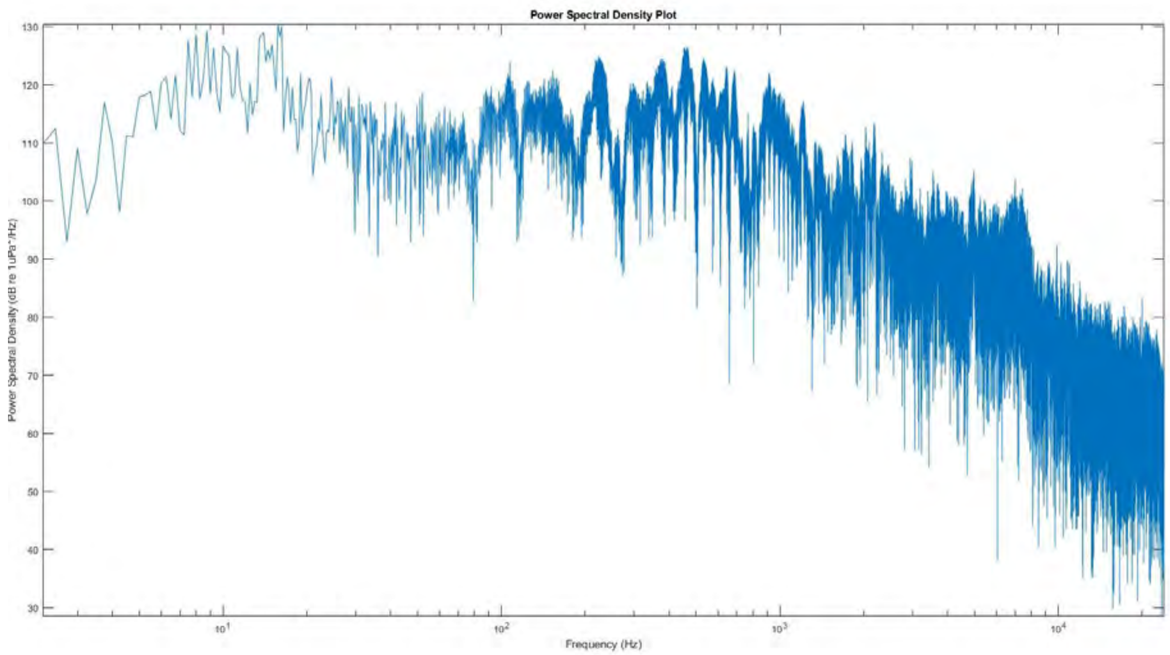
Figure 13 shows the 1/3rd Octave band plot for Pile 2. The plot is similar to the plot for Pile 1 and indicates that the dominant frequency band is at about 500 Hz with possible harmonics seen at 1000 and 2000 Hz.

Figure 13: 1/3rd Octave Band Plot for monitored Pile 2



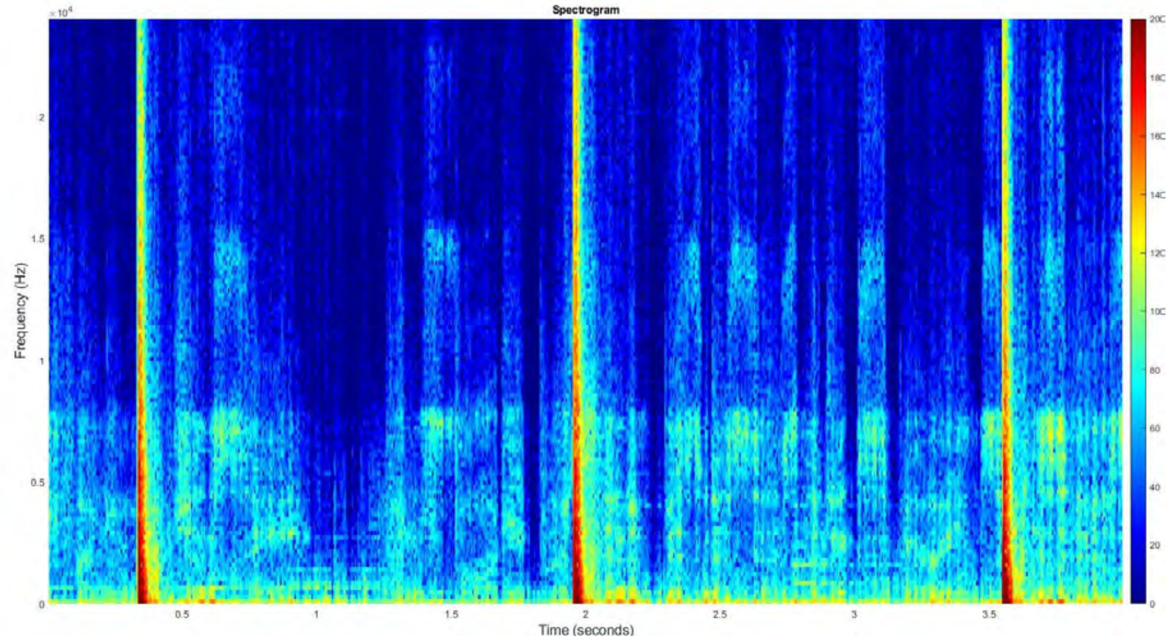
The PSD plot (Figure 14) representing the absolute peak pile strike and two adjacent strikes indicate that most of the energy in each pile strike is below about 1000 Hz as shown in the PSD plot with the dominant frequencies below about 20 Hz as shown in the spectrogram (Figure 15).

Figure 14: Power Spectral Density Plot for monitored Pile 2



The spectrogram plot in Figure 15 indicates that most of the energy is concentrated in the 20 Hz to 5000 Hz range with maximum levels observed below about 1000 Hz.

Figure 15: Spectrogram Plot for monitored Pile 2



Pile 3

Pile 3 is located approximately one foot from the shoreline on the east side of the Puyallup River as it passes under I-5 in approximately 3.5 feet of water. The results for Pile 3 are in Table 2.

Figures 16, 17, 18 and 19 show the time history plot, 1/3rd Octave band plot, PSD plot and spectrogram plot respectively. Pile 3 exceeded cSEL threshold of 197 dB_{cSEL} set for this project. Approximately 855 strikes exceeded the 197 dB cSEL threshold for this project out of a total of 1,253 pile strikes. The distance to the 197 dB threshold from the pile is 22 meters (71 feet) both up and downstream. Pile 3 exceeded the auditory injury threshold for all marine mammal hearing groups except for the mid frequency cetaceans and non-harbor seal pinnipeds (Table 2). Pile 3 exceeded the behavioral threshold for fish (150 dBRMS) and for marine mammals hearing groups (160 dBRMS) with the exception of mid and high frequency cetaceans.

Figure 16 shows the peak, RMS and SEL levels for each attenuated pile strike. The pile strike RMS and SEL levels appeared to be relatively stable up to approximately 326 strikes and then they became more variable over time from that point forward. The peak L50 (peak 50th percentile) was used to statistically differentiate between the bubble curtain being on versus off which allows for a more stable and accurate comparison than the absolute peak. For Pile 3 there was no difference between the bubbles being on versus off. The bubble curtain design used for this pile was modified slightly from that used on Pile 2 but still did not allow the bubble ring inside the containment system to be in contact with the mud bottom allowing some of the sound energy to escape into the water.

Figure 16: Time history plot of individual pile strikes for monitored Pile 3

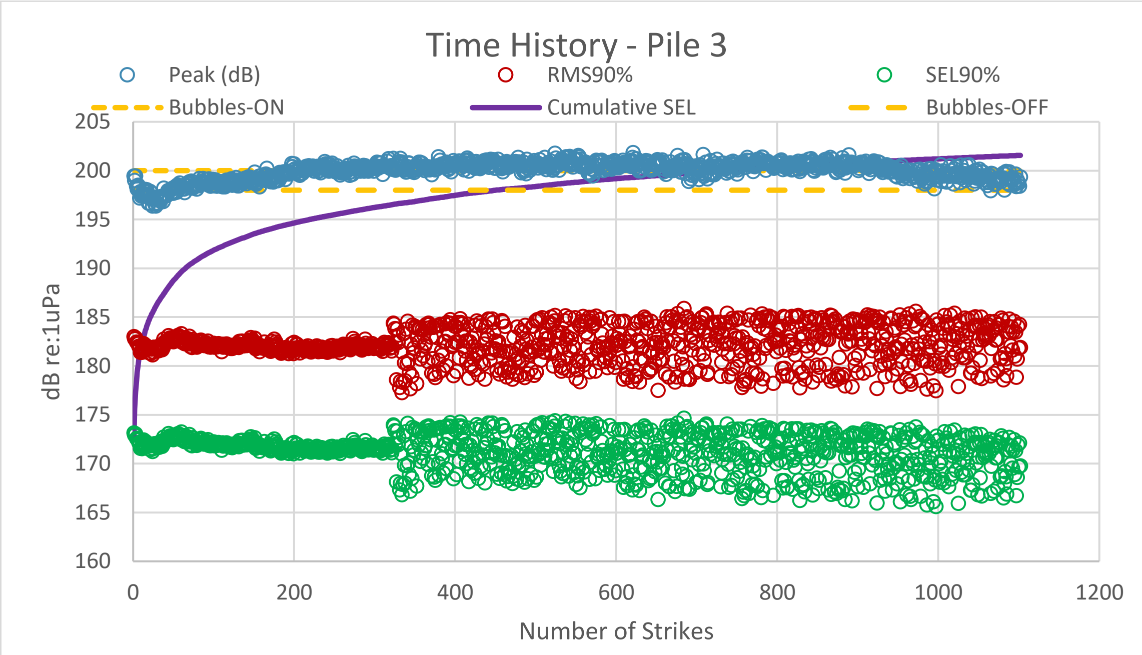


Figure 17 shows the 1/3rd Octave band plot for Pile 3. The plot indicates that the signal is somewhat of a broadband signal with the frequencies slightly more evenly distributed and the dominant frequency band at about 400 Hz with possible harmonics seen at 4000 and 8000 Hz.

Figure 17: 1/3rd Octave Band Plot for monitored Pile 3

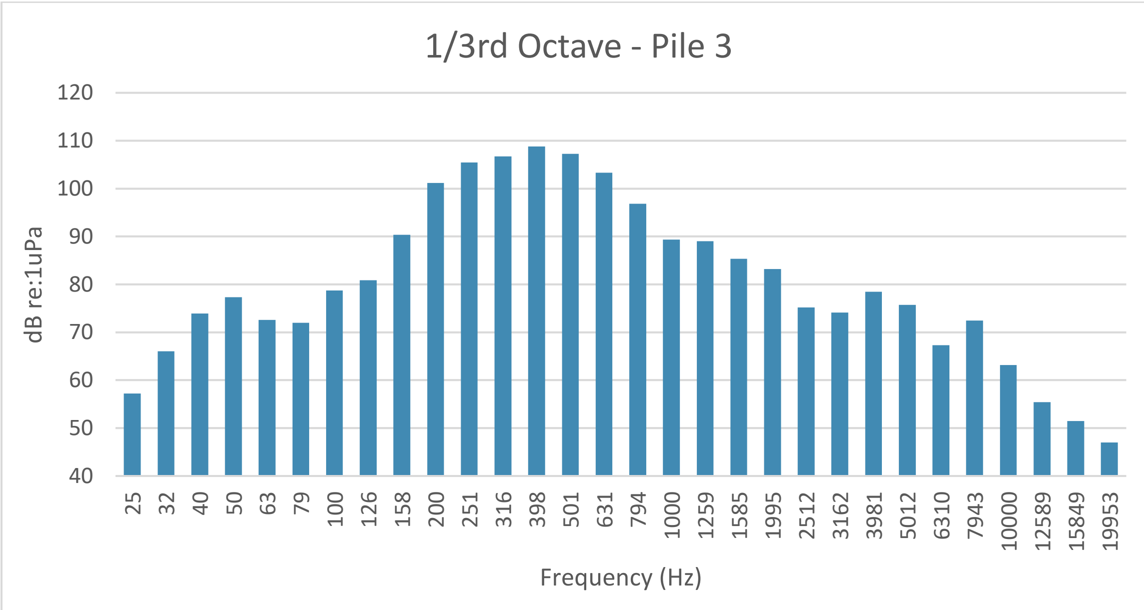


Figure 18 shows the PSD plot for the peak pile strike and two adjacent pile strikes. The plot indicates that the signal is relatively broadband in nature for frequencies below about 800 Hz with the dominant frequency at approximately 50 Hz and sharply dropping off above 800 Hz. If the bubble curtain were functioning properly, you would expect to see more of the higher frequency content suppressed.

Figure 18: Power Spectral Density Plot for monitored Pile 3

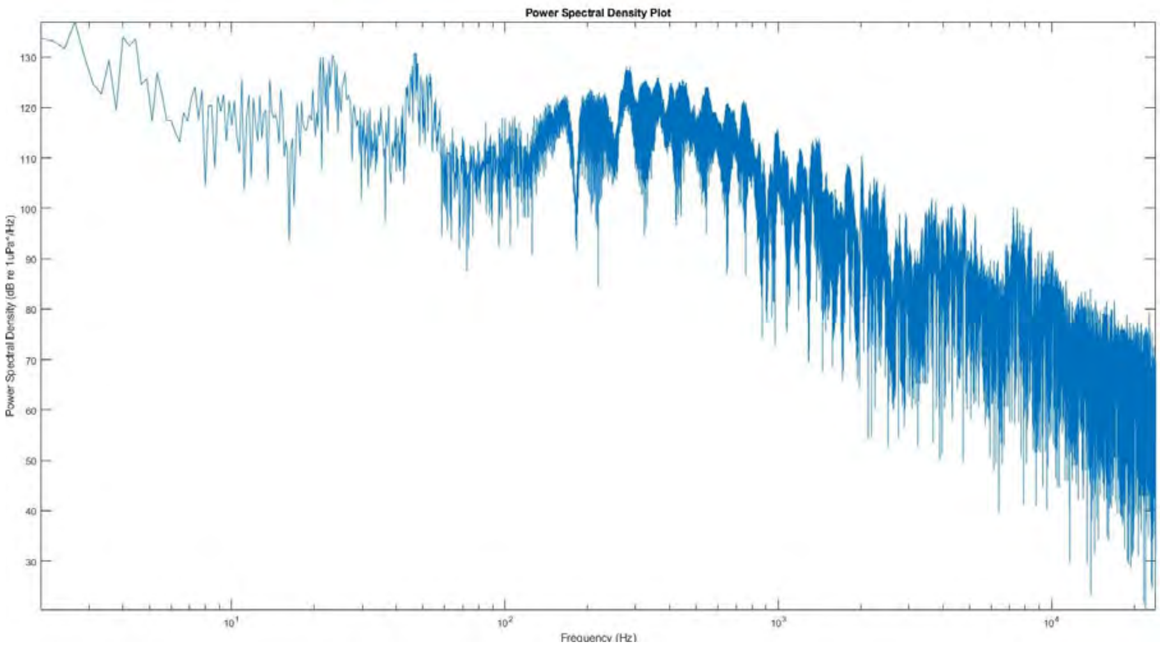
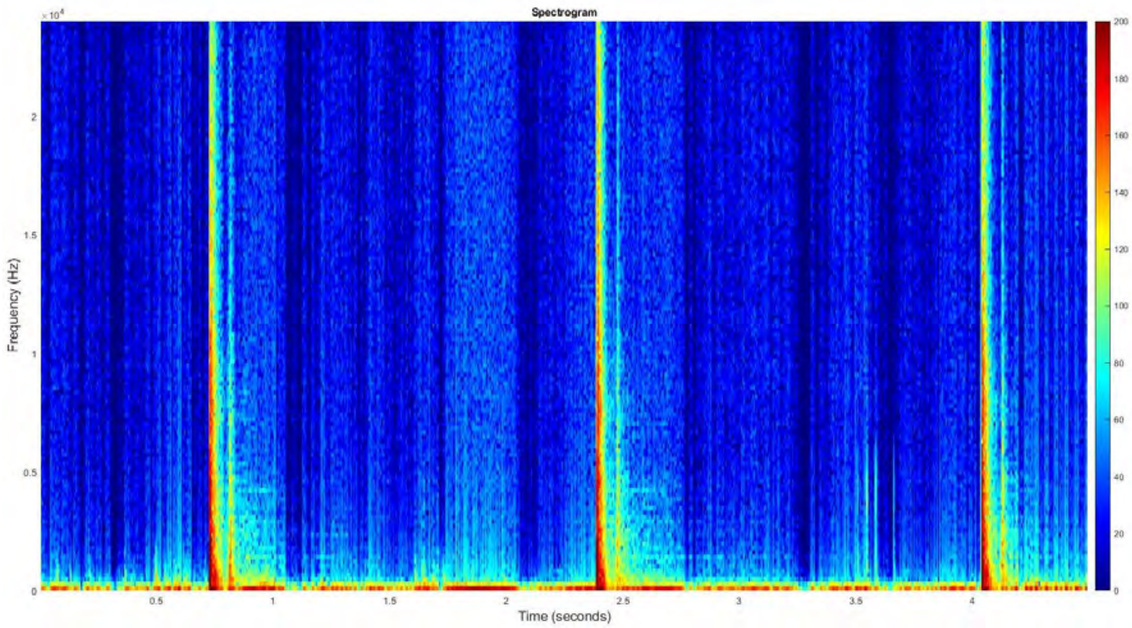


Figure 19 shows the spectrogram plot of the peak pile strike and two additional pile strikes. The color bar to the right indicates the decibel level. The spectrogram plot indicates that most of the energy is in the 20 Hz to 10000 Hz range with maximum levels below about 4000 Hz and a smaller secondary (Scholte Wave) signal immediately after each pile strike.

Figure 19: Spectrogram Plot for monitored Pile 3



Pile 4

Pile 4 is located approximately 30 feet from the shoreline in 6 feet of water. The results for Pile 4 are in Table 2.

Figures 20, 21, 22 and 23 show the time history plot, 1/3rd Octave band plot, PSD plot and spectrogram plot respectively. Pile 4 did not exceed the cSEL threshold of 197 dB_{cSEL} set for this project. The distance to the 197 dB threshold from the pile is 10 meters (33 feet) both up and downstream. Pile 4 exceeded the auditory injury threshold for low frequency cetaceans, high frequency cetaceans and non-harbor seal pinnipeds (Table 2). Pile 4 exceeded the behavioral threshold for fish (150 dBRMS) and for all marine mammal hearing groups (160 dBRMS).

Figure 20 shows the time history plot of Pile 4 and indicates that the noise levels were relatively consistent among pile strikes with relatively little variability for the peak, RMS90% and SEL90% until near the end of the drive. The bubble curtain was further modified prior to use on Pile 4 and had a 5 dB difference between the bubbles being on versus off.

Figure 20: Time history plot of individual pile strikes for monitored Pile 4

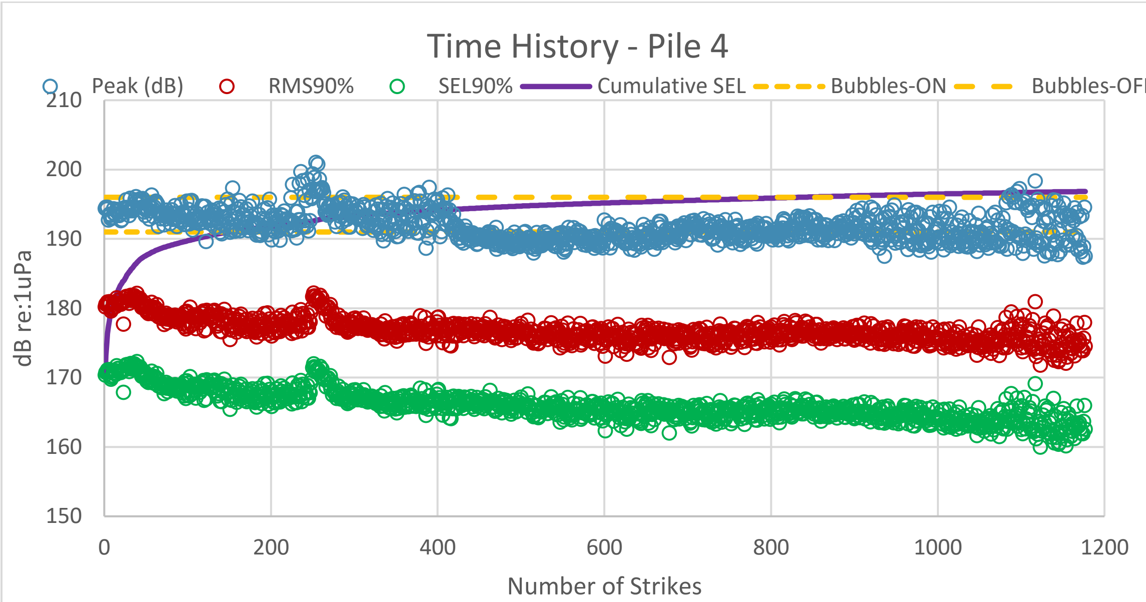


Figure 21 shows the 1/3rd Octave band plot for Pile 4. The plot indicates that the dominant frequency band is at about 400 Hz and the energy dropping off rapidly above about 1000 Hz. This could be an indication that the bubble curtain was reducing the higher frequency amplitudes.

Figure 21: 1/3rd Octave Band Plot for monitored Pile 4

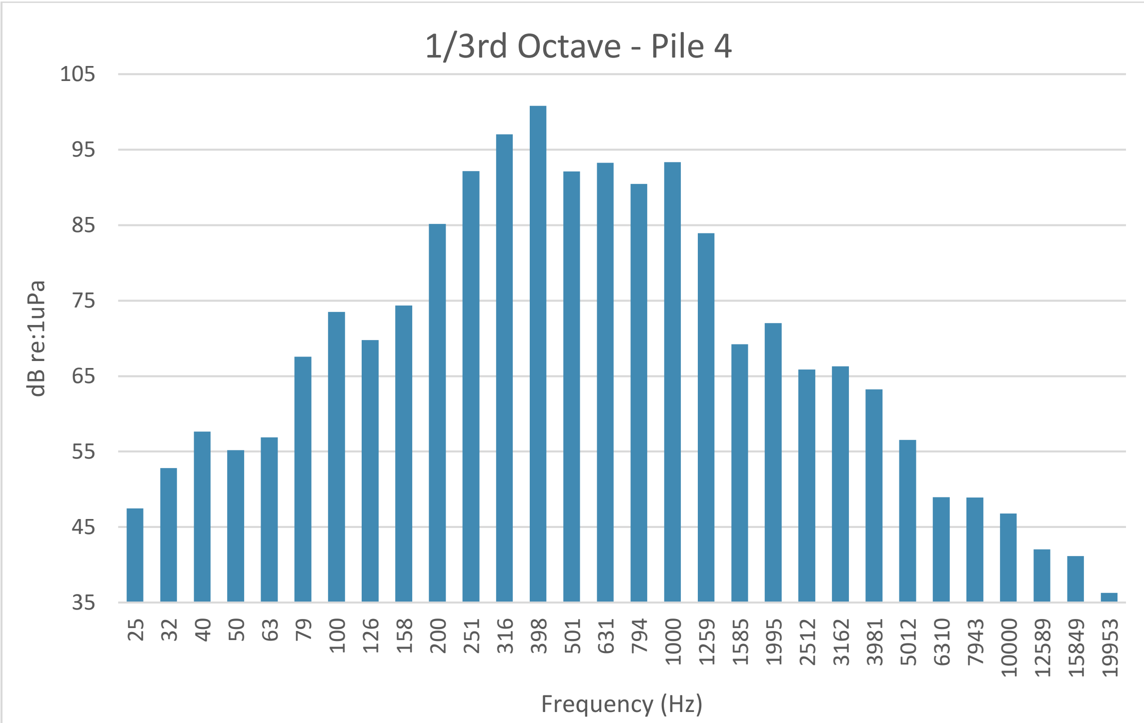


Figure 22 shows the frequency distribution of the peak pile strike and two adjacent pile strikes. There appears to be two dominant frequencies at approximately 20 Hz and 40 Hz with a lesser peak at about 400 Hz which is within the appropriate range for impact pile driving.

Figure 22: Power Spectral Density Plot for monitored Pile 4

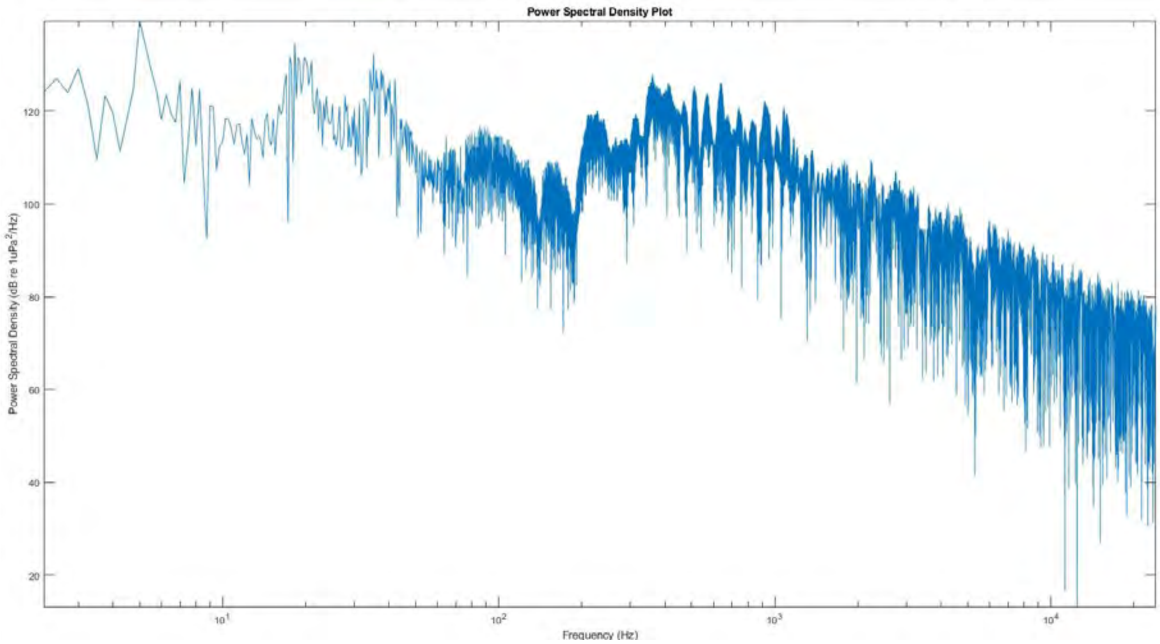
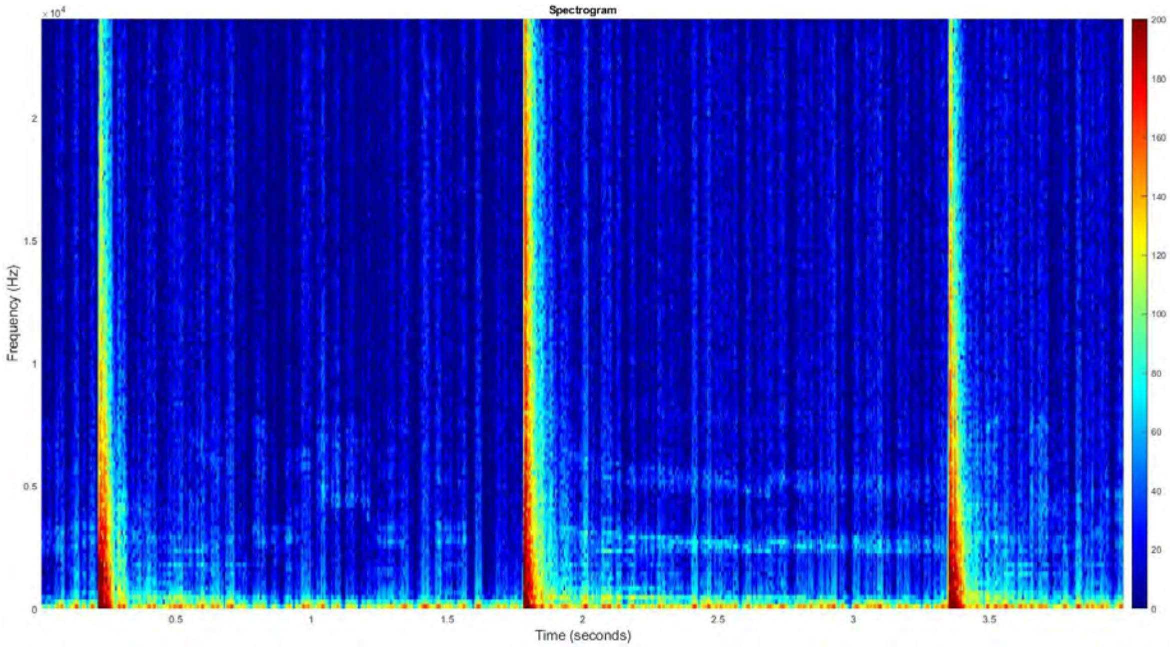


Figure 23 shows the Spectrogram plot of the peak pile strike and two additional pile strikes. The color bar on the right indicates the decibel level for each frequency for Pile 4. The spectrogram shows that most of the energy is in 20 Hz to 5000 Hz range with maximum levels below about 3000 Hz.

Figure 23: Spectrogram Plot for monitored Pile 4



Pile 5

Pile 5 is located approximately twenty feet from the water's edge in approximately 6 feet of water on the east side of the river as it passes under I-5 (Figure 2). The results for Pile 5 are in Table 2. Pile 5 has not exceeded the cSEL threshold for this project. The distance to the 197 dB threshold is 7 meters (24 feet) both up and downstream. Pile 5 exceeded the cSEL thresholds for Low Frequency, High Frequency and Phocid marine mammal hearing groups.

Figure 24 is the time history plot for Pile 5, which includes the peak, RMS, SEL, cumulative SEL and the 50^{th} percentile for the peak on and off conditions. As with the other piles, the pile strikes appeared to be relatively stable for the first two thirds of the pile drive and then they became more variable from that point forward. For Pile 5 there was a 4 dB difference between the bubbles on versus off. The bubble curtain design used for this pile was modified again prior to use so that it allowed the bottom ring to be in contact with the mud bottom thus improving the performance of the bubble curtain.

Figure 24: Time history plot of individual pile strikes for monitored Pile 5

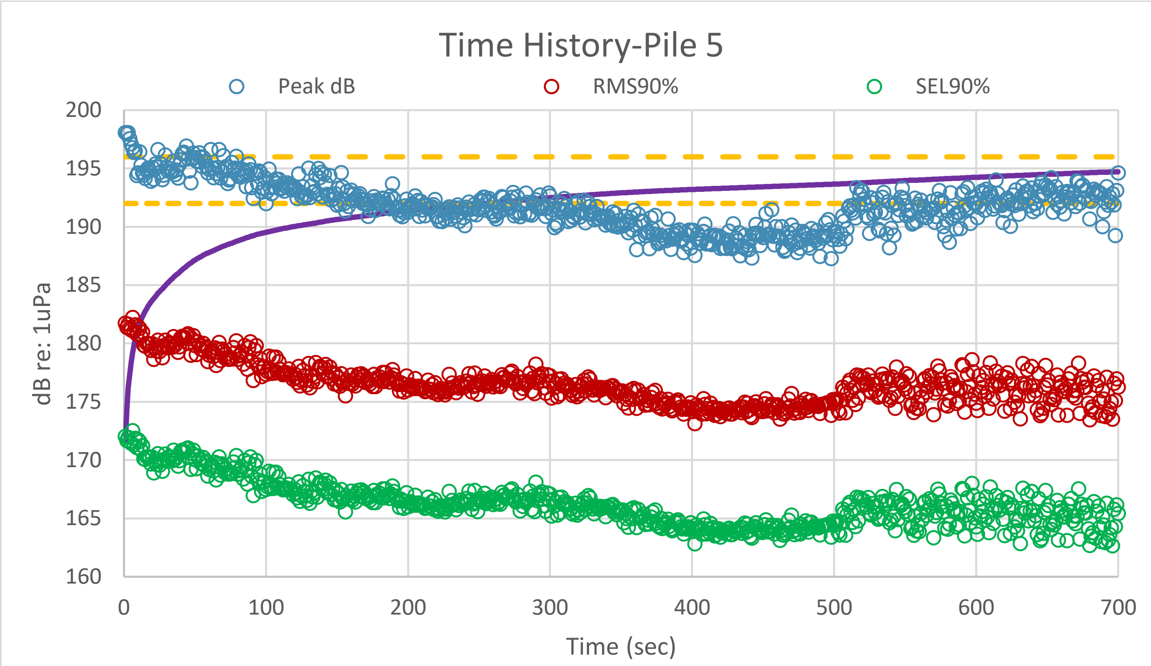


Figure 25 shows the 1/3rd Octave band plot for Pile 5. Similar to the previous piles the plot indicates that the dominant frequency band is at about 400 Hz and the energy dropping off rapidly above about 1000 Hz. This could be an indication that the bubble curtain was reducing the higher frequency amplitudes.

Figure 25: *1/3rd Octave Band Plot for monitored Pile 5*

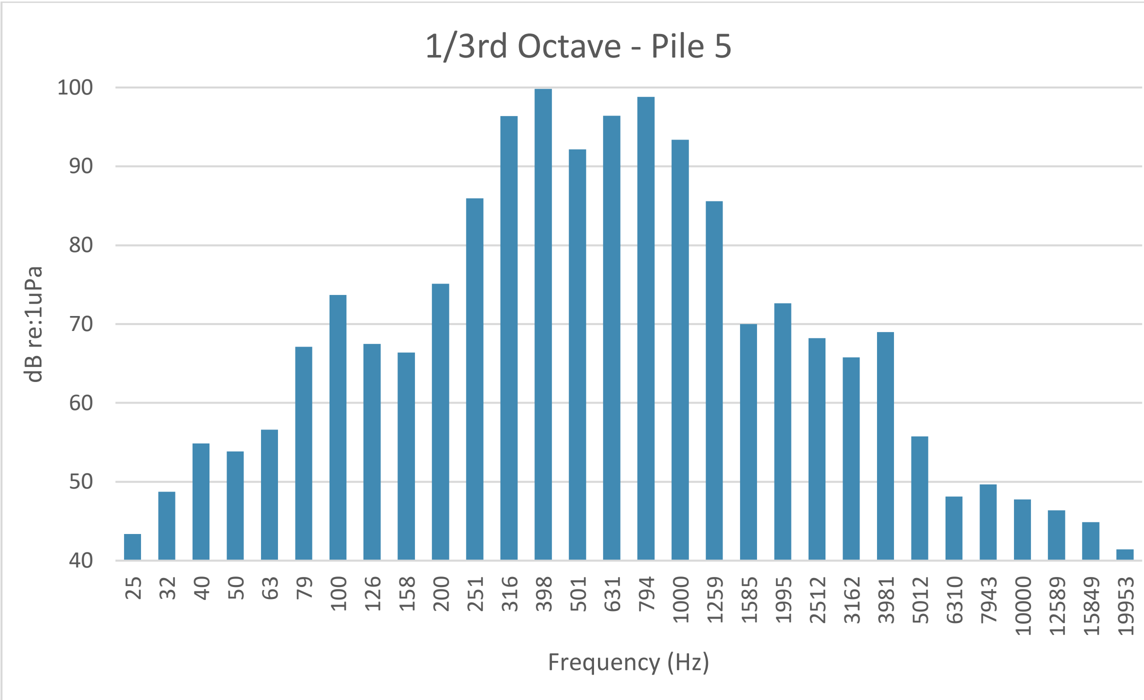


Figure 26 shows the PSD plot for the peak pile strike and two adjacent pile strikes. The plot indicates that most of the energy is below about 1000 Hz with a peak at about 250 Hz.

Figure 26: Power Spectral Density Plot for monitored Pile 5

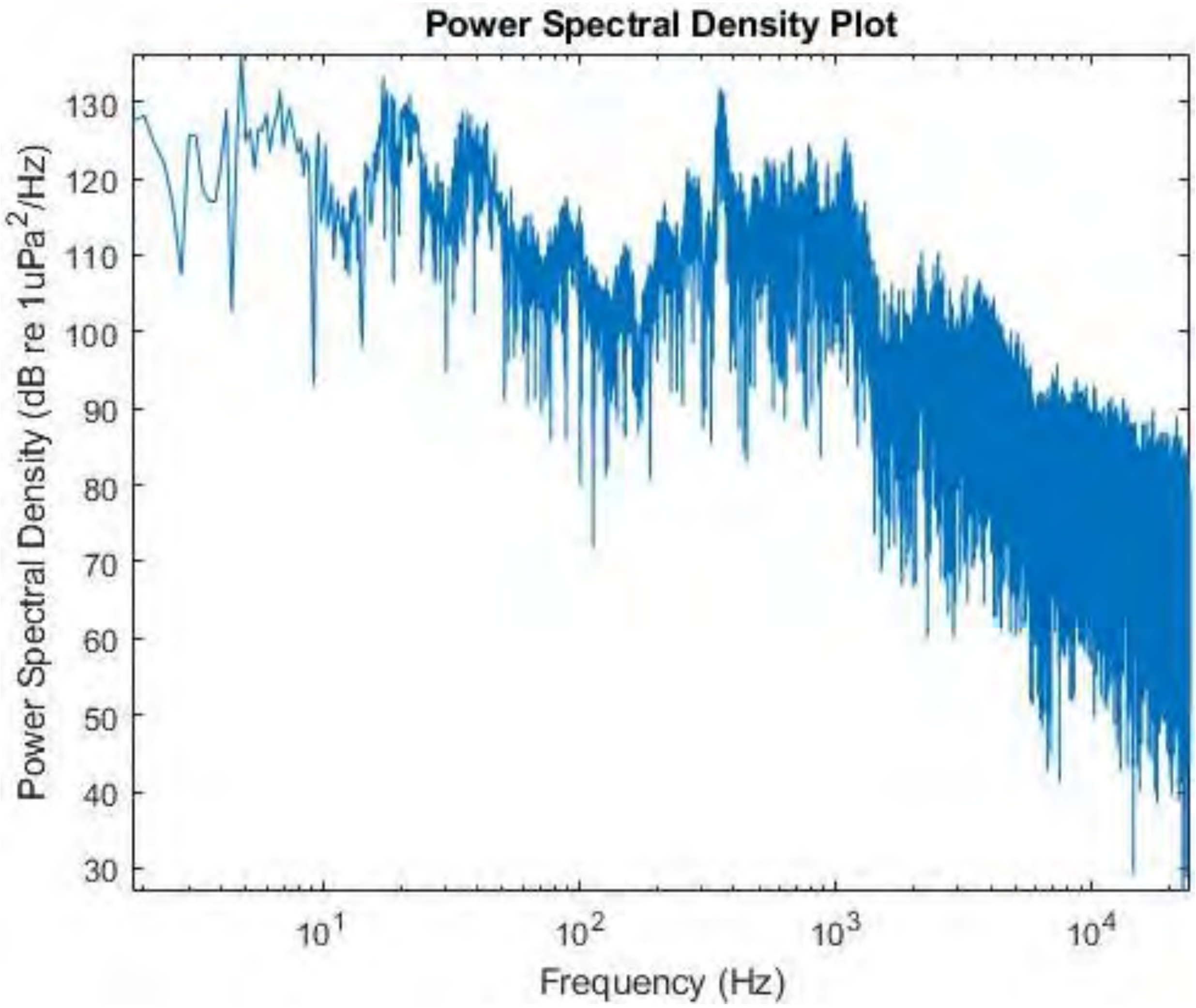
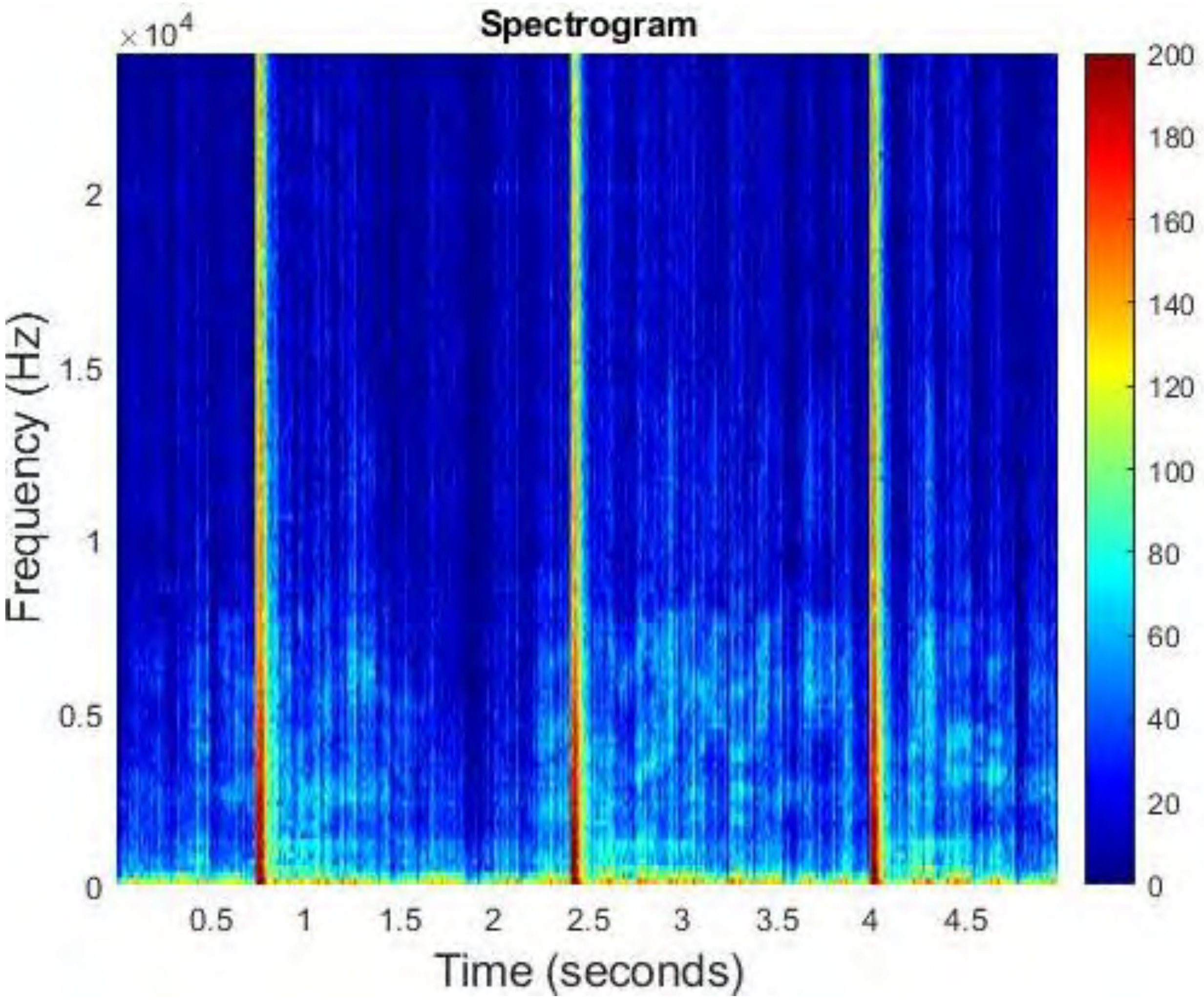


Figure 27 shows the spectral plot of the peak pile strike and two adjacent pile strikes. The Spectrogram plot for Pile 5 shows that there is substantially more energy in the 20 Hz to 4000 Hz range with the maximum levels below about 3000 Hz.

Figure 27: Spectrogram Plot for monitored Pile 5



Pile 6

Pile 6 is located approximately 20 feet from the shoreline in 6 feet of water (Figure 3). The recording for Pile 6 was not saved due to equipment malfunction, however the peak absolute value and total number of strikes was recorded by hand and an estimate of the other metrics can be made based on these values. According to our standard practice, the RMS90% can be estimated by subtracting 15 dB from the peak value and the single strike SEL can be estimated by subtracting 25 dB from the peak value. Then the cSEL can be estimated by adding the value of 10*LOG(total number of strikes) to the single strike SEL estimate. The results for Pile 6 are in Table 2. Pile 6 did exceed the 197 dB cSEL threshold set for this project based on these estimates after about 350 strikes. The distance to the 197 dB cSEL threshold is 22 meters (72 feet) from the pile.

The cSEL values and dB RMS values for each marine mammal hearing group are unable to be calculated due to the loss of the data. From our field notes, it appears that the bubble curtain was providing approximately 1 dB of noise reduction.

Pile 7

Pile 7 is located approximately 60 feet from the shoreline and in approximately 7 feet of water (Figure 2). Due to equipment malfunction the first approximately 1/3rd of the recording was not saved, however, we feel that the data that was captured was representative of the pile drive. The results for Pile 7 are in Table 2. Pile 7 did not exceed the 197 dB_{cSEL} threshold set for this project. The distance to the 197 dB threshold is 6 meters (21 feet) both up and downstream. Pile 7 exceeded the cSEL thresholds only for the Low Frequency and High Frequency cetaceans.

Figures 28, 29, 30 and 31 show the time history plot, 1/3rd Octave plot, PSD plot and spectrogram plot respectively. The peak, RMS90% and SEL90% values contain some slight variability towards the end of the drive but remained relatively consistent throughout the pile driving period. Pile 7 had a 3 dB noise reduction when the bubble curtain was turned on.

Figure 28: Time history plot of individual pile strikes for monitored Pile 7

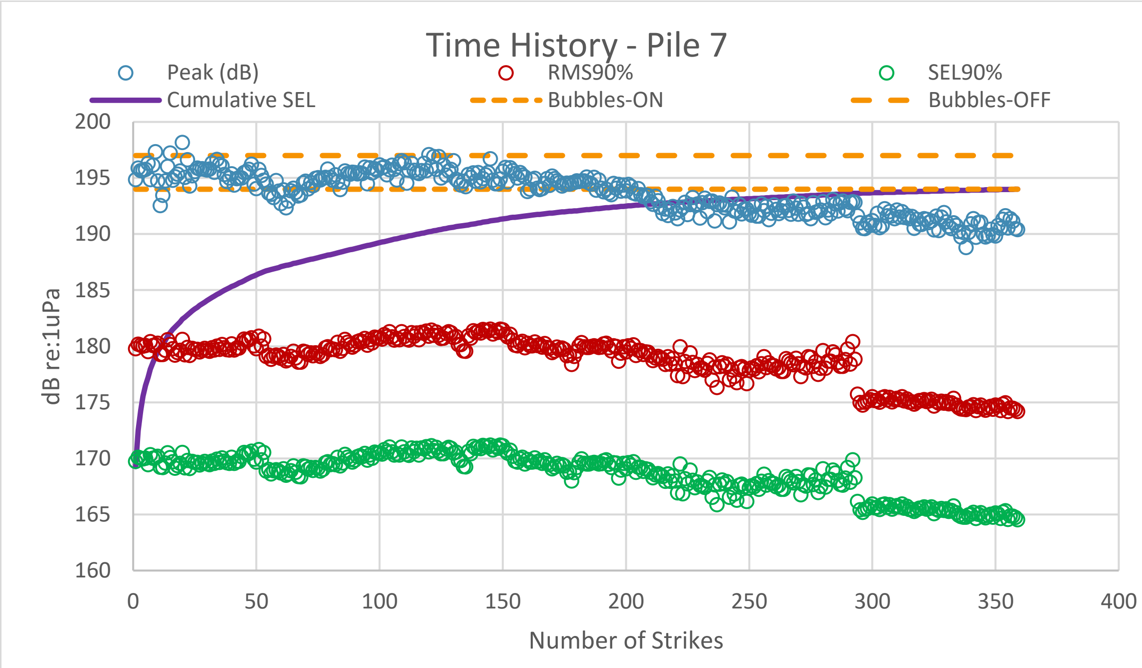
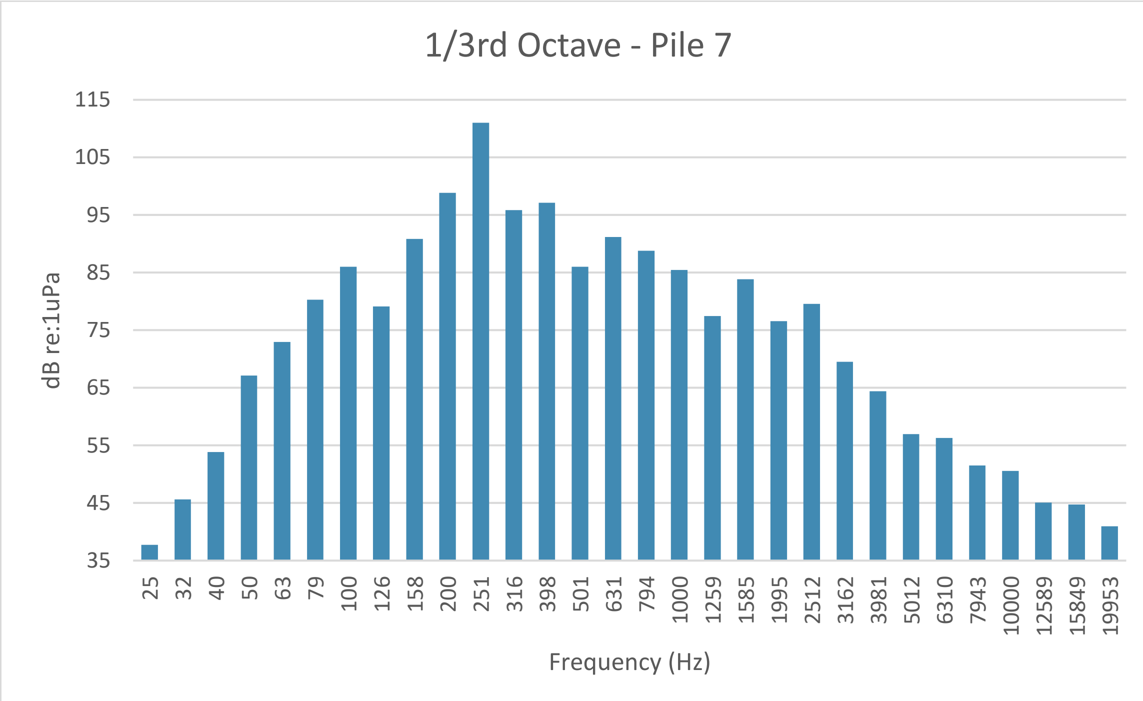


Figure 29 shows the 1/3rd Octave band plot for Pile 7. The plot indicates that the dominant frequency band is at about 250 Hz with a drop off in amplitudes above this level.

Figure 29: 1/3rd Octave Band Plot for monitored Pile 7



The PSD and spectrogram plots representing the absolute peak pile strike and one strike on either side of that strike indicate that most of the energy in each pile strike is below about 1000 Hz as shown in the PSD plot with the dominant frequencies below about 125 Hz as shown in the spectrogram.

Figure 29 shows the frequency distribution of the peak pile strike and two adjacent pile strikes. There was a dominant frequency at approximately 600 Hz which is within the appropriate range for impact pile driving.

Figure 30: Power Spectral Density Plot for monitored Pile 7

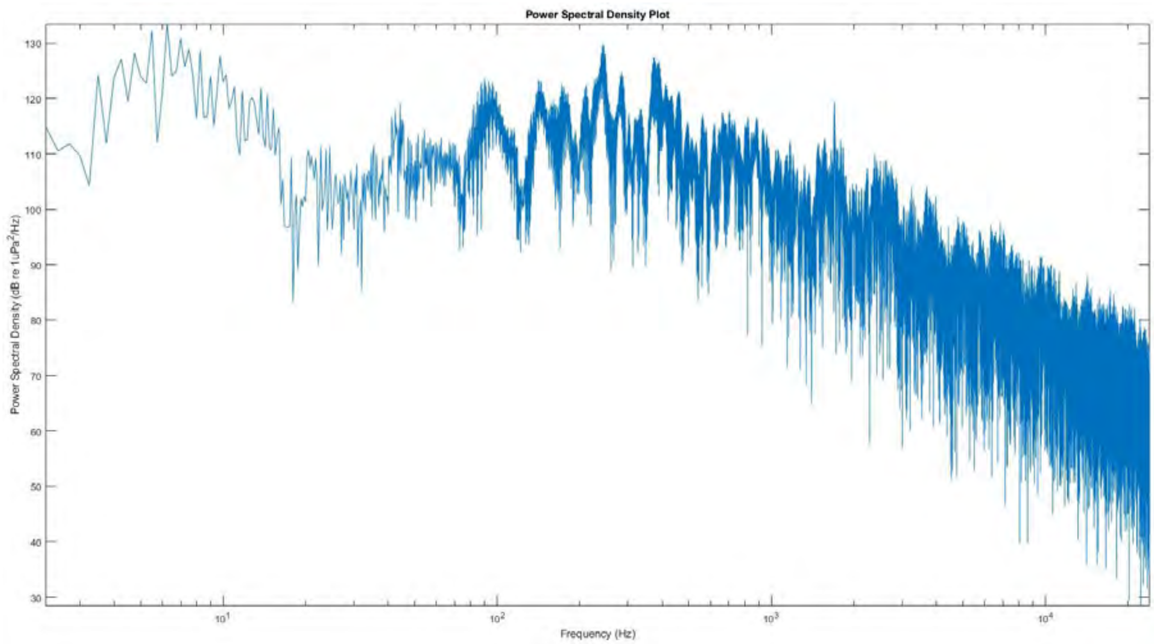
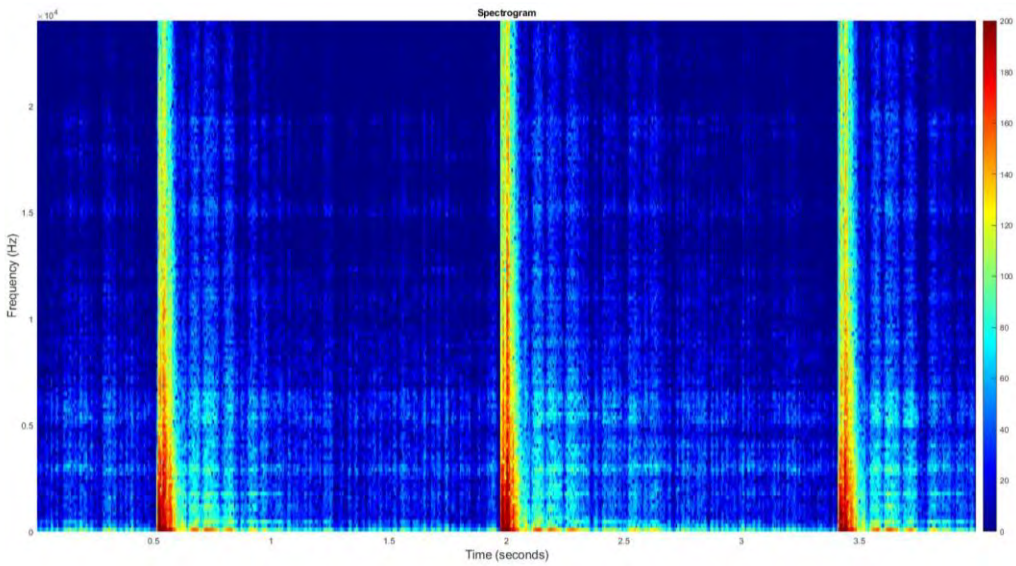


Figure 31 shows the Spectrogram plot for Pile 7. The spectrogram shows that there is substantially more energy (red color) in the pile strikes for this pile below approximately 250 Hz with maximum levels observed below about 1000 Hz.

Figure 31: Spectrogram Plot for monitored Pile 7



Pile 8

Pile 8 is located approximately 40 feet from the shoreline in 6 feet of water (Figure 2). The results for Pile 8 are in Table 2. Pile 8 has not exceeded the cSEL threshold for this project. The distance to the 197 dB threshold is 6 meters (21 feet) both up and downstream. Pile 8 exceeded the cSEL thresholds for Low Frequency, High Frequency and Phocid marine mammal hearing groups.

Figures 32, 33, 34 and 35 show the time history plot, 1/3rd Octave plot, PSD plot and spectrogram plot respectively. The peak, RMS90% and SEL90% values contain some slight variability for the initial part of the drive but are relatively consistent throughout the pile driving period with a slight decrease towards the end of the drive. The measured values indicate that the bubble curtain was achieving an estimated reduction of approximately 4 dB range.

Figure 32: Time history plot of individual pile strikes for monitored Pile 8

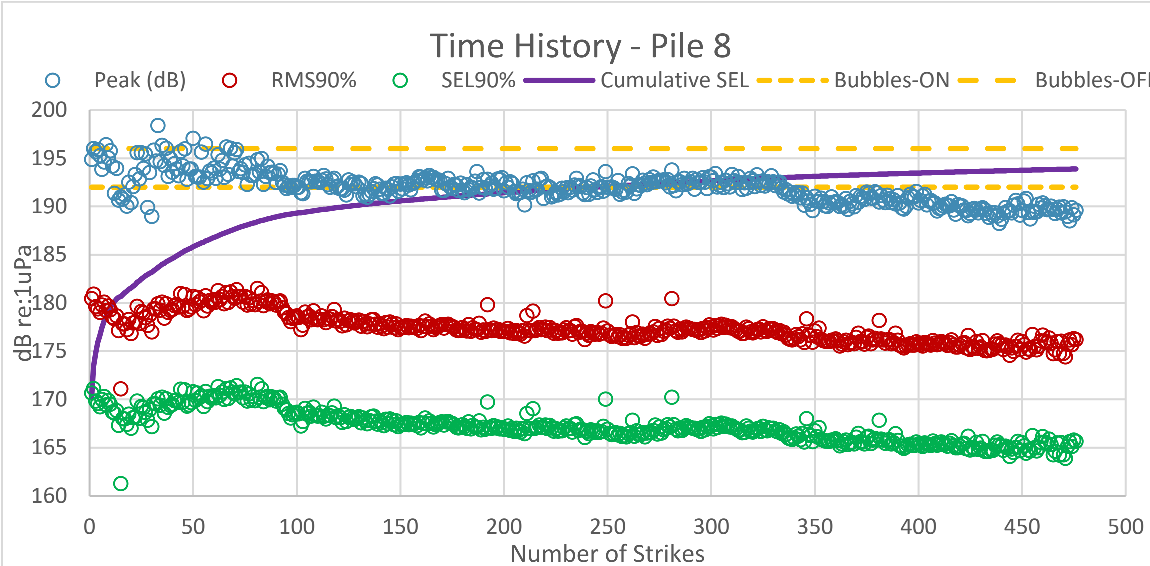


Figure 33 shows the 1/3rd Octave band plot for Pile 8. The plot indicates that the dominant frequency band is at about 320 Hz.

Figure 33: 1/3rd Octave Band Plot for monitored Pile 8

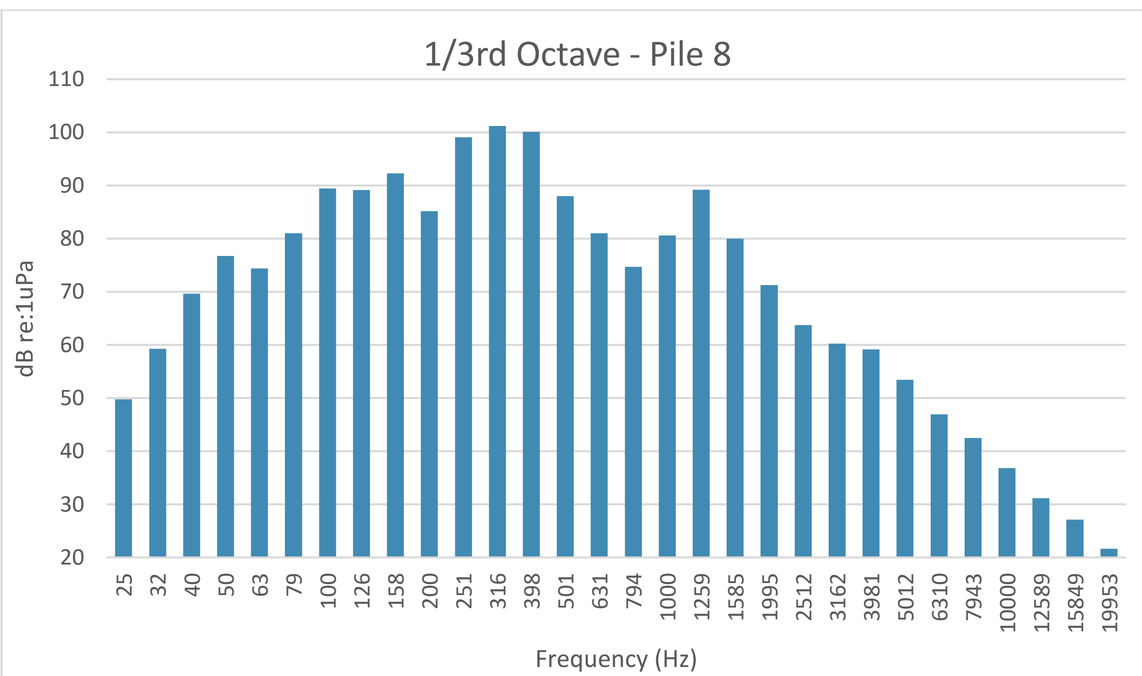


Figure 34 shows the frequency distribution of the peak pile strike and two adjacent pile strikes. The PSD plot indicate that most of the energy in each pile strike is below about 1000 Hz with the dominant frequencies at about 15 Hz and secondary peaks at 250 Hz and 300 Hz.

Figure 34: Power Spectral Density Plot for monitored Pile 8

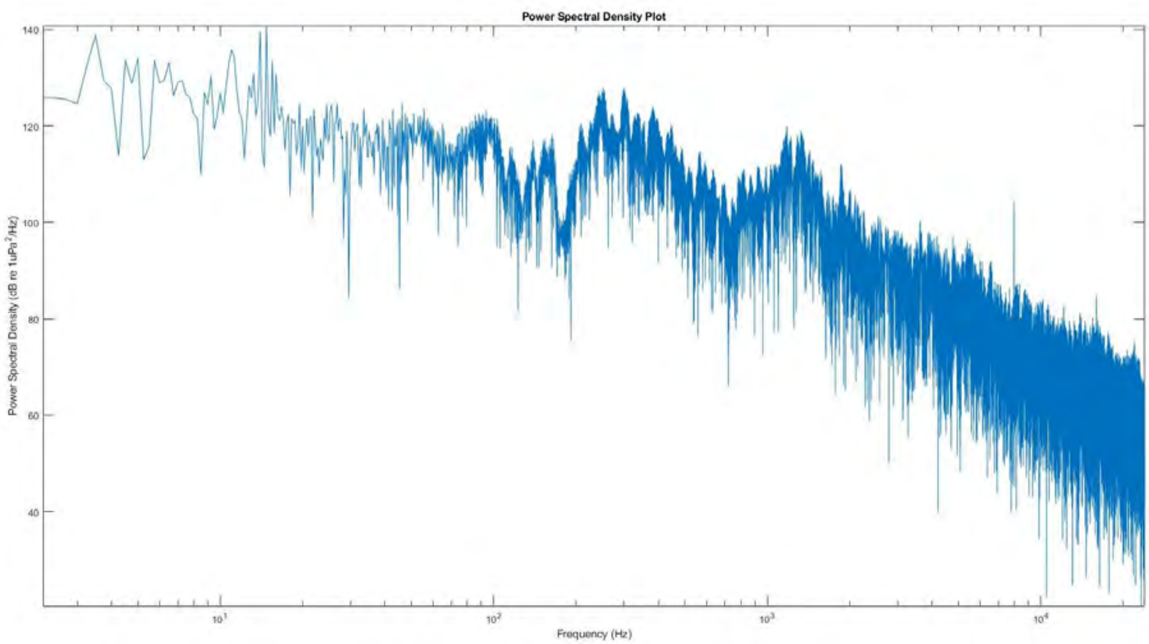
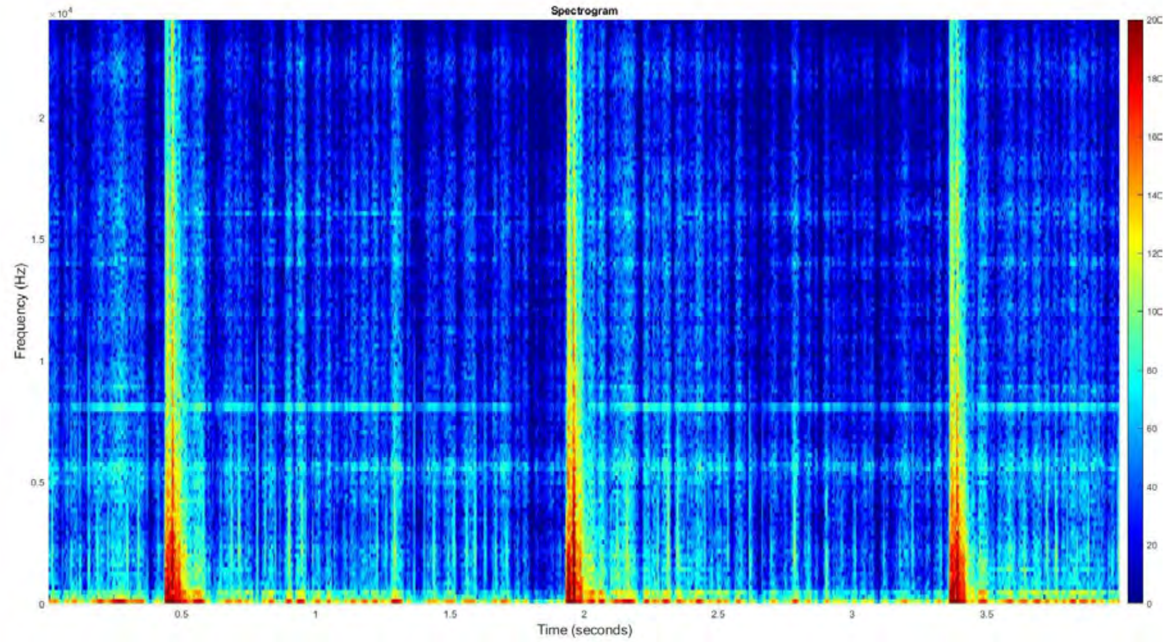


Figure 35 shows the Spectrogram plot for Pile 8. The spectrogram shows that there is substantially more energy between 20 Hz and 3000 Hz with maximum levels at about 1000 Hz. There is also a band of energy at about 750 Hz which could possibly be the bubble curtain.

Figure 35: Spectrogram Plot for monitored Pile 8



Pile 9

Pile 9 is located approximately 70 feet from the shoreline and in approximately 7 feet of water (Figure 2). The results for Pile 9 are in Table 2. Pile 9 did not exceed the 197 dB_{cSEL} threshold for this project. The distance to the 197 dB threshold is 9 meters (28 feet) both up and downstream. Pile 9 exceeded the cSEL thresholds for Low Frequency, High Frequency and Phocid marine mammal hearing groups.

Figures 36, 37, 38 and 39 show the time history plot, 1/3rd Octave polt, PSD plot and spectrogram plot respectively. The peak, RMS90% and SEL90% values were consistent throughout the drive with a slight increase in the middle of the drive. The measured values indicate that the bubble curtain was not able to achieve any noise reduction.

Figure 36: Time history plot of individual pile strikes for monitored Pile 9

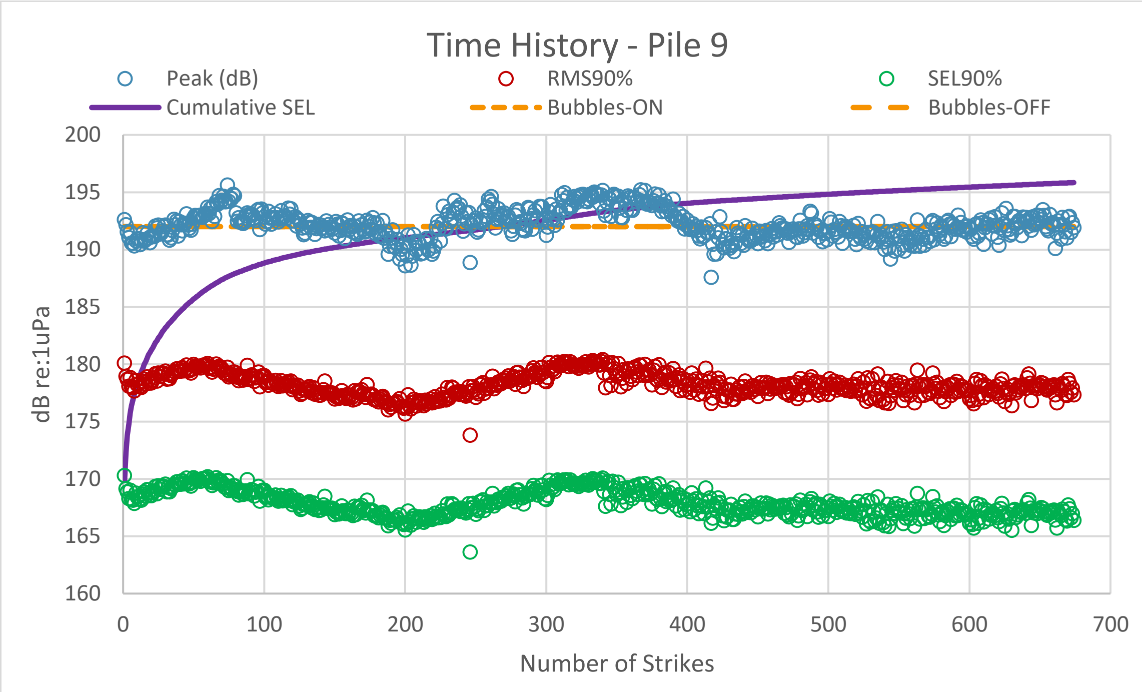
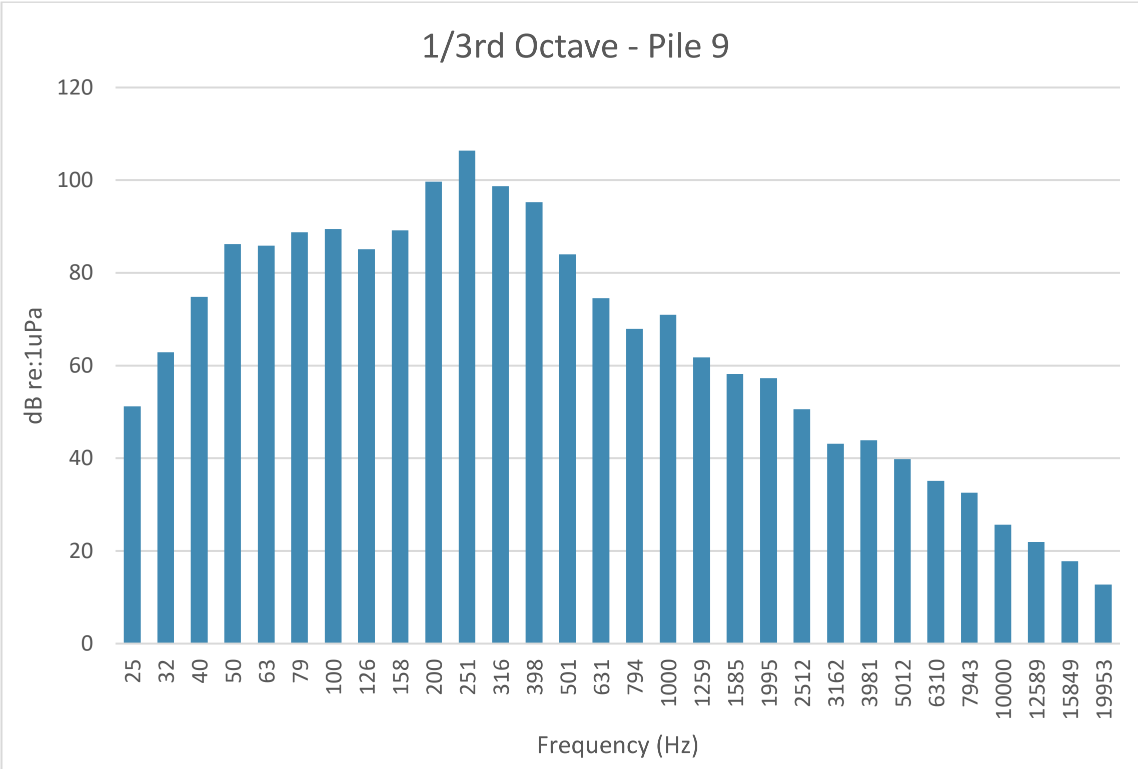


Figure 37 shows the 1/3rd Octave band plot for Pile 9. The plot indicates that the dominant frequency band is at about 250 Hz with the frequencies above dropping off.

Figure 37: 1/3rd Octave Band Plot for monitored Pile 9



The PSD and spectrogram plots representing the absolute peak pile strike and one strike on either side of that strike indicate that most of the energy in each pile strike is below about 1000 Hz as shown in the PSD plot with the dominant frequencies below about 275 Hz as shown in the spectrogram.

Figure 37 shows the frequency distribution of the peak pile strike and two adjacent pile strikes. There was a dominant frequency at approximately 275 Hz which is within the appropriate range for impact pile driving.

Figure 38:   Power Spectral Density Plot for monitored Pile 9

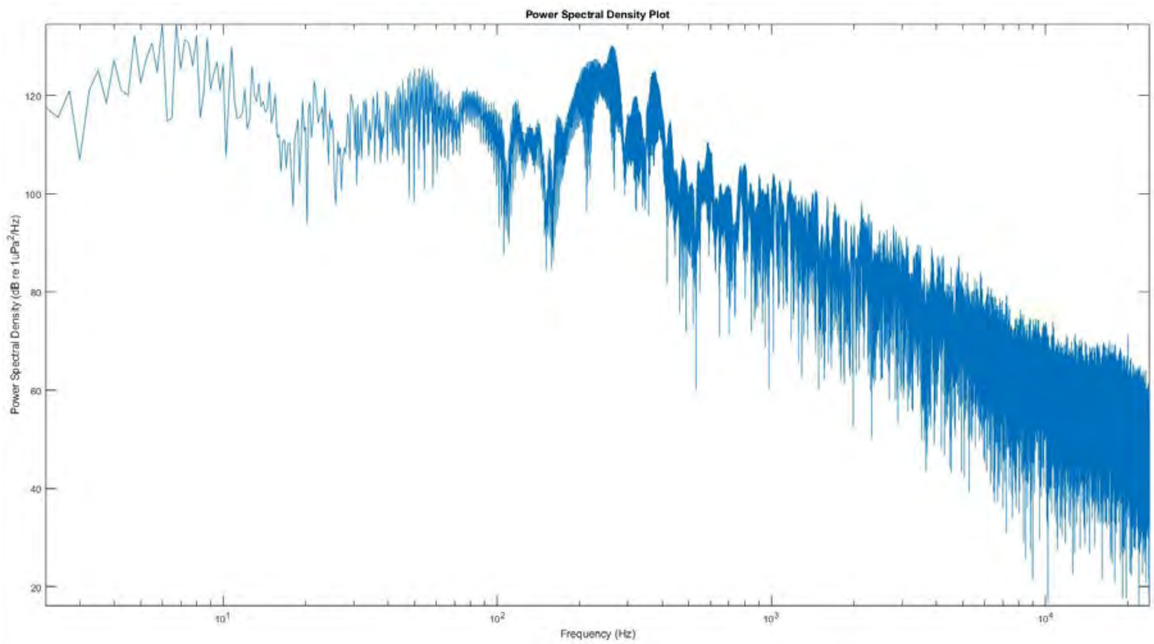
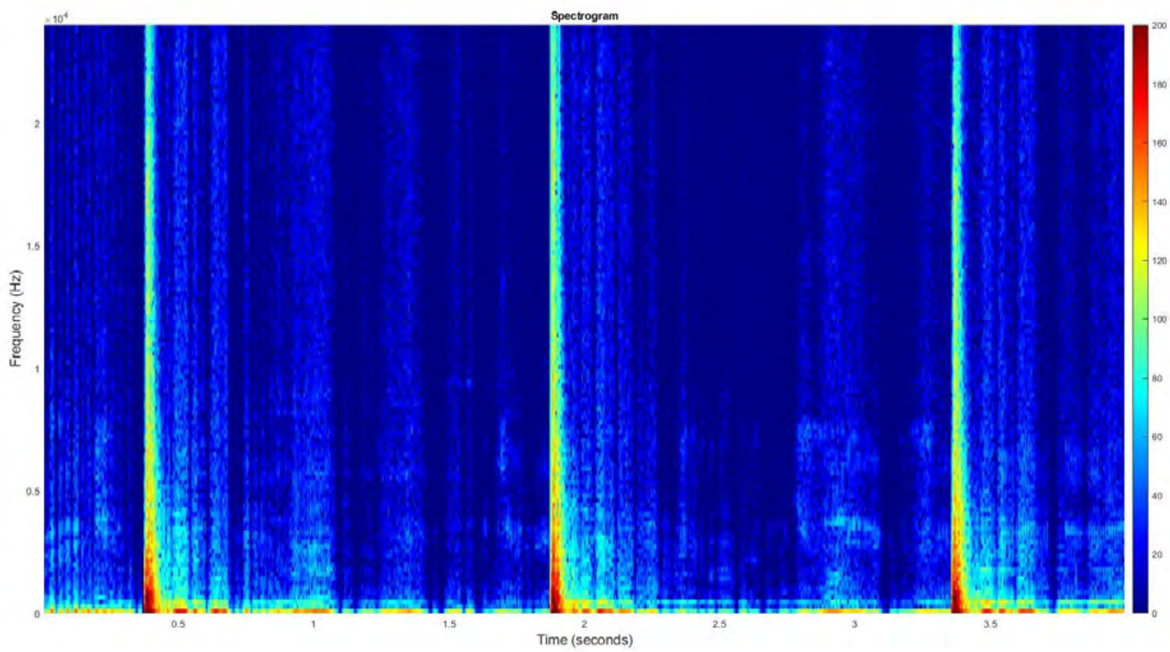


Figure 39 shows the Spectrogram plot for Pile 9. The spectrogram shows that there is substantially more energy (red color) in the pile strikes for this pile below approximately 250 Hz with maximum levels observed below about 1000 Hz.

Figure 39: Spectrogram Plot for monitored Pile 9



Pile 10

Pile 10 is located approximately 50 feet from the shoreline and in approximately 6 feet of water (Figure 2). The results for Pile 10 are in Table 2. Pile 102 did not exceed the 197 dB_{cSEL} threshold for this project. The distance to the 197 dB threshold is 6 meters (21 feet) both up and downstream. Pile 10 exceeded the cSEL thresholds for Low Frequency and High Frequency cetaceans.

Figures 40, 41, 42 and 43 show the time history plot, 1/3rd Octave band plot, PSD plot and spectrogram plot respectively. The peak, RMS90% and SEL90% values were relatively consistent throughout the pile driving period. The measured values indicate that the bubble curtain was achieving a 4 dB reduction.

Figure 40: Time history plot of individual pile strikes for monitored Pile 10

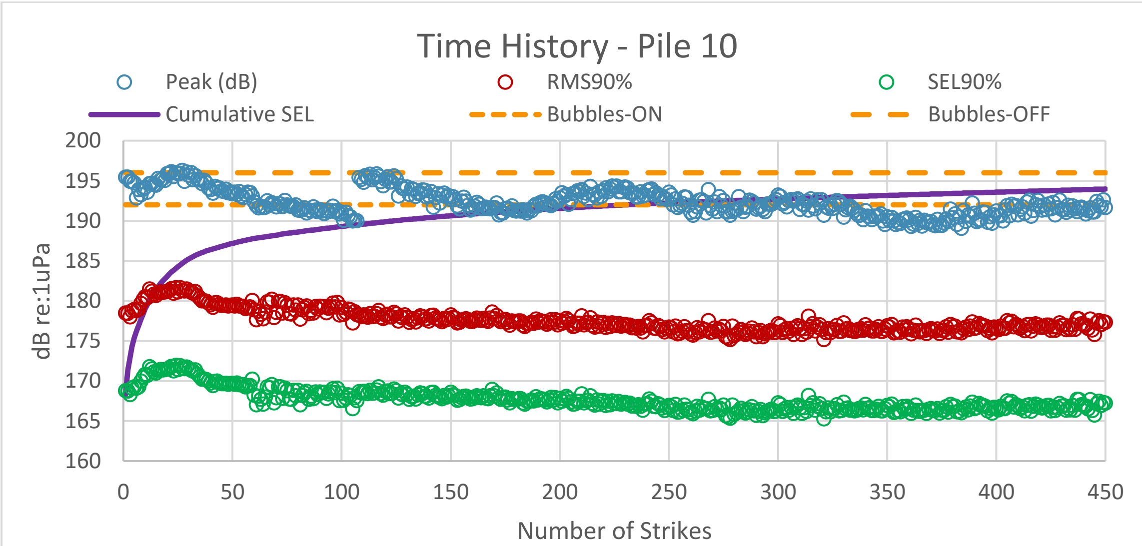
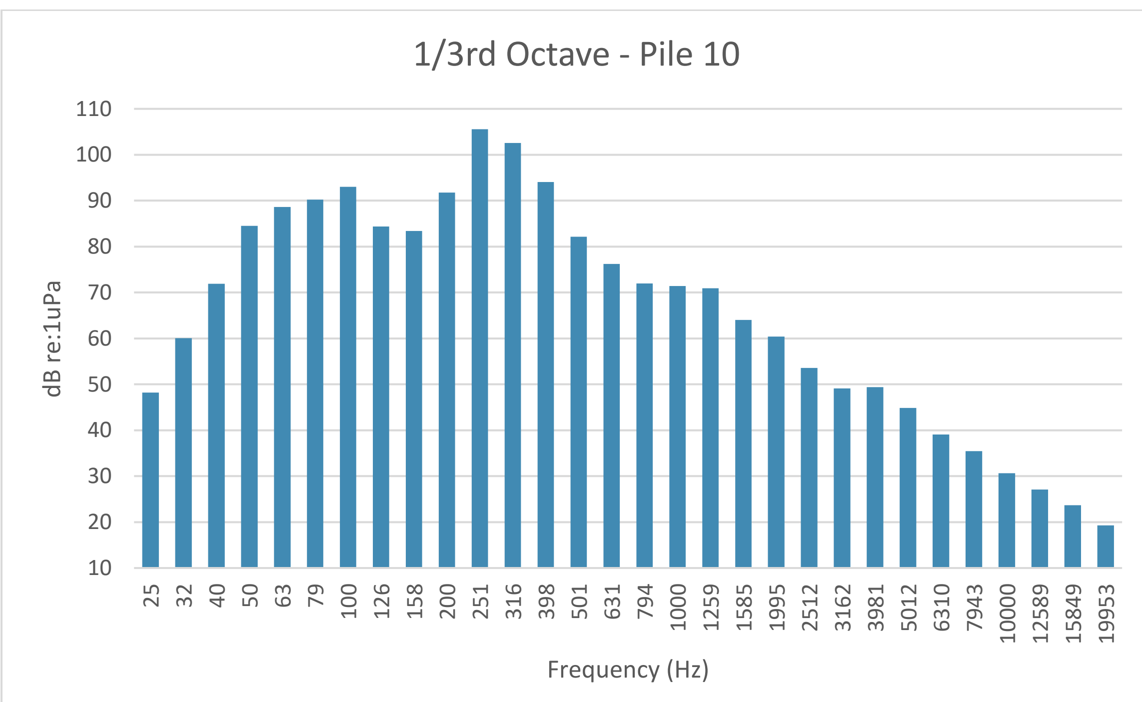


Figure 41 shows the 1/3rd Octave band plot for Pile 10. The plot indicates that the dominant frequency band is at about 250 Hz with frequencies dropping off above that.

Figure 41: 1/3rd Octave Band Plot for monitored Pile 10



The PSD and spectrogram plots representing the absolute peak pile strike and one strike on either side of that strike indicate that most of the energy in each pile strike is below about 800 Hz as shown in the PSD plot with the dominant frequencies below about 250 Hz as shown in the spectrogram.

Figure 42: Power Spectral Density Plot for monitored Pile 10

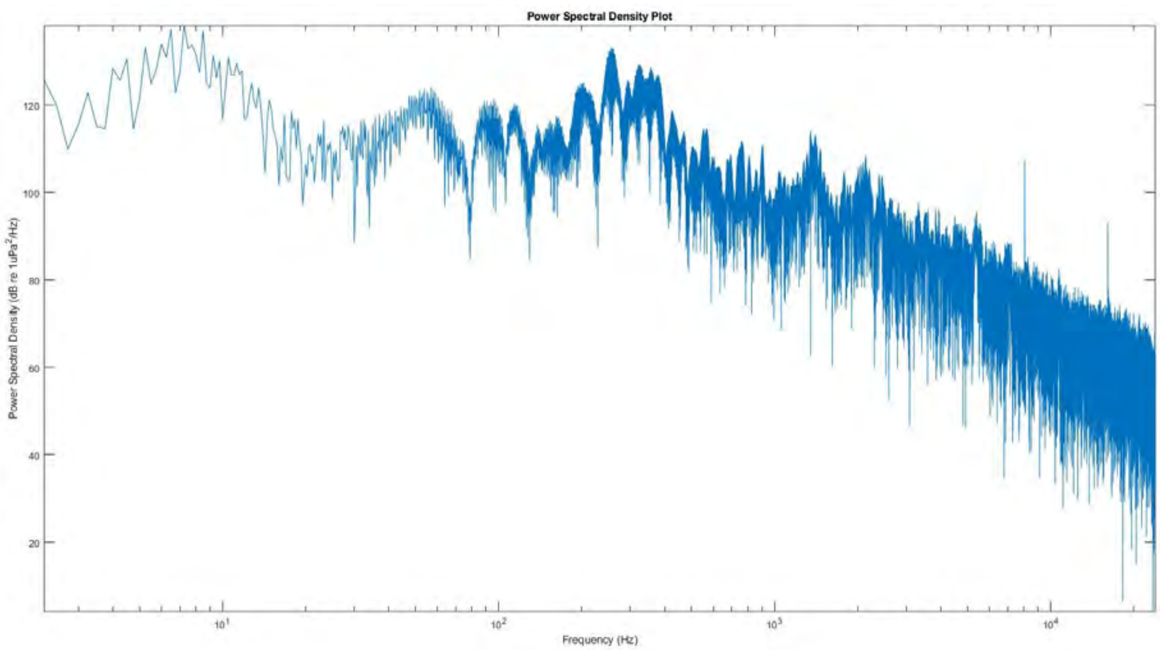
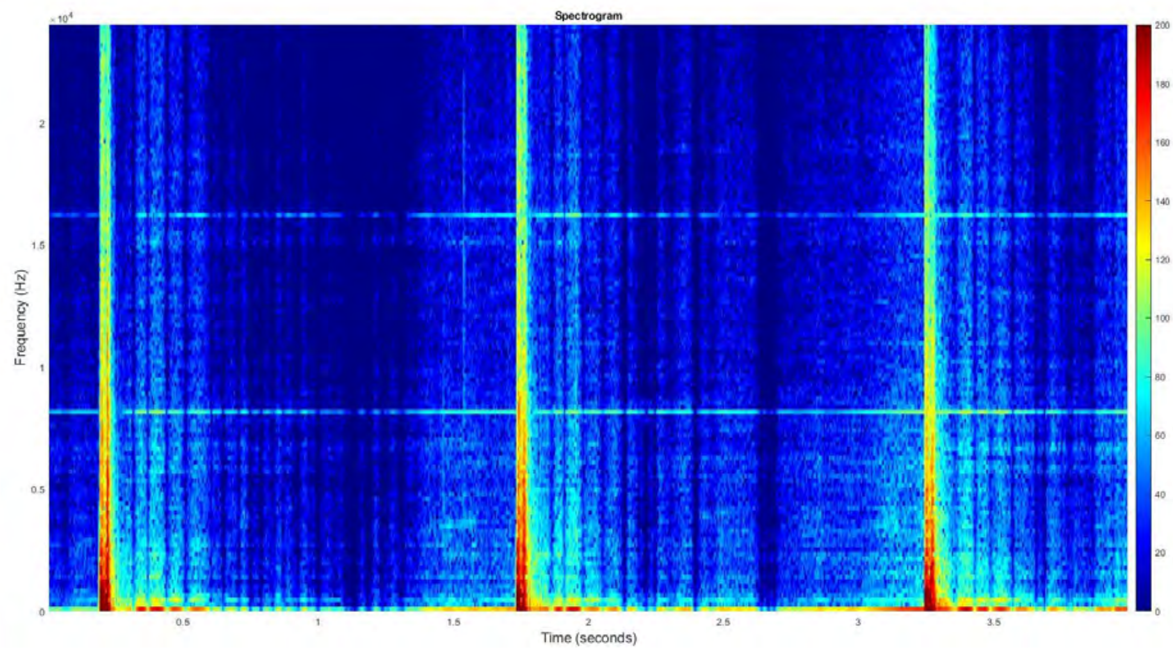


Figure 43 shows the Spectrogram plot for Pile 10. The spectrogram shows that there is substantially more energy (red color) in the pile strikes for this pile below approximately 250 Hz.

The spectrogram plot indicates that most of the energy is concentrated in the 20 Hz to 5000 Hz range with maximum levels observed below about 1000 Hz. There is also a horizontal band at about 750 Hz and another possible harmonic at about 1600 Hz which is likely caused by the bubble curtain.

Figure 43: Spectrogram Plot for monitored Pile 10



Pile 11

Pile 11 is located approximately 60 feet from the shoreline in approximately 6 feet of water (Figure 2). The recording for Pile 11 was not saved due to equipment malfunction, however the absolute peak value and total number of strikes was recorded and an estimate of the other metrics can be made based on these values as described for Pile 6 above. The results for Pile 11 are in Table 2. Pile 2 just exceeded the 197 dB cSEL threshold for this project. The distance to the 197 dB cSEL threshold is 12 meters (39 feet).

The cSEL and RMS values for each marine mammal hearing group are unable to be calculated due to the loss of data. Based on our field notes the bubble curtain was providing between approximately 1 dB to 6 dB of noise reduction.

Table 2: Summary of Underwater Attenuated Sound Levels for 24-in Piles at I-5 at Puyallup River

Pile #	Date & Time	Hearing Group	Hydro-phone Depth (feet)	Total Number Of Strikes	Absolute Highest Peak (dB)	Highest Peak Bubbles Off (dB)	Δ	Peak L_{50} (dB)	Peak L_{50} Bubbles Off (dB)	Δ	$RMS_{90\%}$ L_{50} (dB)	$RMS_{90\%}$ L_{50} Bubbles Off (dB)	Δ	Single Strike $SEL_{90\%}$ L_{50} (dB)	Single Strike $SEL_{90\%}$ Bubbles Off (dB)	Δ	cSEL (dB)	Exceed dB cSEL Threshold? (Y/N)	Threshold (dBcSEL)	Distance to cSEL Threshold (feet)	Distance To Behavioral Threshold (feet)
1	7-23-19	Broadband	2	1,756	204	202	2	199	200	1	184	184	0	173	172	1	204	Y	197	97	6,098
		Low Freq.			204			199			183			172			203	Y	183	711	1,127
		Mid. Freq.			188			180			159			147			179	N	185	13	28
		High Freq			186			177			154			143			175	Y	155	711	13
		Phocids			198			191			174			163			194	Y	185	711	283
		Otariids			197			191			174			163			194	N	203	8	283
2	7-31-19	Broadband	2	1,277	201	201	0	198	199	1	180	182	2	170	172	2	200	Y	197	52	3,300
		Low Freq.			200			198			179			169			199	Y	183	385	610
		Mid. Freq.			185			172			153			143			174	N	185	6	11
		High Freq			183			167			148			138			169	Y	155	283	5
		Phocids			193			190			171			161			191	Y	185	83	179
		Otariids			193			190			171			161			191	N	203	5	179
3	7-31-19	Broadband	2	1,253	202	202	0	200	198	0	182	182	0	172	172	0	202	Y	197	71	4,486
		Low Freq.			201			200			181			170			200	Y	183	449	829
		Mid. Freq.			186			176			157			146			177	N	185	10	21
		High Freq			183			172			153			142			173	Y	155	523	11
		Phocids			196			190			171			160			191	Y	185	83	179
		Otariids			195			190			171			160			191	N	203	5	179
4	8-6-19	Broadband	3	1,291	201	199	0	191	196	5	177	181	5	166	171	6	197	N	197	33	2,082
		Low Freq.			200			190			175			164			196	Y	183	243	330
		Mid. Freq.			194			180			161			150			184	N	185	28	38
		High Freq			194			180			161			150			184	Y	155	2,830	38
		Phocids			196			183			166			156			188	Y	185	52	83
		Otariids			196			183			166			155			187	N	203	3	83
5	8-6-19	Broadband	3	757	200	199	0	192	196	4	176	181	5	166	171	5	195	N	197	24	1,786
		Low Freq.			199			191			175			165			194	Y	183	179	330
		Mid. Freq.			183			168			148			138			169	N	185	3	5
		High Freq			181			165			143			133			165	Y	155	153	2

Pile #	Date & Time	Hearing Group	Hydro-phone Depth (feet)	Total Number Of Strikes	Absolute Highest Peak (dB)	Highest Peak Bubbles Off (dB)	Δ	Peak L_{50} (dB)	Peak L_{50} Bubbles Off (dB)	Δ	$RMS_{90\%}$ L_{50} (dB)	$RMS_{90\%}$ L_{50} Bubbles Off (dB)	Δ	Single Strike $SEL_{90\%}$ L_{50} (dB)	Single Strike $SEL_{90\%}$ Bubbles Off (dB)	Δ	cSEL (dB)	Exceed dB cSEL Threshold? (Y/N)	Threshold (dBcSEL)	Distance to cSEL Threshold (feet)	Distance To Behavioral Threshold (feet)
		Phocids			193			184			167			157			186	Y	185	38	97
		Otariids			193			183			167			157			186	N	203	2	97
6	8-9-19	Broadband	3	987	197	196	0	-	-	-	182	181	0	-	-	-	202	Y	197	71	4,486
		Low Freq.			-			-			-			-			-	-	183	-	-
		Mid. Freq.			-			-			-			-			-	-	185	-	-
		High Freq			-			-			-			-			-	-	155	-	-
		Phocids			-			-			-			-			-	-	185	-	-
		Otariids			-			-			-			-			-	-	203	-	-
7	8-10-19	Broadband	3	763	198	198	0	194	197	3	179	182	3	169	172	3	194	N	197	21	1,314
		Low Freq.			197			192			178			167			192	Y	183	131	523
		Mid. Freq.			187			171			151			141			171	N	185	4	8
		High Freq			187			168			147			137			170	Y	155	330	5
		Phocids			191			183			167			157			183	N	185	24	97
		Otariids			191			183			167			157			182	N	203	1	97
8	8-10-19	Broadband	3	504	198	200	2	192	196	4	177	180	3	167	170	3	194	N	197	21	2,082
		Low Freq.			198			190			175			165			192	Y	183	131	330
		Mid. Freq.			190			179			162			152			184	N	185	28	208
		High Freq			190			179			162			152			184	Y	155	2,830	208
		Phocids			193			186			169			159			187	Y	185	45	131
		Otariids			192			182			165			155			185	N	203	2	71
9	8-10-19	Broadband	3	742	196	196	0	192	192	0	178	179	1	168	169	1	196	N	197	28	2,428
		Low Freq.			193			190			175			165			193	Y	183	153	330
		Mid. Freq.			189			177			161			150			179	N	185	13	38
		High Freq			189			177			161			150			179	Y	155	1,314	38
		Phocids			192			177			159			149			188	Y	185	52	28
		Otariids			189			177			161			150			180	N	203	1	38
10	8-10-19	Broadband	3	1,089	196	197	1	192	196	4	177	181	4	167	171	4	194	N	197	21	2,082
		Low Freq.			196			190			174			164			191	Y	183	113	283
		Mid. Freq.			196			177			159			149			178	N	185	11	28

Pile #	Date & Time	Hearing Group	Hydro-phone Depth (feet)	Total Number Of Strikes	Absolute Highest Peak (dB)	Highest Peak Bubbles Off (dB)	Δ	Peak L_{50} (dB)	Peak L_{50} Bubbles Off (dB)	Δ	$RMS_{90\%}$ L_{50} (dB)	$RMS_{90\%}$ L_{50} Bubbles Off (dB)	Δ	Single Strike $SEL_{90\%}$ L_{50} (dB)	Single Strike $SEL_{90\%}$ Bubbles Off (dB)	Δ	cSEL (dB)	Exceed dB cSEL Threshold? (Y/N)	Threshold (dBcSEL)	Distance to cSEL Threshold (feet)	Distance To Behavioral Threshold (feet)
		High Freq			196			177			159			149			178	Y	155	1,127	28
		Phocids			196			178			158			148			183	N	185	24	24
		Otariids			196			178			160			150			180	N	203	1	33
11	8-10-19	Broadband	3	954	193	190	3	-	-	-	178	175	3	168	165	3	198	Y	197	38	523
		Low Freq.			-			-			-			-			-	-	183	-	-
		Mid. Freq.			-			-			-			-			-	-	185	-	-
		High Freq			-			-			-			-			-	-	155	-	-
		Phocids			-			-			-			-			-	-	185	-	-
		Otariids			-			-			-			-			-	-	203	-	-

*-Estimated by subtracting 15 dB from the peak value for the RMS90% and 25 dB from the peak value for the single strike SEL90%.

6.2 DAILY CUMULATIVE SEL

The daily cSEL's were calculated using an actual $SEL_{90\%}$ for each individual pile strike for Piles 2 and 3 on July 31st, Piles 4 and 5 on August 6th and Piles 7, 9, 10 and 11 on August 10th. The the estimated cSEL for Pile 11 were estimated using 10*LOG(number of strikes) and logarithmically added to the cSEL value for Piles 7, 9 and 10 to get an estimated daily cSEL. The table below provides the daily cSEL for each day of monitoring and the distance to the 197 dB cSEL threshold.

Table 3: Summary Distance to Daily 197 dBcSEL Threshold

Date	cSEL (dB)	Distance to 197 dBcSEL Threshold (ft)
7/23/19	204	97
7/31/19	200	52
8/6/19	197	33
8/9/19	202	71
8/10/19	199	45

7 SUMMARY

Eleven, 24-inch steel piles with 14-inch H-pile stingers and closed ends were monitored for the I-5 Tacoma HOV project. The duration of impact driving each pile was longer than we typically see for projects like these and produced underwater sound levels that were slightly higher than normal for 24-inch piles. The reason for this could be that the bottom of the piles where the 'stinger' attached was closed causing the pile to have to displace the substrate rather than drive through it and requiring more energy to do so. The bubble curtain was also not functioning as well as expected and it is not clear whether the closed end piles would have contributed somehow to its underperformance. The underwater sound levels analyzed, produced the following results:

- Peak broadband underwater attenuated sound levels measured at 10 meters varied slightly in a range between 193 dB_{Peak} and 204 dB_{Peak} with the peak L_{50} ranging between 191 dB_{peak} to 200 dB_{peak}.
- The measured $RMS_{90\%}$ L_{50} levels ranged between 176 $dB_{RMS90\%}$ and 184 $dB_{RMS90\%}$.
- The noise level reductions from the bubble curtain ranged between 0 dB and 5 dB with an overall average of 2 dB. Typical noise reductions from 24-inch piles for previous projects are in the 9 dB to 12 dB range.
- Cumulative Sound Exposure Levels (cSEL) for all piles driven on the same day, ranged between 197 dB_{cSEL} and 204 dB_{cSEL}.
- For Piles 6 and 11 due to equipment malfunction the recordings were not saved and the calculated values of RMS and SEL are estimates.
- Only Piles 1, 2, 3, 6 and 11 exceeded the 197 dBcSEL threshold for this project. For the daily cSEL the distance to the 197 dB_{cSEL} threshold ranged between 33 and 97 feet.

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.