I90/Bridge Resurfacing Project

UNDERWATER NOISE MONITORING REPORT

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ACRONYMS AND ABBREVIATIONS

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

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 I-90 Bridge Resurfacing Project, between July and August of 2018. A total of five piles were monitored, two at Bridge 140 (MP 86.3 Vic.) and three at Bridge 154 (MP 106.6 Vic.) (Table 1). Unconfined bubble curtains were deployed for all piles impact driven to attenuate potential underwater noise effects. Piles were vibed in initially and then pile templates were used to keep the piles vertical while driving. Measurements were collected at 10 meters from the piles.

Only the last two piles monitored at Bridge 154 exceeded the 206 dB_{peak} threshold for fish at the measured distances. The peak attenuated sound levels measured ranged between 181 dB_{peak} and 209 dB_{peak} while monitoring the impact pile driving operation as shown in Table 1 and 2. The daily Cumulative Sound Exposure Level (cSEL) for all five piles monitored did not exceed the threshold of 187 dB_{cSEL} at 10 meters except for the last two piles monitored at Bridge 154.

Table 1: Bridge 140 Summary of 30-inch Pile Attenuated Impact Driving Underwater Sound Levels.

Pile #	Date	Hydro-Phone Range (m)	Absolute Highest Peak (dB)	$RMS_{90\%}$ (dB)	Single Strike $SEL_{90\%}$ (dB)	Cumulative SEL (dB)
1	7/30/18	10	184	164	155	182
2	7/30/18	10	185	168	158	

Table 2: Bridge 154 Summary of 30-inch Pile Attenuated Impact Driving Underwater Sound Levels.

Pile #	Date	Hydro-Phone Range (m)	Absolute Highest Peak (dB)	$RMS_{90\%}$ (dB)	Single Strike $SEL_{90\%}$ (dB)	Cumulative SEL (dB)
1	8/1/18	10	181	158	148	169
2	8/4/18	10	207	182	172	194
3	8/4/18	10	209	182	172	

1 INTRODUCTION

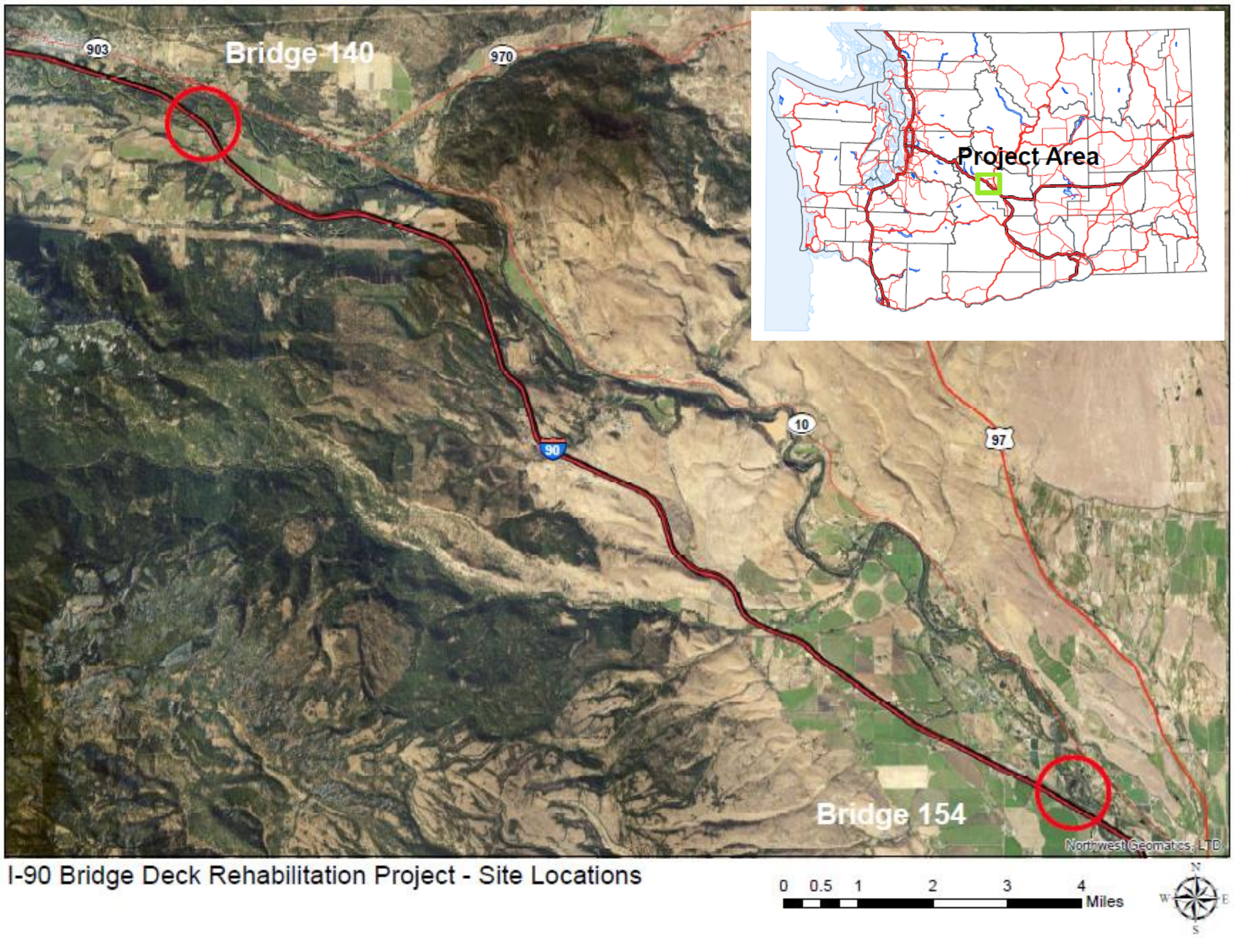
The Washington State Department of Transportation (WSDOT) is rehabilitating the eastbound and westbound bridge decks at two bridges on I-90. The two bridge decks on the Yakima River Bridges are seven miles west of Ellensburg (Bridge 154, MP 102.6 Vic.) and two miles east of Cle Elum (Bridge 140, MP 86.3 Vic.). They are showing signs of deterioration. This project will repair and resurface the existing bridge decks in both the eastbound and westbound lanes, which will extend the life of these bridges for decades to come. See vicinity map (Figure 1).

This report summarizes the impact pile driving results measured on the Yakima River at two locations in an effort to collect site-specific data on underwater noise levels during the months of July and August 2018. Two 30-inch diameter steel piles were monitored at Bridge 140 and three 30-inch piles were monitored at Bridge 154.

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

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 Bridge 140 and Bridge 154 near Cle Elum and Ellensburg WA



2 PROJECT AREA

The two bridge decks on the Yakima River Bridges are seven miles west of Ellensburg (Bridge 154) and two miles east of Cle Elum (Bridge 140). They are showing signs of deterioration. This project will repair and resurface the existing bridge decks in both the eastbound and westbound lanes, which will extend the life of these bridges for decades to come..

3 PILE INSTALLATION LOCATION

Two 30- inch steel piles installed during initial impact pile driving activity at the I-90 Bridge 140 were monitored. Figures 2 and 3 indicates the approximate location of the Bridge 140 and Bridge 154 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 3 feet deep.

Figure 2: Approximate Locations of Piles 1 and 2 at I-90 Bridge 140 near Cle Elum. Yellow dot is approximate location of the hydrophone

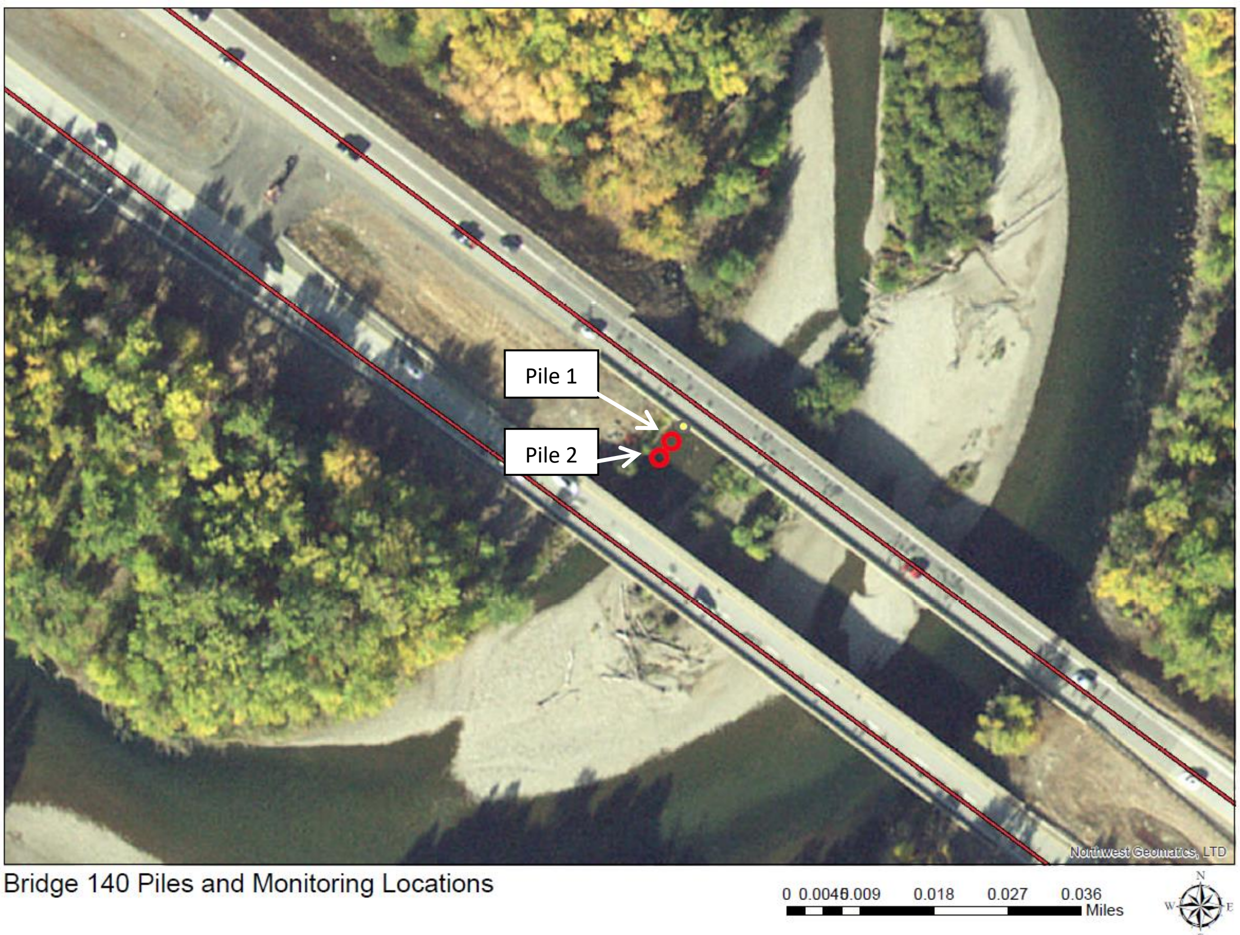


Figure 3: Approximate Locations of Piles 1, 2 and 3 at I-90 Bridge 154 near Ellensburg. Yellow dot is approximate location of the hydrophone

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

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

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:

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

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.

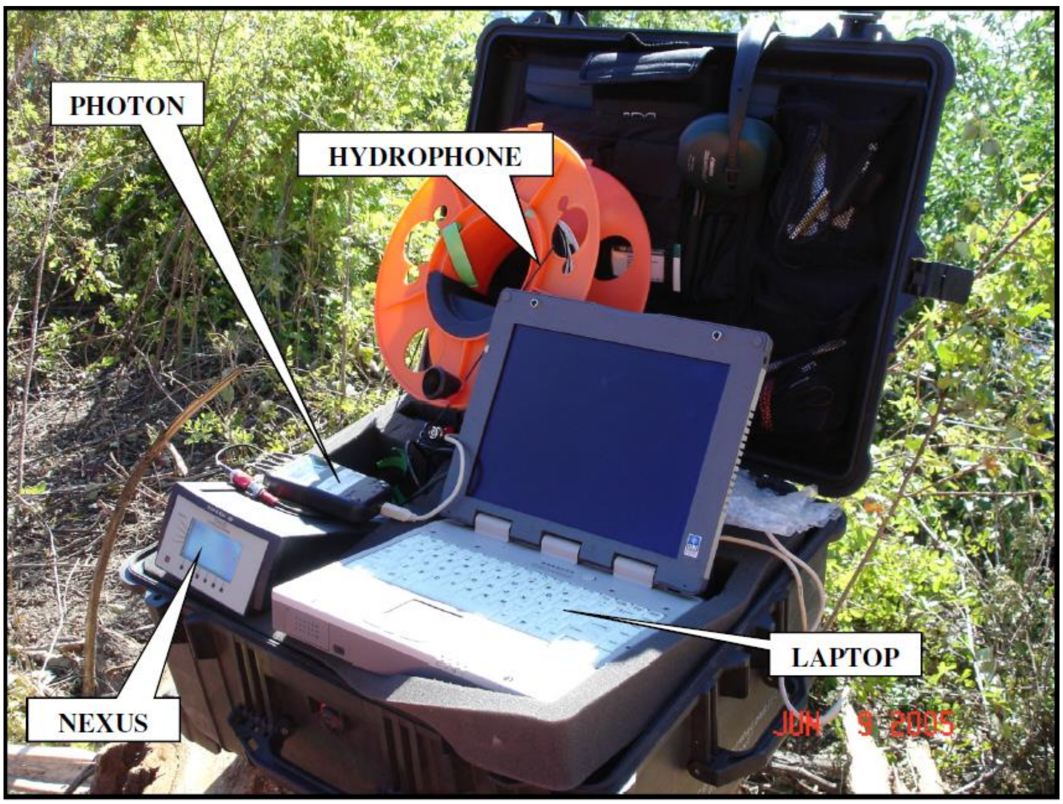
$$cSEL = SEL_{90\%} + 10 \text{ LOG (total number of pile strikes)} \qquad \text{(eq. 3)}$$

5 METHODOLOGY

5.1 Typical Equipment Deployment

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 pole anchored on the shoreline keeping tension on the line. The hydrophone was placed at a distance of 10 meters from the pile being monitored. An unconfined bubble curtain was deployed for all piles driven to mitigate potential underwater noise effects, however, for two piles at Bridge 154 the bubble curtain was not completely encircling the pile during impact pile driving.

Figure 4: 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 4. The output of the Nexus signal conditioner is received by a Brüel and Kjær Photon 4-channel signal spectrum analyzer that is attached to a Dell ATG laptop computer similar to the one shown in Figure 4.

The equipment captures underwater sound levels from the pile driving operations in the format of an RTPro signal file for processing later. The WSDOT has the system and software calibration checked annually against NIST traceable standard.

Signal 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 μPa^2•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.

The underwater noise thresholds applied to this project are shown in Table 3 and are applied to all fish.

Table 3: Fish thresholds for In-Water Construction Activity

Group	**Underwater Noise Thresholds**		
	Impact Pile Driving Disturbance Threshold	**Auditory Injury Threshold**	
	dB RMS	dB Peak SPL	dB Cumulative SEL
Fish ≥ 2 grams	Behavior effects threshold 150 dB RMS	206	187
Fish < 2 grams		206	183

6 PILE INSTALLATION RESULTS

6.1 UNDERWATER SOUND LEVELS

WSDOT conducted hydroacoustic monitoring for two 30-inch steel piles struck with an impact hammer in water depths 3 feet or greater at Bridge 140 and three 30-inch piles driven in water depths 3 feet or greater at Bridge 154. Data from all piles analyzed in the paragraphs below are also summarized in Table 4.

Bridge 140, Pile 1

Pile 1 at Bridge 140 is located approximately 20 feet from the waters edge in approximately 3 feet of water on the west side of the river as it passes under I-90 (Figure 2). Due to high levels of background noise from strumming of the rope the hydrophone was attached to and water turbulence around the hydrophone some of the pile strikes were rejected from this analysis. The results for Pile 1 can be found in Table 4. Figure 5 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, RMS90% and SEL90% values with a slight rise towards the end of the pile driving. Pile 1 has not exceeded the dual interim threshold for fish for either the peak or cSEL values.

Figure 5: Time history plot of individual impact strikes for Bridge 140, Pile 1

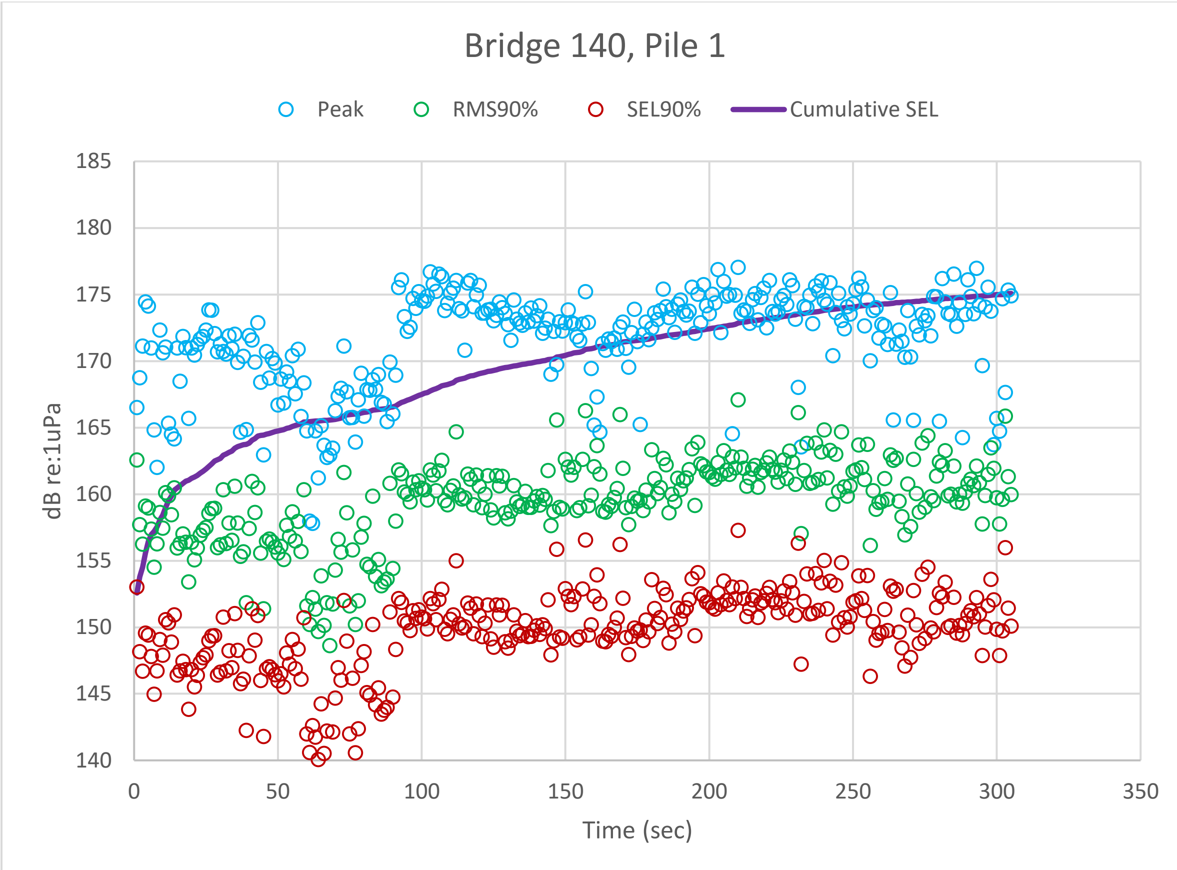


Figure 6 shows the Power Spectral Density (PSD) plot (sound pressure level as a function of frequency) for the pile drive. The plot indicates that most of the energy is below 1000 Hz.

Figure 6: Power Spectral Density Plot for Bridge 140, Pile 1

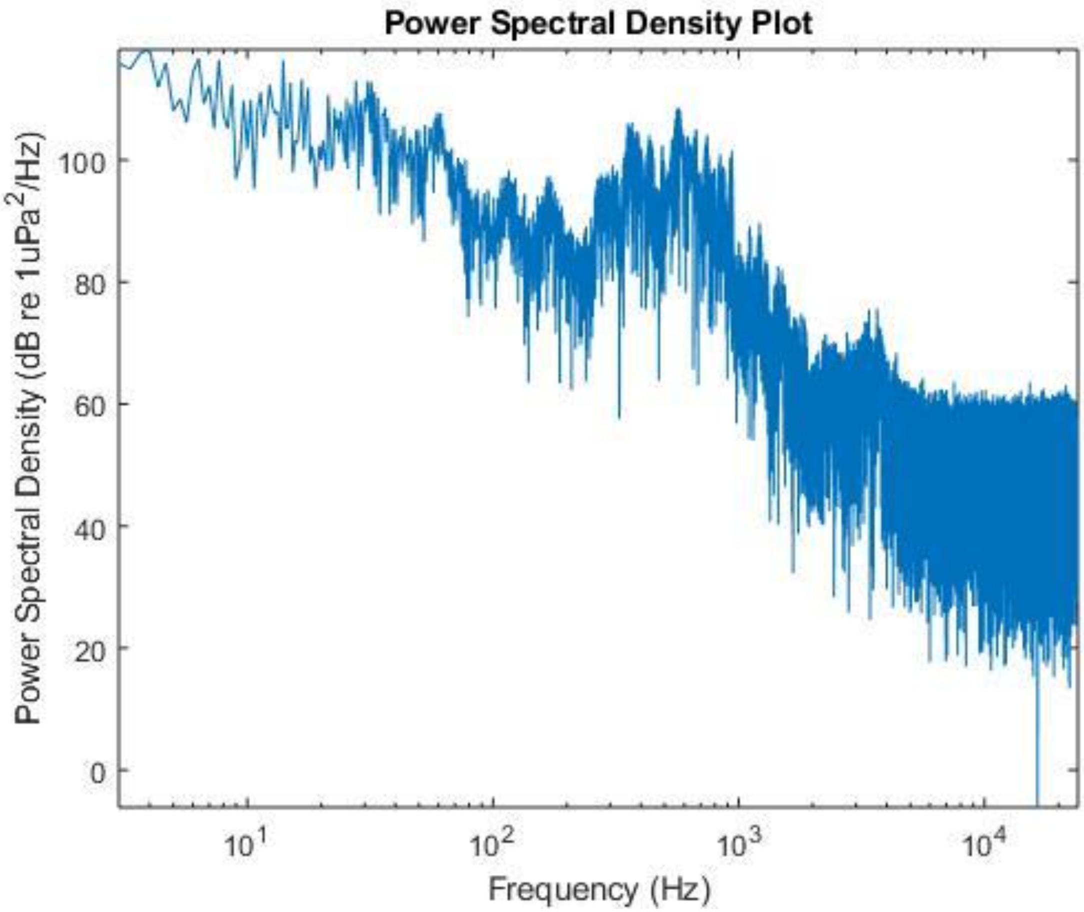
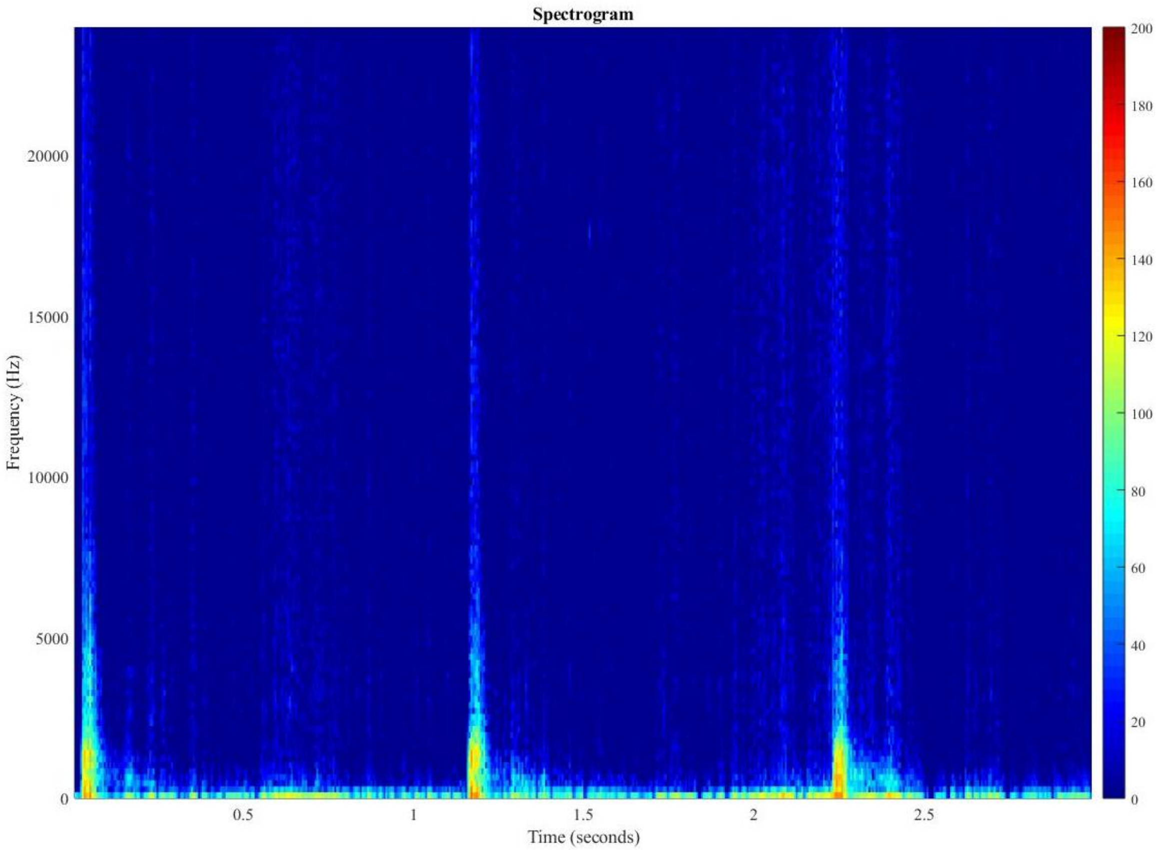


Figure 7 shows the spectrogram plot (sound intensity as a function of time and frequency) of three consecutive pile strikes. The color bar to the right indicates the decibel level of the different frequencies. The plot indicates that most of the energy is in the initial part of the pile strike and occurs in frequencies less than 1000 Hz.

Figure 7: Spectrogram Plot for Bridge 140, Pile 1



Bridge 140, Pile 2

Pile 2 is located approximately 10 feet from the shoreline and approximately 10 feet south of Pile 1 (Figure 2). The results for Pile 2 are in Table 4. Due to high levels of background noise from strumming of the rope the hydrophone was attached to and water turbulence around the hydrophone some of the pile strikes were rejected from this analysis. Pile 2 did not exceeded the dual interim threshold for fish for either the peak or cSEL.

Figures 8, 9 and 10 show the time history plot, PSD plot and spectrogram plot respectively. The peak, RMS90% and SEL90% values contain some slight variability 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 8: Time history plot of individual pile strikes for Bridge 140, Pile 2

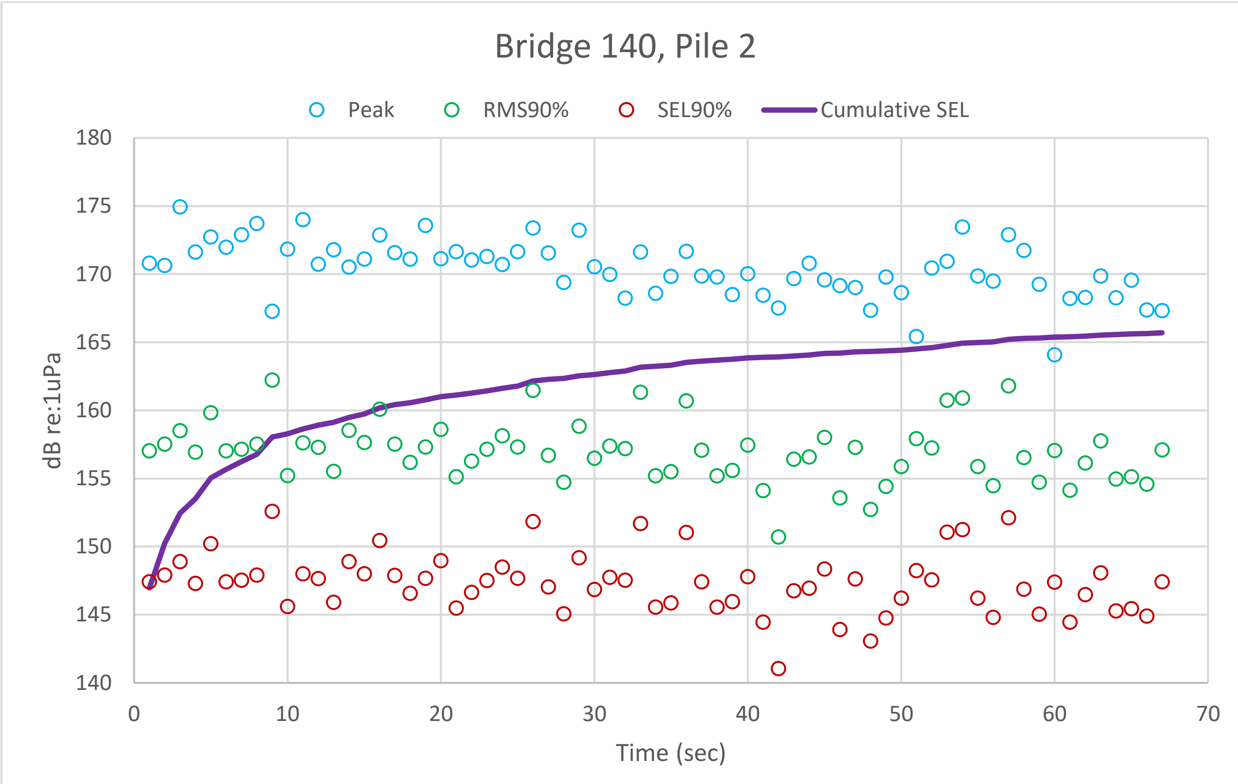


Figure 9: Power Spectral Density Plot for Bridge 140, Pile 2

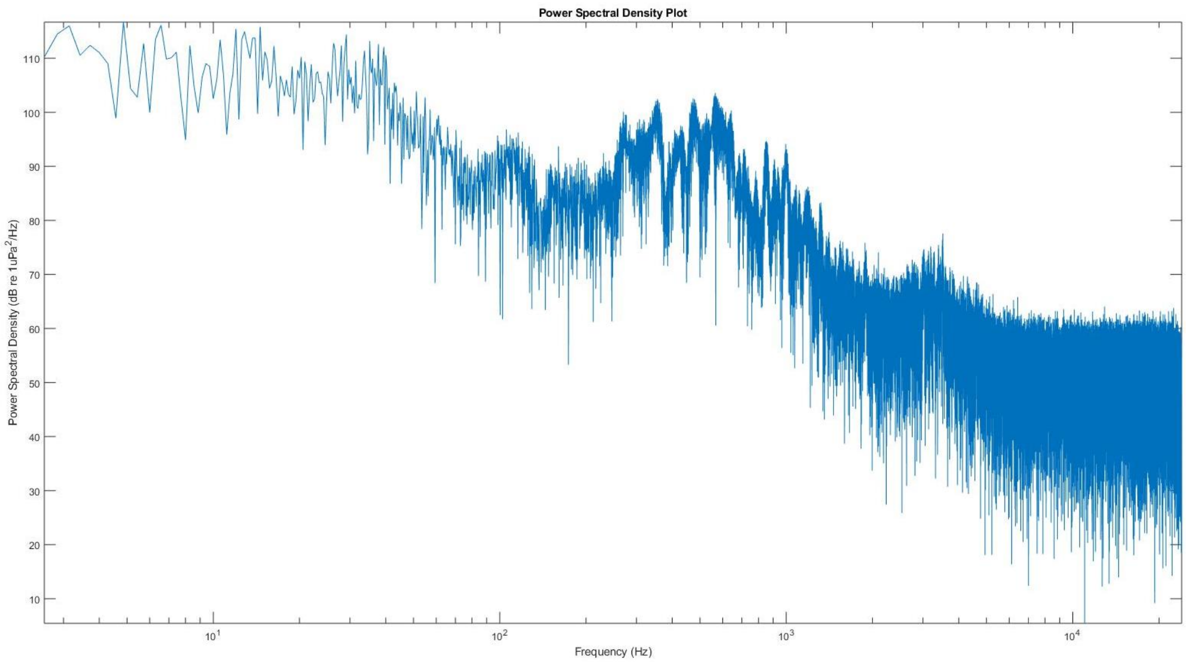
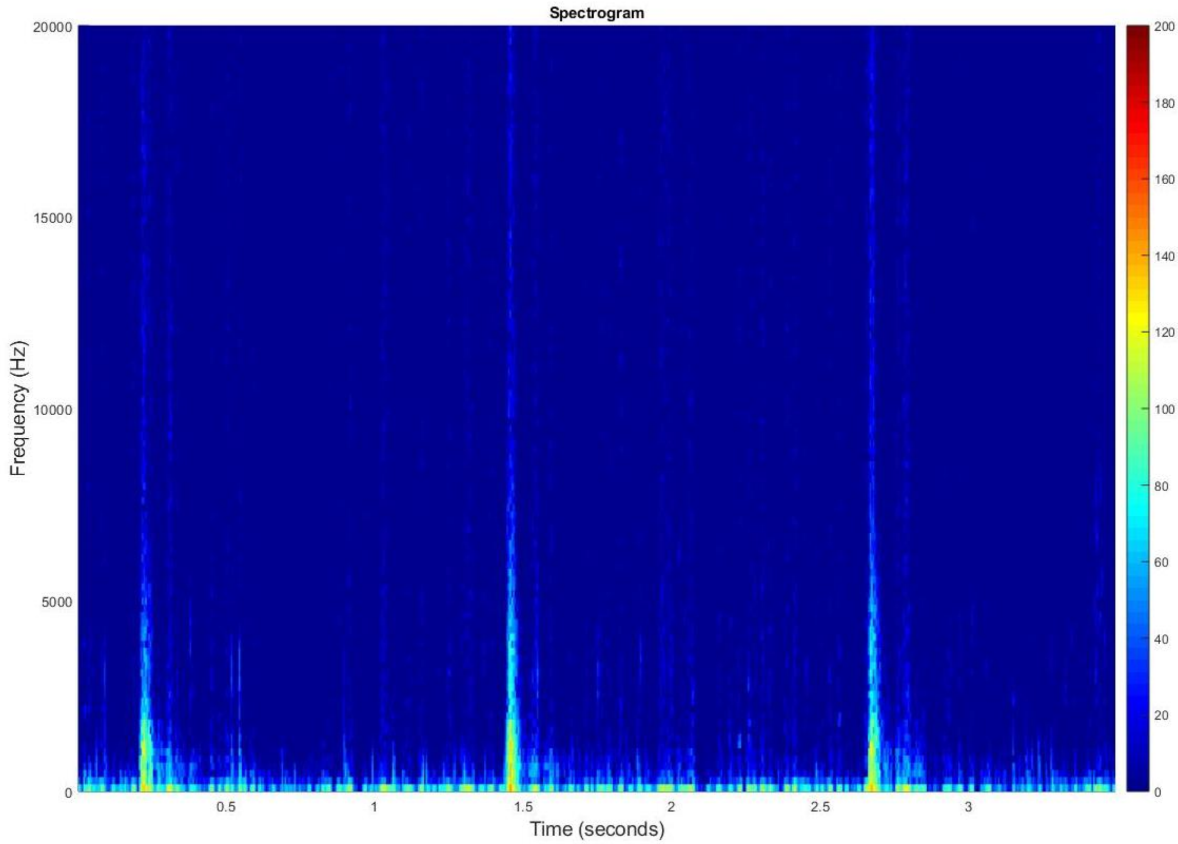


Figure 10: Spectrogram Plot for Bridge 140, Pile 2



Bridge 154, Pile 1

Pile 1 at this second site is located approximately 10 feet from the shoreline on the west side of the Yakima River as it passes under I-90 in approximately 3 feet of water. The results for Pile 1 at this site are in Table 4. Pile 1 did not exceed the dual interim thresholds for fish for either the peak or cSEL.

Figures 11, 12 and 13 show the time history plot, the PSD plot and the spectrogram respectively. The time history plots in Figure 11 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 11:   Time history plot of individual pile strikes for Bridge 154, Pile 1

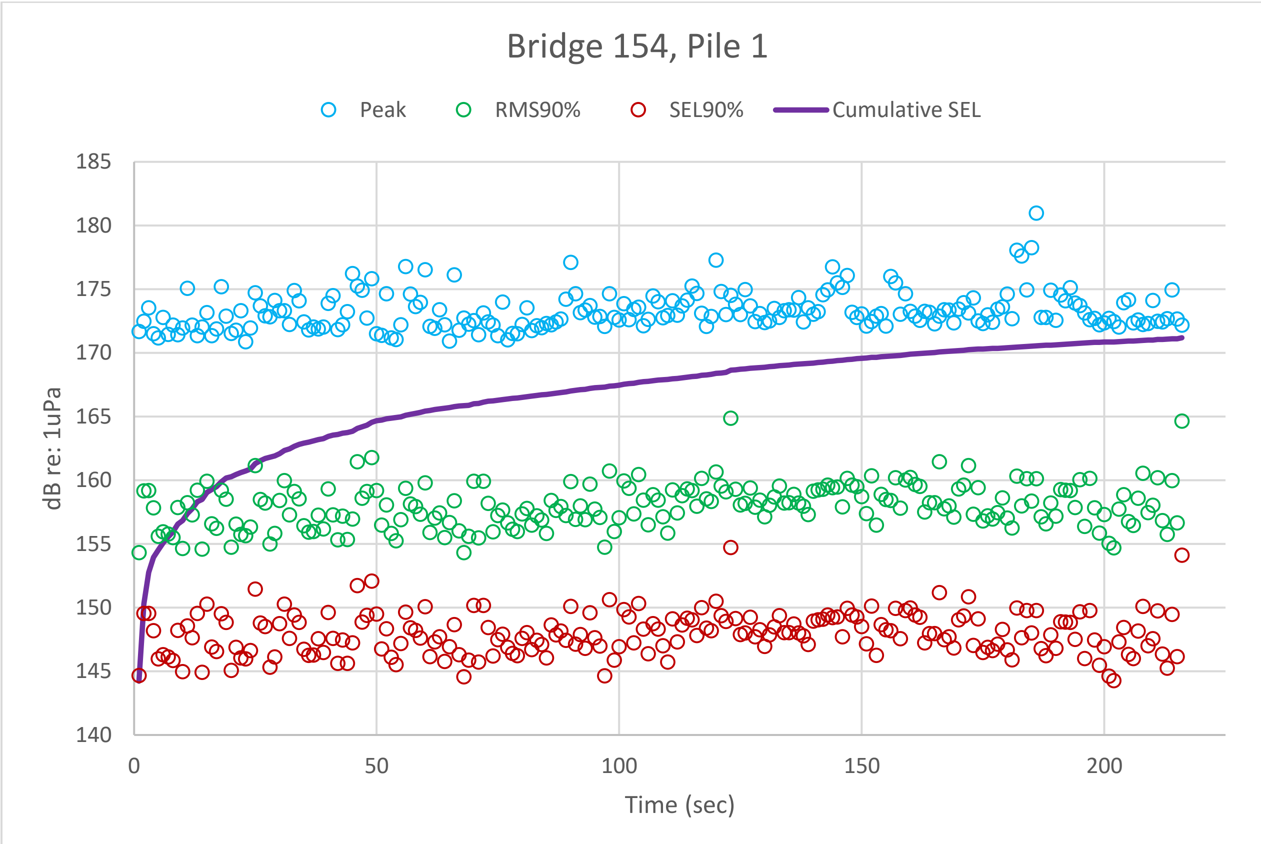


Figure 12:   Power Spectral Density Plot for Bridge 154, Pile 1

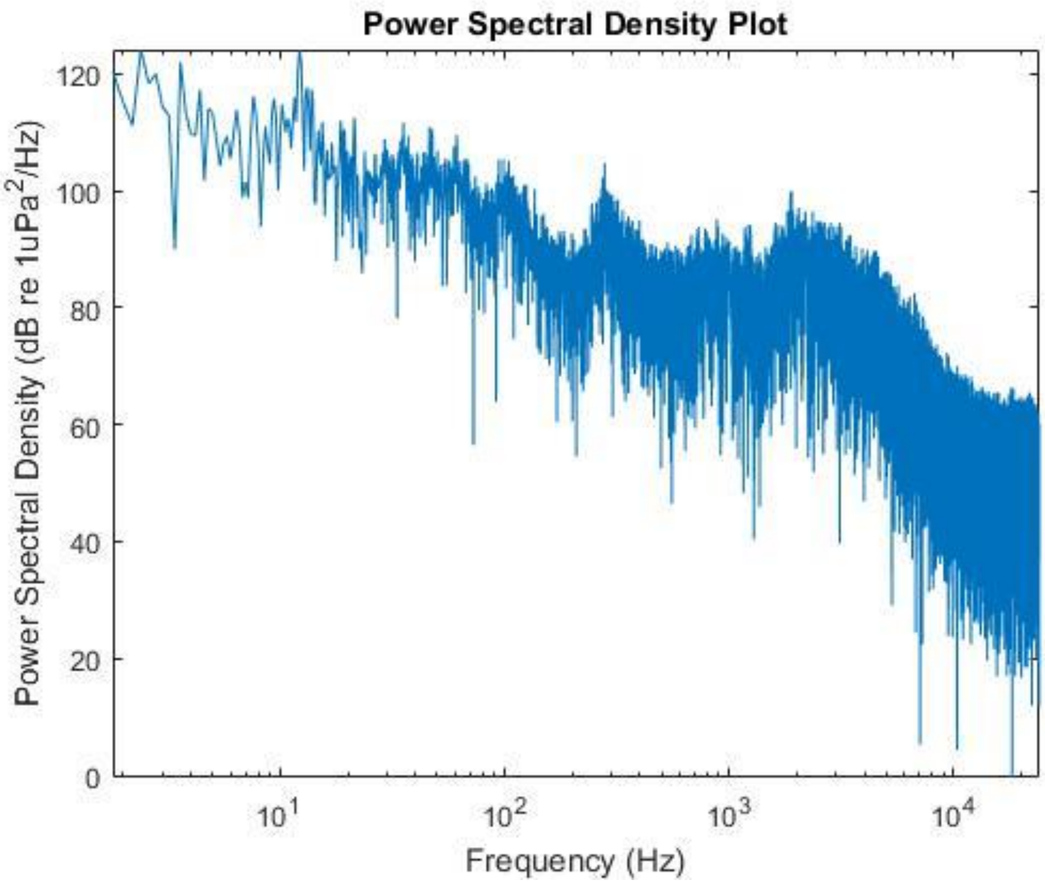
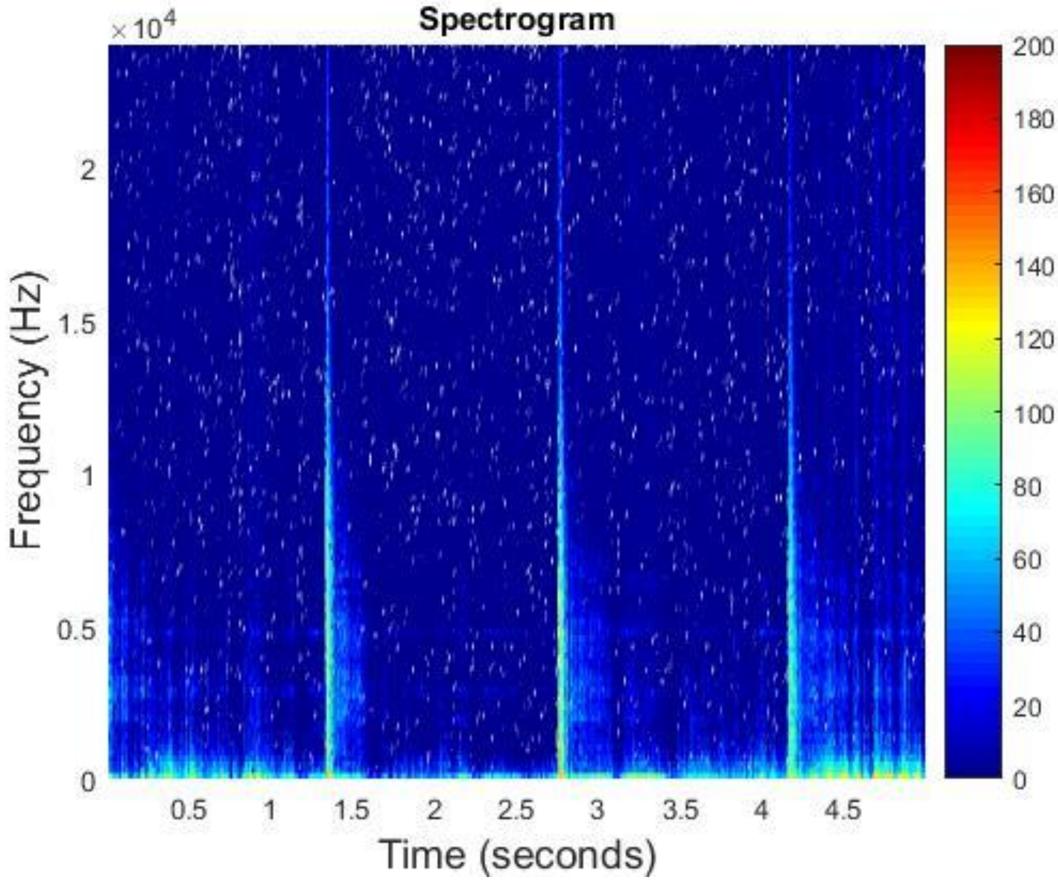


Figure 13: Spectrogram Plot for Bridge 154, Pile 1



Pile 1 for this site did not exceed the dual interim thresholds for fish for either the peak or cSEL.

Bridge 154, Pile 2

Pile 2 at this site is located approximately 10 feet south of Pile 1. The results for Pile 2 can be found in Table 4. Pile 2 has exceeded the dual interim thresholds for fish for both the peak and the cSEL. This was likely due to the bubble curtain not being deployed in a manner that completely covers the pile and may not have been seated properly on the bottom. Figure 14 shows the time history plot of the entire pile driving event and indicates that the noise levels were relatively consistent among pile strikes with relatively little variability. Figure 15 shows how the bubble curtain was improperly deployed during pile driving.

Figure 14: Time history plot of individual pile strikes for Bridge 154, Pile 2

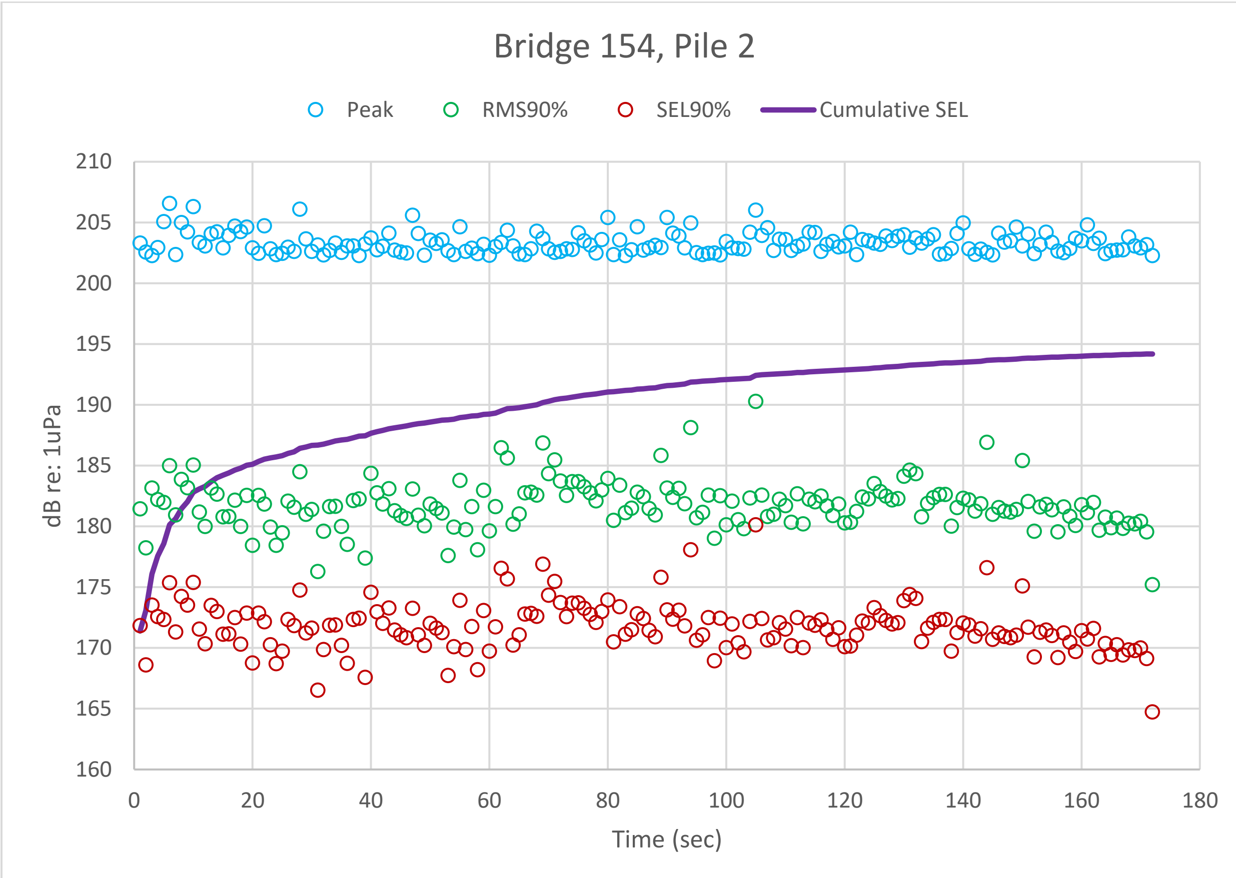


Figure 15: Photo of Deployment of Bubble Curtain Around Piles 2 and 3, Bridge 154.

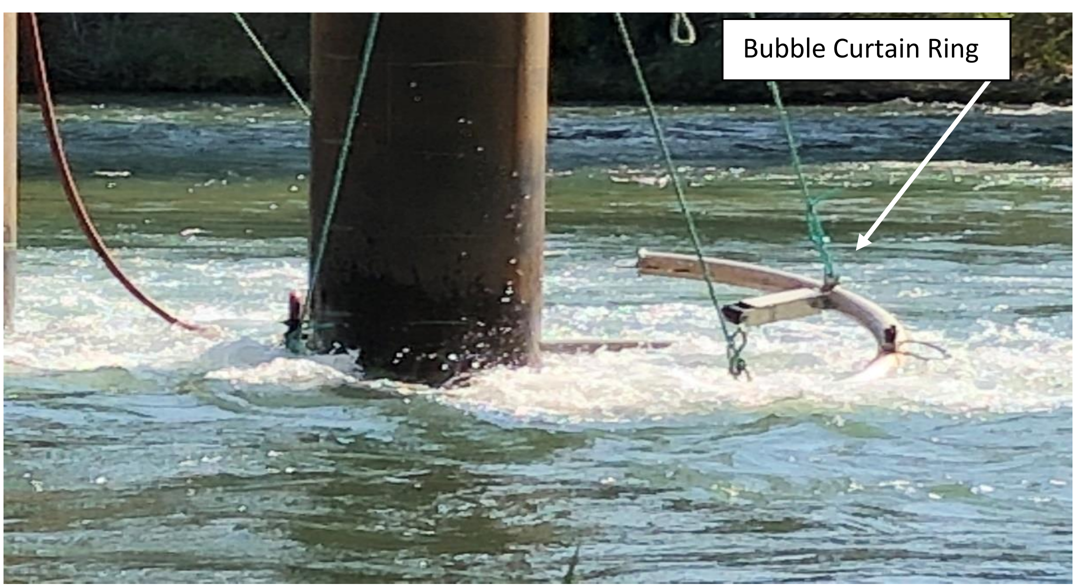


Figure 16 shows the frequency distribution of the peak pile strike and two adjacent pile strikes. There was a dominant frequency at approximately 300 Hz which is more pronounced than the same frequency for the other piles where the bubble curtain was properly deployed.

Figure 16: Power Spectral Density Plot for Bridge 154, Pile 2

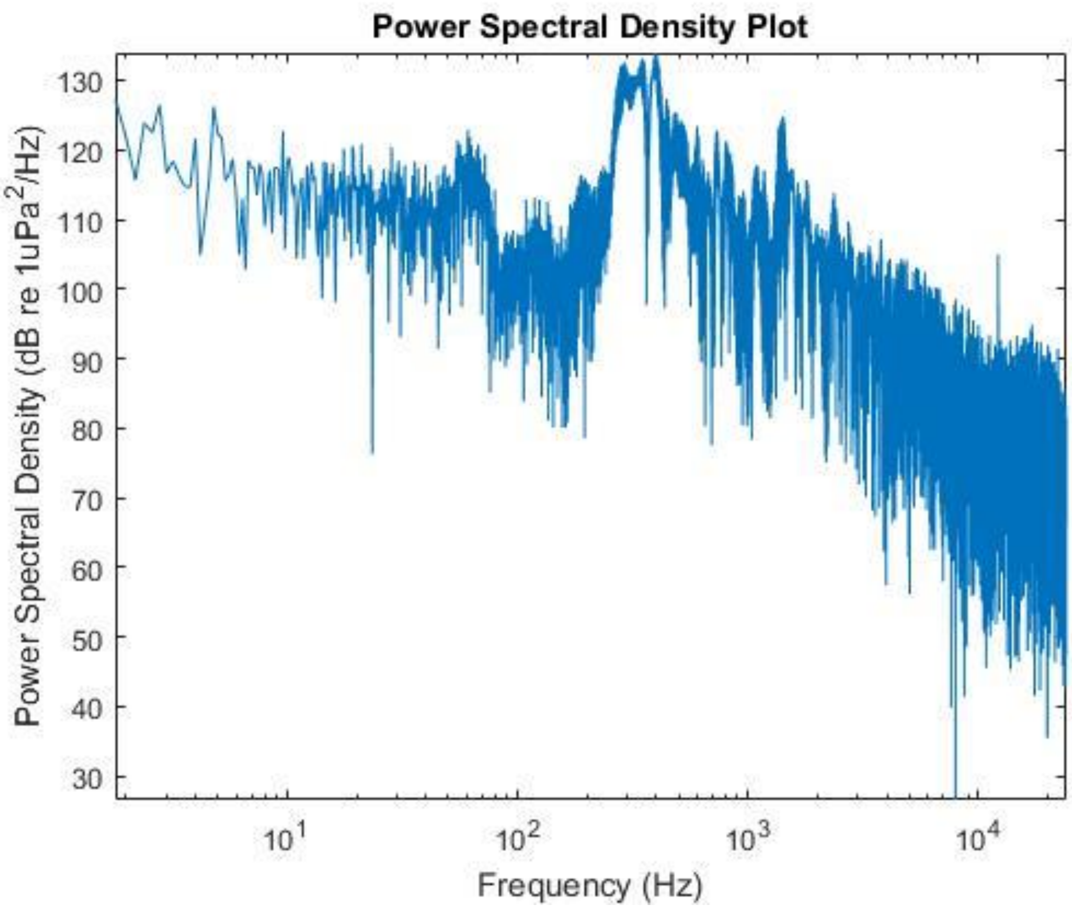
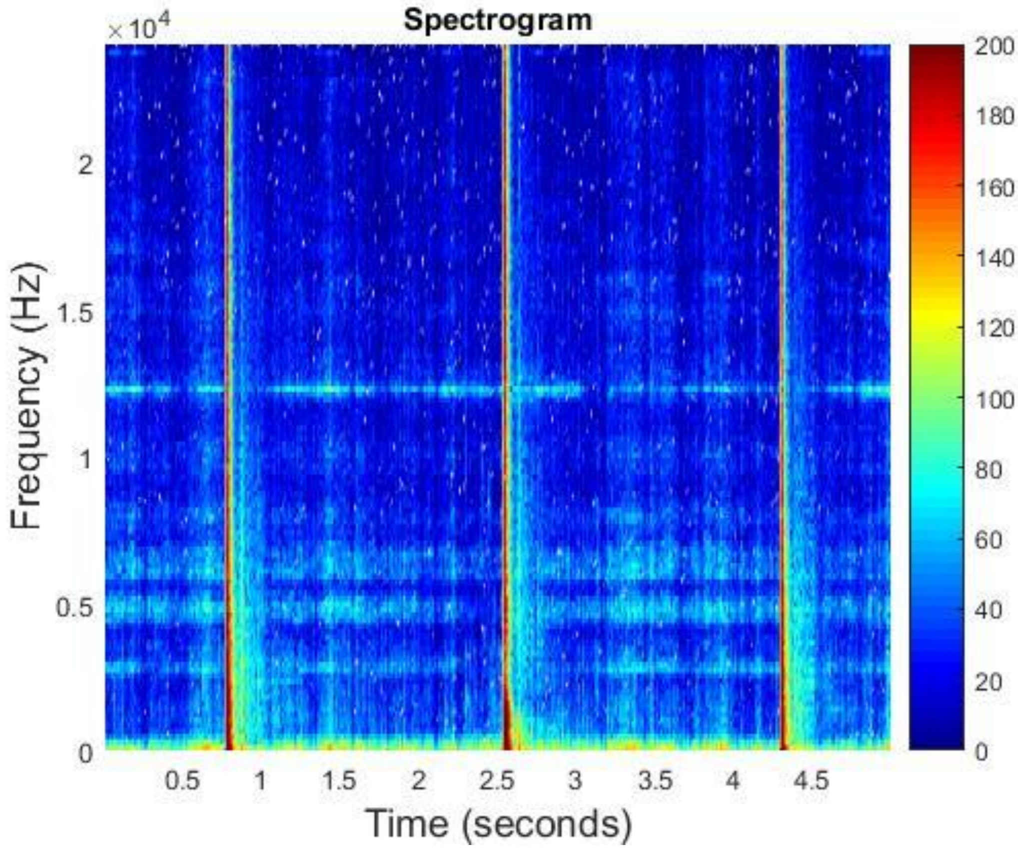


Figure 17 shows the Spectrogram plot for Pile 2. The spectrogram shows that there is substantially more energy (red color) in the pile strikes for this pile due to the improper deployment of the bubble curtain.

Figure 17: Spectrogram Plot for Bridge 154, Pile 2



Bridge 154, Pile 3

Pile 3 at this site is located approximately 10 feet south of Pile 2. The results for Pile 3 can be found in Table 4. Pile 3 has exceeded the dual interim thresholds for fish for both the peak and the cSEL. This was likely due to the bubble curtain not being deployed in a manner that completely covers the pile and may not have been seated properly on the bottom. Figure 18 shows the time history plot of the peak, RMS90% and SEL90% including the cumulative SEL plot over the entire pile drive. The time history plot shows that the pile strikes were relatively consistent over time. Figure 15 shows an example of how the bubble curtain was deployed for this pile.

Figure 18: Time history plot of individual pile strikes for Bridge 154, Pile 3

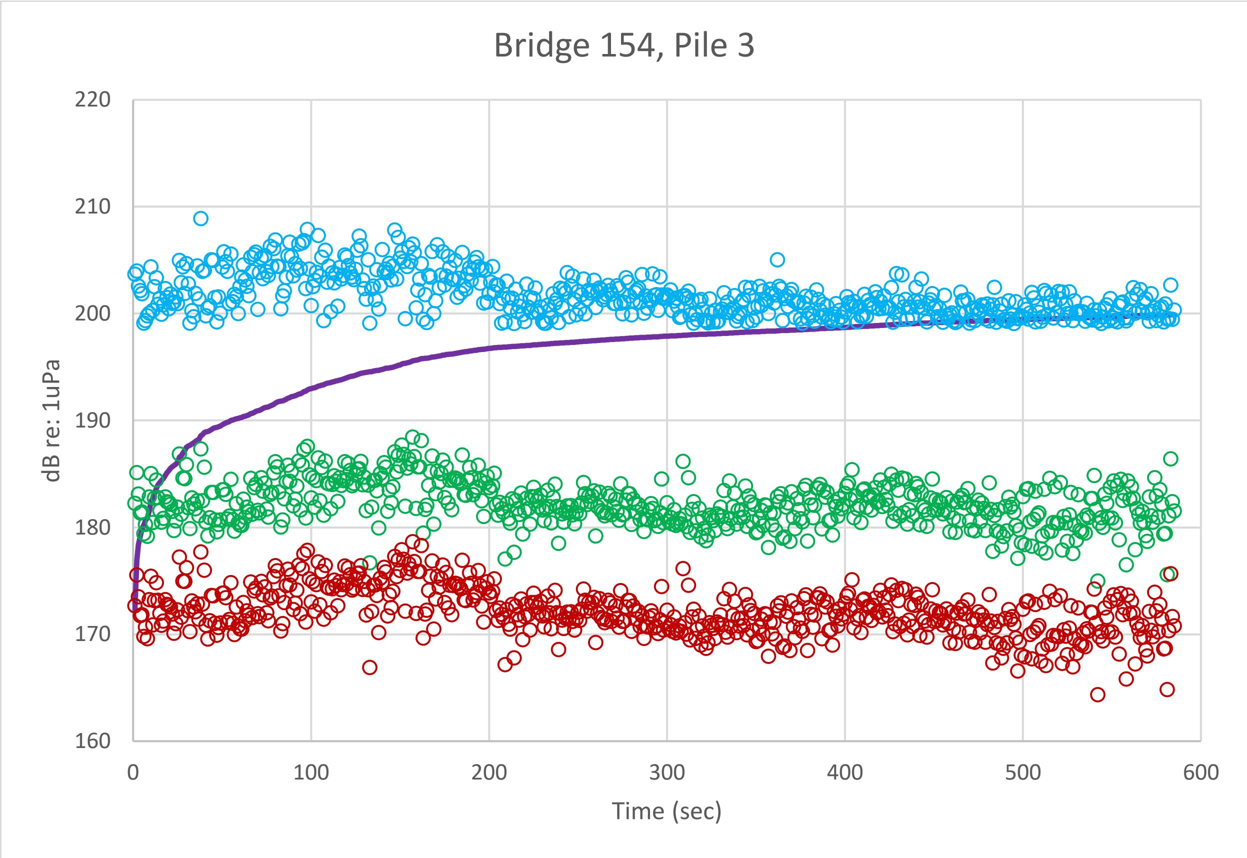


Figure 19 shows the frequency distribution of the peak pile strike and two adjacent pile strikes. There is a general increase in frequencies between approximately 300 Hz and 1000 Hz which is more pronounced than the same frequency range for the other piles where the bubble curtain was properly deployed.

Figure 19: Power Spectral Density Plot for Bridge 154, Pile 3

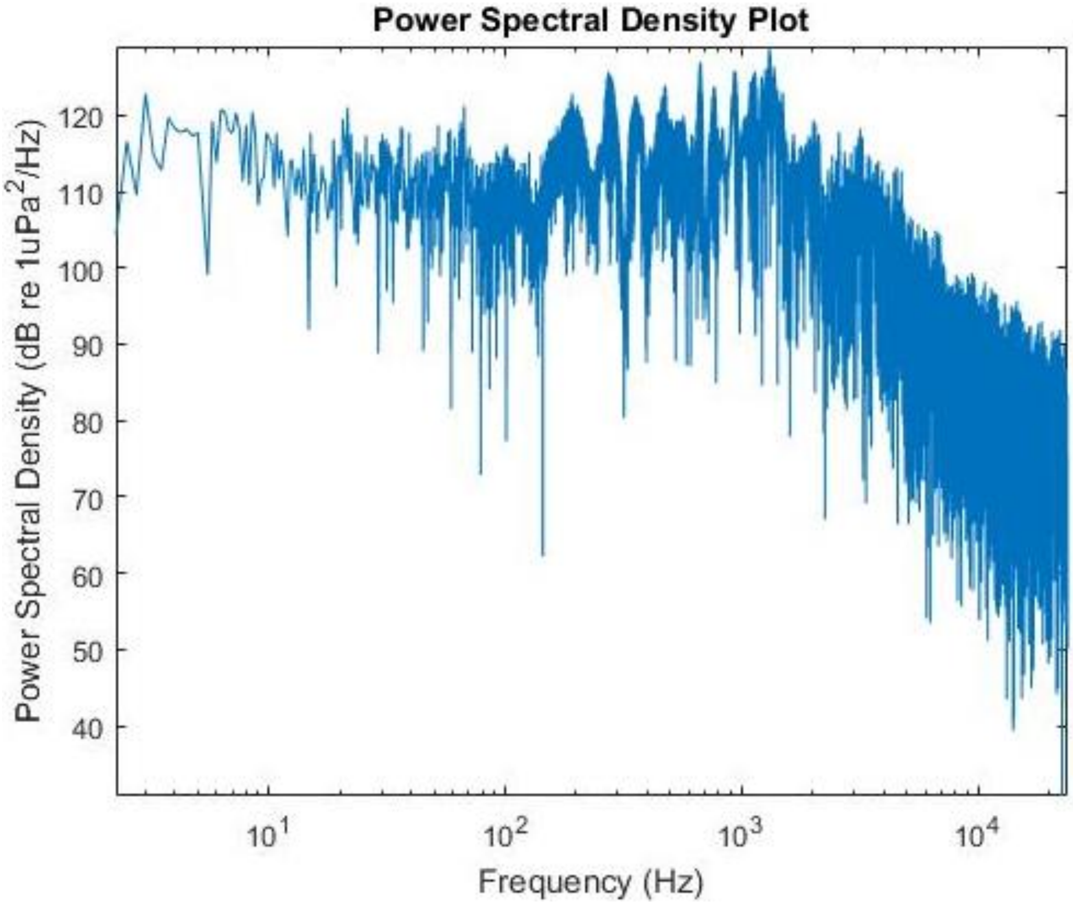
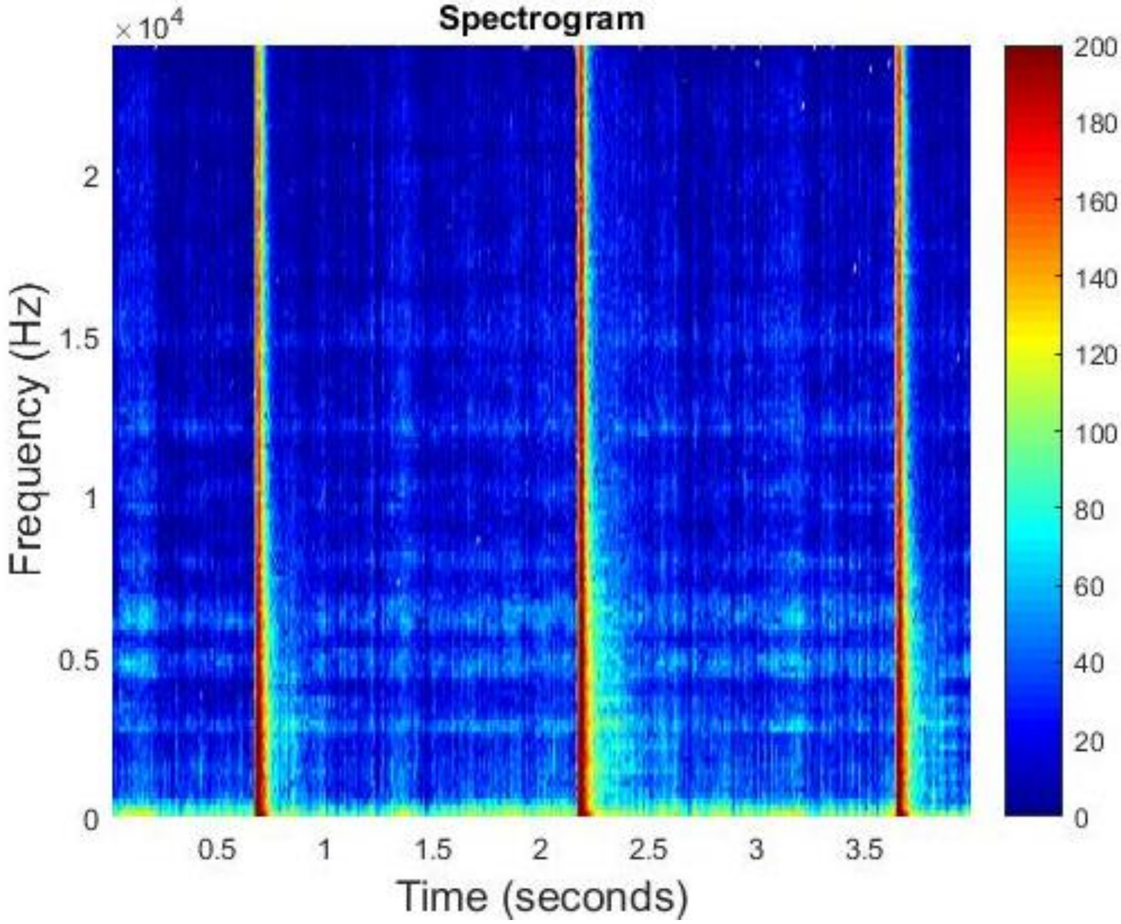


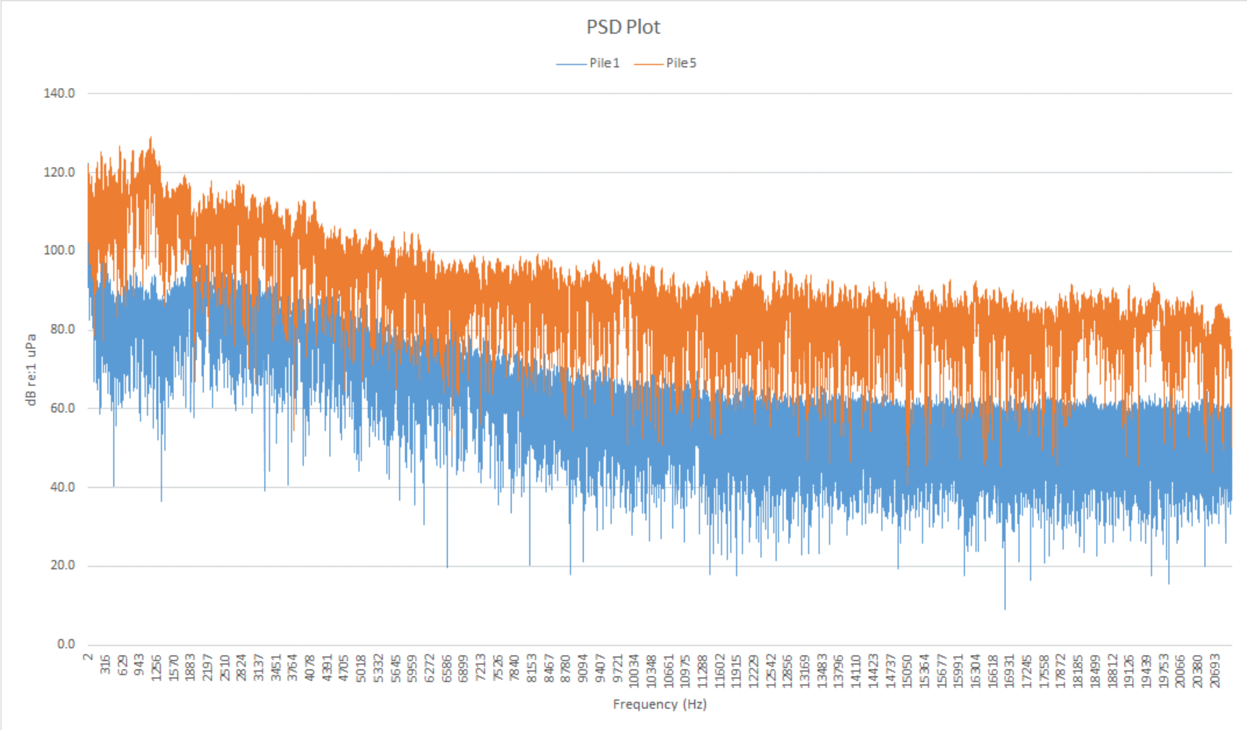
Figure 20 shows the spectrogram plot for Pile 2. The spectrogram shows that there is substantially more energy (red color) in the pile strikes for this pile at most of the frequencies due to the improper deployment of the bubble curtain.

Figure 20: Spectrogram Plot for Bridge 154, Pile 2



When the PSD plots for Bridge 154, Pile 1, which had the bubble curtain deployed correctly, and Pile 3 which had an improper deployment (Figure 15), are overlaid on the same plot you can see that there is substantially more energy in the Pile 3 plot than there is for Pile 1 at all frequencies (Figure 21). This indicates that the bubble curtain on Pile 3 was not having any effect on reducing the underwater noise levels.

Figure 21: Combined PSD Plots for Pile 1 (blue, with bubble curtain) and Pile 3 (red, insufficient bubble curtain)



Tables 4 and 5 summarize the results of underwater noise monitoring at Bridges 140 and 154 respectively.

Table 4: Summary of Underwater Attenuated Sound Levels for 30-in Piles at Bridge 140

Pile #	Date & Time	Hydro-phone Depth (feet)	Total Number Of Strikes	Absolute Highest Peak (dB)	Peak L_{50} (dB)	$RMS_{90\%}$ L_{50} (dB)	Single Strike $SEL_{90\%}$ (dB)	cSEL (dB)
1	7/30/18 12:47 PM	1.5	590	177	173	160	150	176
2	7/30/18 12:57 AM	1.5	204	175	170	157	147	

Table 5: Summary of Underwater Attenuated Sound Levels for 30-in Piles at Bridge 154

Pile #	Date & Time	Hydro-phone Depth (feet)	Total Number Of Strikes	Absolute Highest Peak (dB)	Peak L_{50} (dB)	$RMS_{90\%}$ L_{50} (dB)	Single Strike $SEL_{90\%}$ (dB)	cSEL (dB)
1	8/1/18 8:00 AM	1.5	216	181	173	158	148	169
2	8/4/18 7:41 AM	1.5	172	207	203	182	172	194
3	8/4/18 10:46 AM	1.5	585	209	201	182	172	

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 6).

Table 6: Summary of daily broadband cumulative SEL's

Day	Daily cSEL (dB)	Distance (m)
7/30/2018	176	10
8/1/2018	169	10
8/4/2018	194	10

6.3 Calculated Attenuation Distance to Thresholds

Because the last two piles impacted at Bridge 154 exceeded the dual interim thresholds for fish the distance from the piles to where the sound levels attenuated to the thresholds were calculated using the following formula.

$$R_1 = R_2 * 10^{((\text{source} - \text{threshold})/15)}$$

Where R_1 is the distance at which the threshold is achieved and R_2 is the measured source distance from the pile. Table 7 shows the peak and cSEL source levels and distances to where they attenuate to the interim thresholds. The attenuation distance for the peak threshold of 206 dB is between 12 and 16 meters (39 and 52 feet) both upstream and downstream and east across the river channel. The attenuation distance for the cSEL threshold of 187 dB is 29 meters (95 feet) up and downstream and across the river channel.

Table 7: Calculated distances to interim thresholds

Pile	Peak Source Level (dB)	Attenuation Distance (m)	cSEL Source Level (dB)	Attenuation Distance (m)
Pile 2	207	12	194	29
Pile 3	209	16		

7 SUMMARY

A total of five, 30-inch steel piles were monitored for the I-90 Bridge Deck Rehabilitation project. The underwater sound levels analyzed, produced the following results.

- Peak broadband underwater attenuated sound levels measured at 10 meters varied in a range between 177 dB_{Peak} and 209 dB_{Peak} with the peak L_{50} ranging between 173 dB_{peak} to 203 dB_{peak}.
- The measured $RMS_{90\%}$ L_{50} levels ranged between 158 $dB_{RMS90\%}$ and 182 $dB_{RMS90\%}$.
- Cumulative Sound Exposure Levels (cSEL) for all piles driven on a particular day, ranged between 169 dB_{cSEL} and 194 dB_{cSEL}.
- For the last two piles monitored at Bridge 154 the sound levels were substantially higher likely due to a bubble curtain that was not deployed properly. Only these last two piles exceeded the interim peak and cumulative SEL thresholds for fish.

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 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, $10\mathrm{Log}_{10}(N)$. 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 $10\mathrm{Log}_{10}$ of the value. This was the cumulative SEL for all of the pile strikes.