I90/Bridge Resurfacing Project

UNDERWATER NOISE MONITORING REPORT

Part 2

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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 four 30-inch steel piles for the Washington State Department of Transportation (WSDOT) at the I-90 Bridge Resurfacing Project, on December 19, 2018. The piles were monitored at Bridge 154 (Table 1). An unconfined bubble curtain was deployed for all piles impact driven to attenuate potential underwater noise effects. Piles were vibed in initially and then impacted during measurements. Measurements were collected at 10 meters from the piles.

The data from two of the piles monitored at Bridge 154 was not saved due to equipment malfunction. None of the piles exceeded the 206 dB_{peak} threshold for fish at the measured distance. The peak attenuated sound levels measured ranged between 191 dB_{peak} and 195 dB_{peak} while monitoring the impact pile driving operation as shown in Table1. The daily Cumulative Sound Exposure Level (cSEL) for all four piles monitored did exceed the threshold of 187 dB_{cSEL} at 10 meters. The distance to the daily cSEL threshold of 187 dB from the 10 meter location is 54 meters (177 feet) both up and downstream.

Table 1: 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)	Daily Cumulative SEL (dB)
1	12/19/18	10	194	179	169	198
2			191	171	162	
3			195	180	170	
4			194	175	166	

1 INTRODUCTION

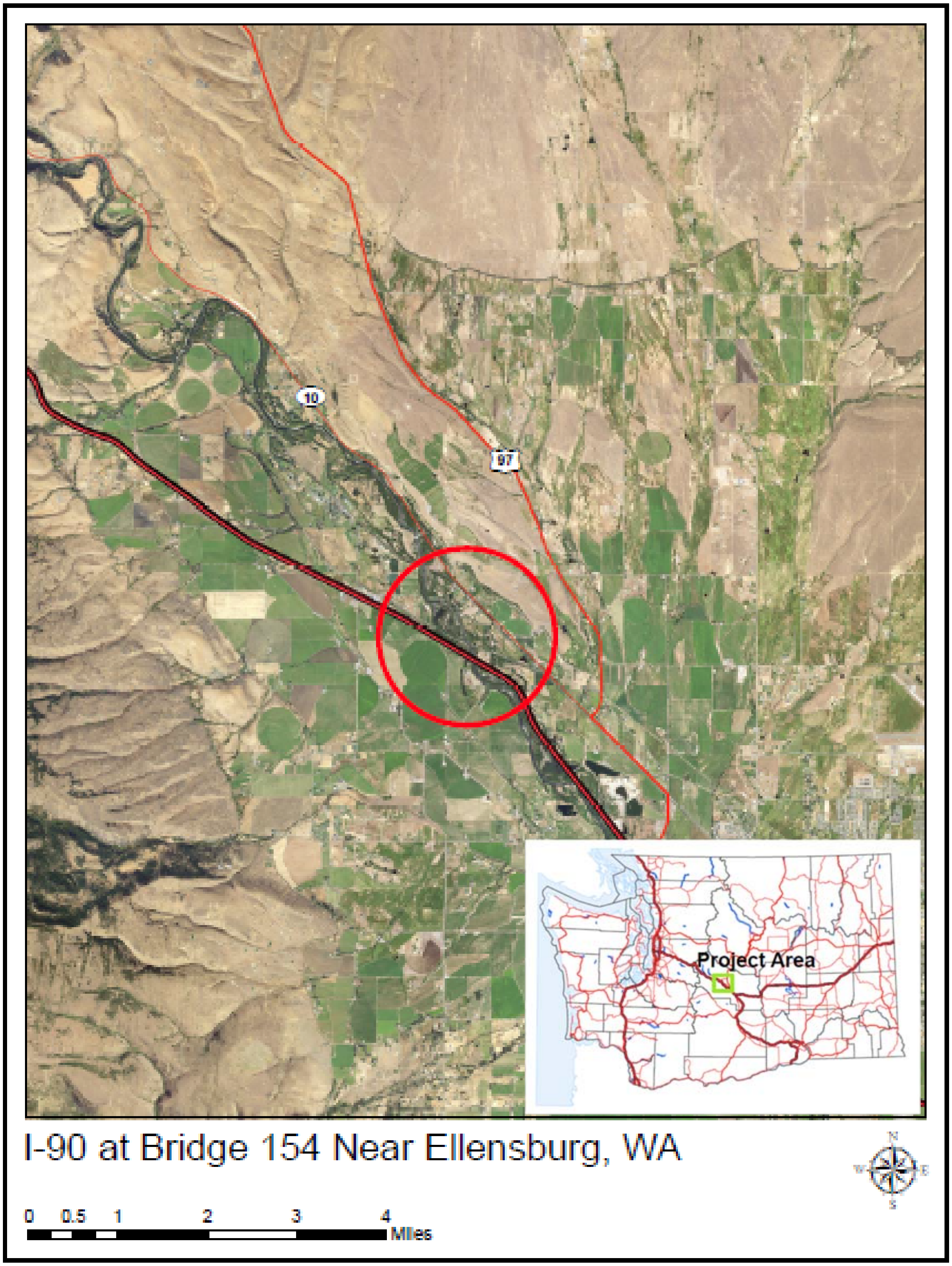
The Washington State Department of Transportation (WSDOT) is rehabilitating the eastbound and westbound bridge decks at two bridges on I-90. One of the two bridge decks on the Yakima River where this monitoring occurred is seven miles west of Ellensburg (Bridge 154). They are showing signs of deterioration. 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 Bridge 154 in an effort to collect site-specific data on underwater noise levels during the month of December 2018. Four 30-inch diameter steel 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.

The results were 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 Bridge 154 near Ellensburg, WA



2 PROJECT AREA

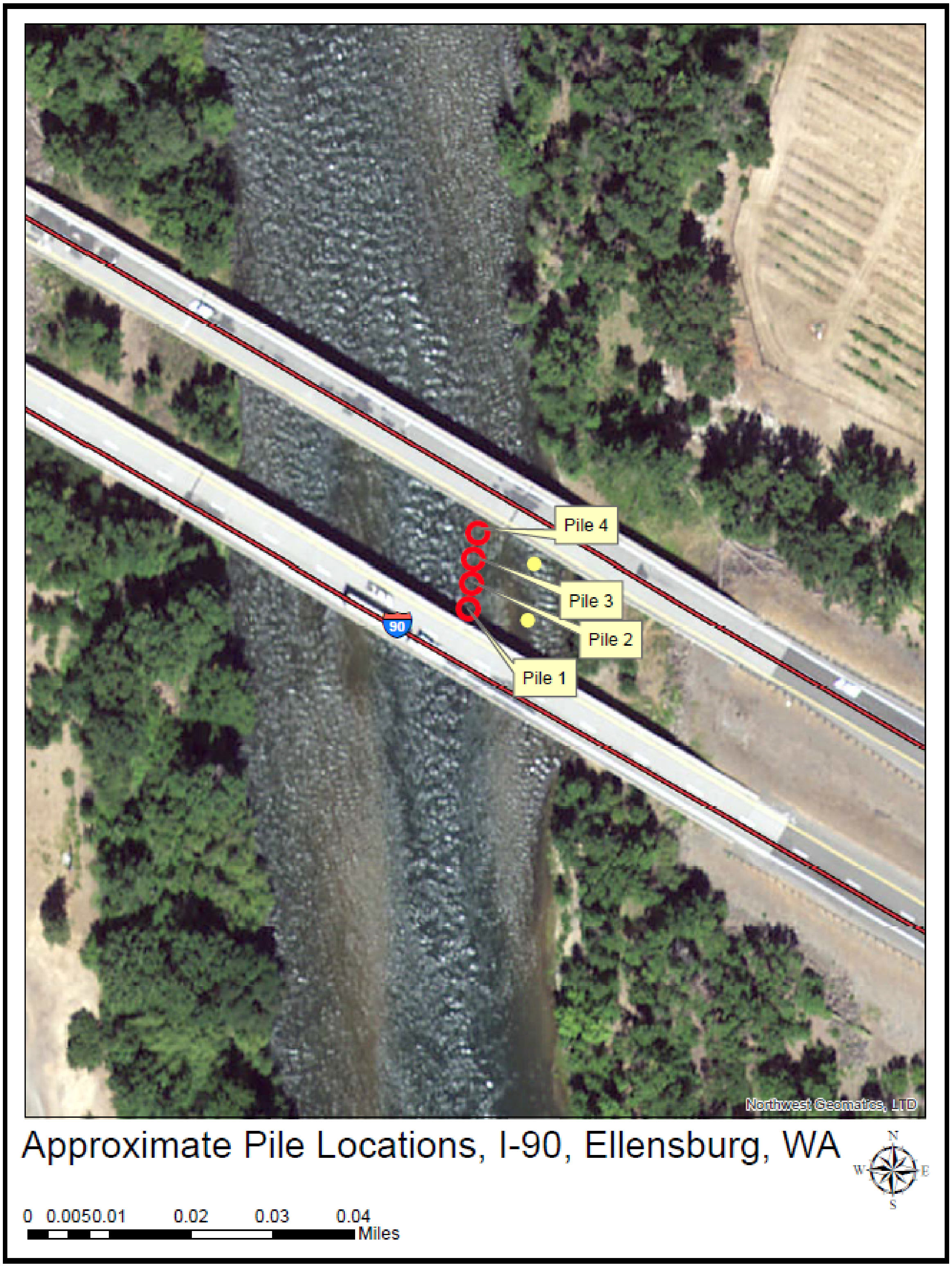
Bridge 154 on the Yakima River is seven miles west of Ellensburg. This project will repair and resurface the existing bridge deck in both the eastbound and westbound lanes, which will extend the life of the bridge for decades to come.

3 PILE INSTALLATION LOCATION

Four 30- inch steel piles installed during impact pile driving activity at the I-90 Bridge 154 were monitored. Figure 2 indicates the approximate location of the 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 through 4 at I-90 Bridge 154 near Ellensburg. Yellow dot is approximate location of the hydrophones



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

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

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.

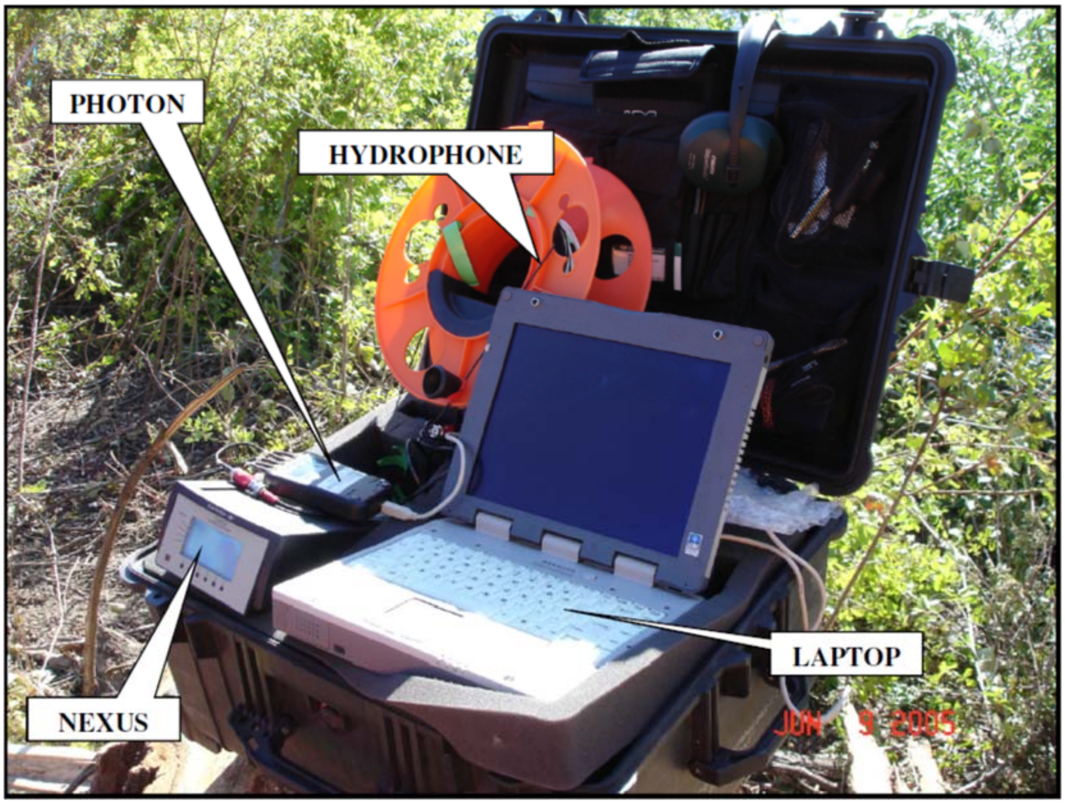
$$cSEL = SEL_{90\%} + 10 \text{ LOG (total number of pile strikes)} \qquad \text{(eq. 3)}$$

5 METHODOLOGY

5.1 TYPICAL EQUIPMENT DEPLOYMENT

The hydrophone was deployed from the shore. The monitoring equipment is outlined below and shown in Figure 3. 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 connected to a chain to reduce line strumming producing pseudonoise and potentially interfering with the measured levels. 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.

Figure 3: Near Field Acoustical Monitoring Equipment



Underwater sound levels were measured near the piles using one Reson TC 4013 hydrophone deployed on a weighted nylon cord. The measurement system includes a Brüel and Kjær Nexus type 2692 4-channel signal conditioner, which kept the high underwater sound levels within the dynamic range of the signal analyzer Figure 3. The output of the Nexus signal conditioner is received by a Brüel and Kjær Photon 4-channel signal spectrum analyzer that is attached to a Dell ATG laptop computer similar to the one shown in Figure 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 $\mu Pa^2 \bullet sec$.

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 applied to this project are shown in Table 2 and are applied to all fish.

Table 2: 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 four 30-inch steel piles struck with an impact hammer in water depths of 3 feet at Bridge 154. The results of two of the piles were not saved due to equipment malfunction. Data from all piles analyzed in the paragraphs below are also summarized in Table 3.

Bridge 154, Pile 1

Pile 1 at Bridge 154 is located approximately 50 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). The recording for Pile 1 was not saved due to equipment malfunction, however the peak absolute value and total number of strikes was recorded 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. The n the cSEL can be estimated by adding 10*LOG(total number of strikes) to the single strike SEL estimate. The estimated results for Pile 1 can be found in Table 3. Pile 1 has not exceeded the interim peak threshold for fish but did exceed the interim threshold for cSEL at 195 dB_{cSEL}. The distance to the 187 dB threshold from the 10 meter location is 34 meters (112 feet) both up and downstream.

Bridge 154, Pile 2

Pile 2 is located approximately 50 feet from the shoreline and approximately 10 feet southwest of Pile 1 (Figure 2). The results for Pile 2 are in Table 3. Pile 2 did not exceeded the dual interim threshold for fish for either the peak or cSEL.

Figures 4, 5 and 6 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 with a slight increase towards the middle of the drive and then a gradual and slight decrease towards the end of the drive. The measured values indicate that the bubble curtain was performing normally with estimated sound level reductions of approximately 12 dB to 13 dB range. 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 4: Time history plot of individual pile strikes for Bridge 154, Pile 2

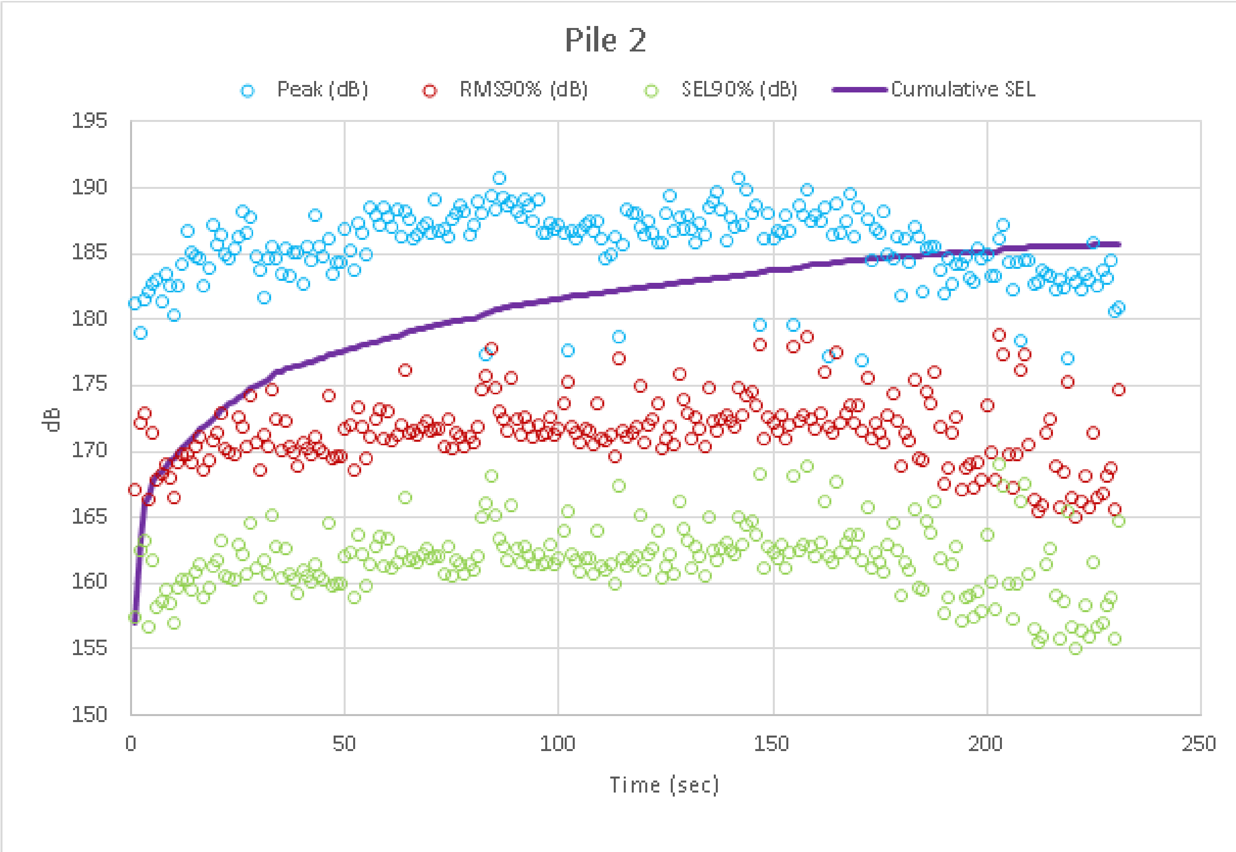


Figure 5: Power Spectral Density Plot for Bridge 154, Pile 2

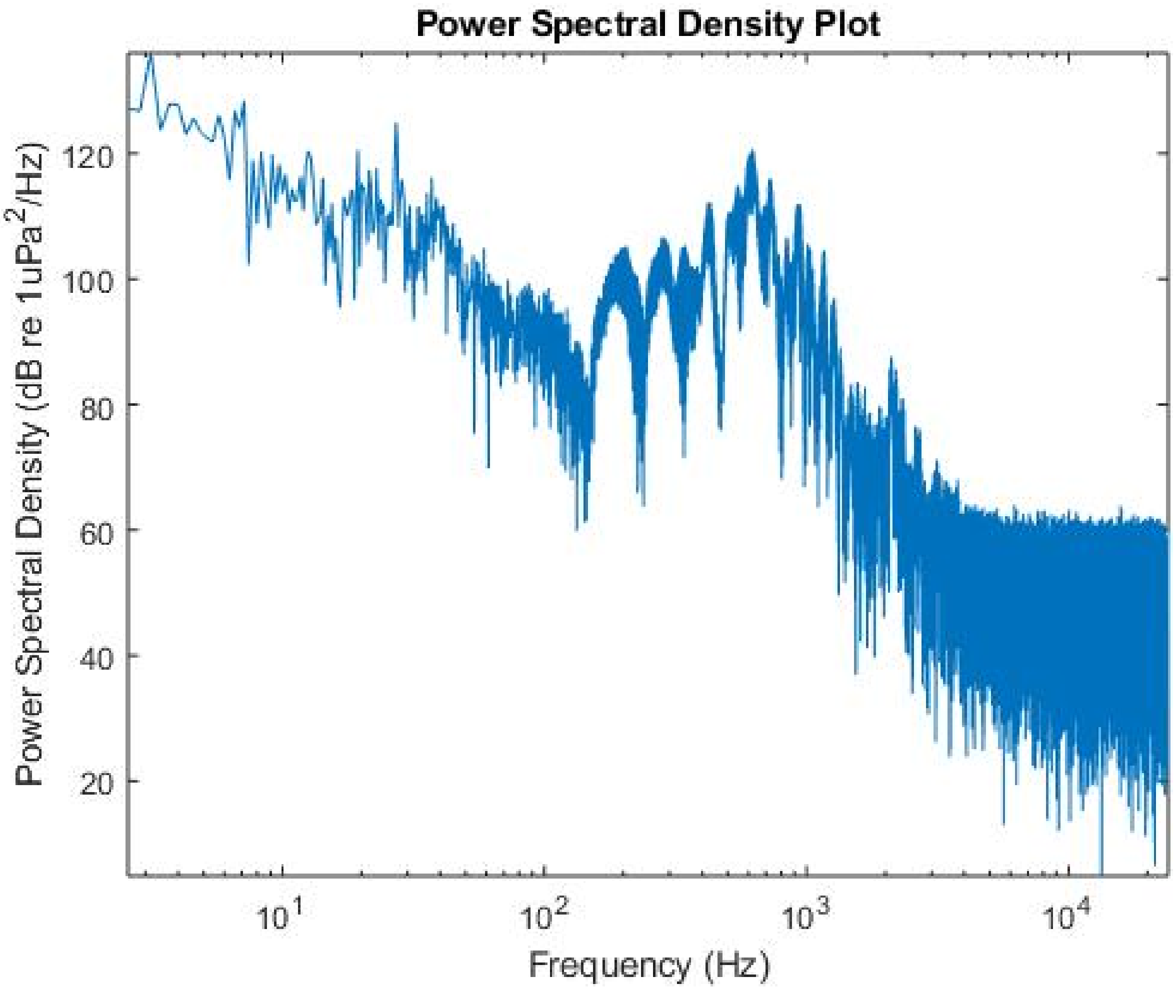
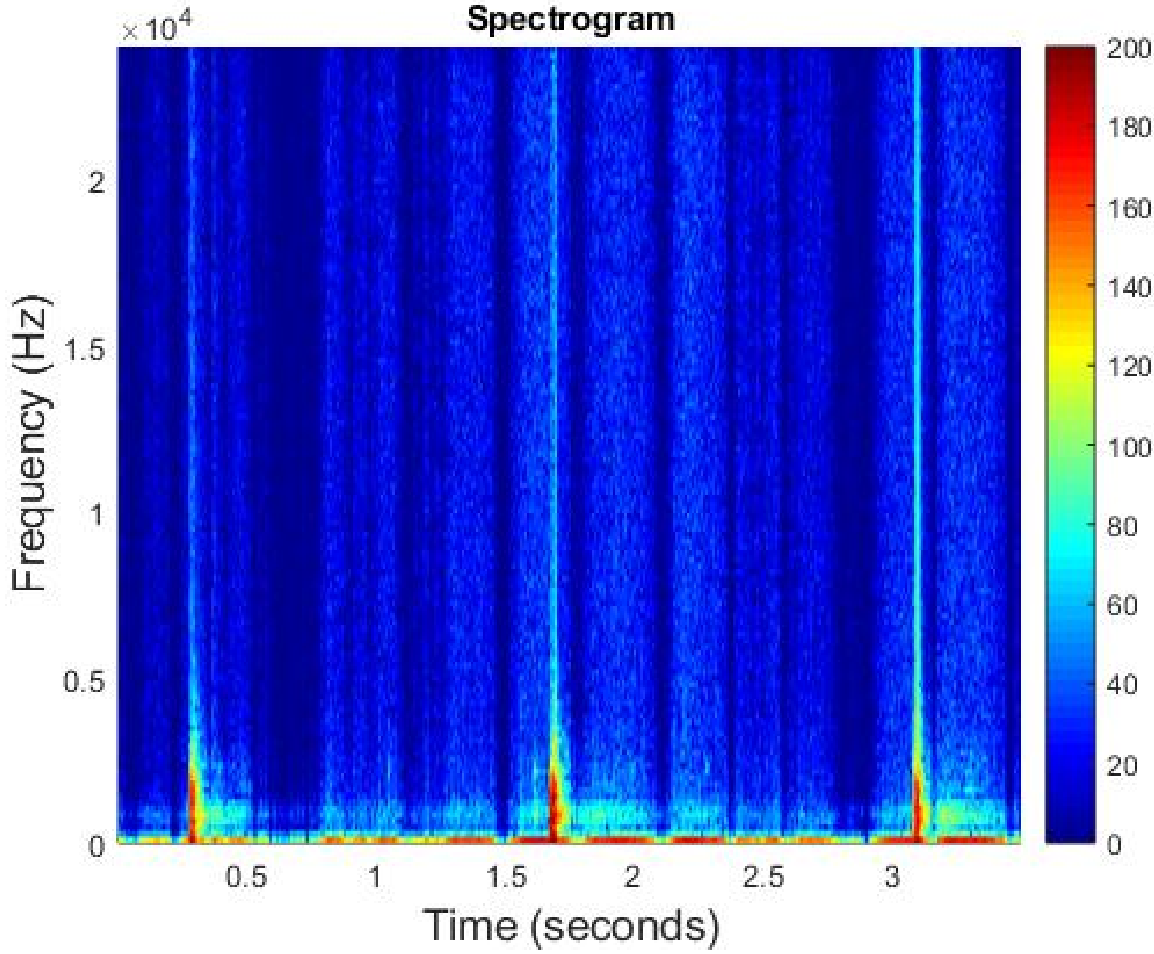


Figure 6: Spectrogram Plot for Bridge 154, Pile 2



Bridge 154, Pile 3

Pile 3 is located approximately 50 feet from the shoreline on the west side of the Yakima River as it passes under I-90 in approximately 3 feet of water and approximately 10 feet southwest of Pile 2. The recording for Pile 3 was not able to be 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 1 above. The estimated results for Pile 3 can be found in Table 3. Pile 3 did not exceed the interim peak threshold for fish but did exceed the cSEL interim threshold at 194 dB_{cSEL}. The distance to the 187 dB_{cSEL} threshold from the 10 meter location is 29 meters (95 feet).

Bridge 154, Pile 4

Pile 4 at this site is located approximately 50 feet from the shoreline in 3 feet of water and 10 feet southwest of Pile 3. The results for Pile 4 can be found in Table 3. Due to equipment malfunction the first half of the drive was not recorded, however, the remaining portion of the pile drive is representative of the entire pile drive. Figure 7 shows the time history plot of the recorded portion of the pile driving event and indicates that the noise levels were relatively consistent among pile strikes with relatively little variability for the peak, RMS90% and SEL 90%. Pile 4 has not exceeded the dual interim thresholds for fish for both the peak and the cSEL.

Figure 7: Time history plot of individual pile strikes for Bridge 154, Pile 4

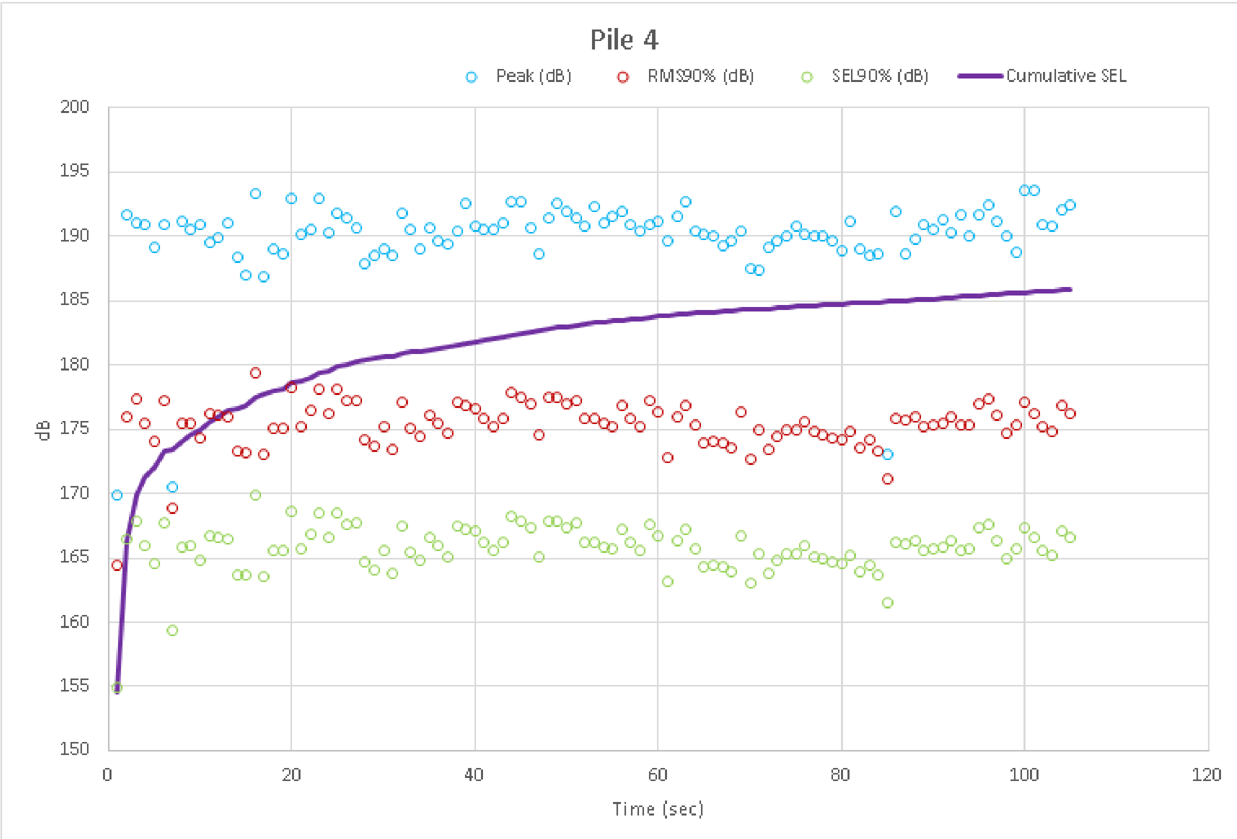


Figure 8 shows the frequency distribution of the peak pile strike and two adjacent pile strikes. There was a dominant frequency at approximately 600 Hz which is within the appropriate range for impact pile driving.

Figure 8: Power Spectral Density Plot for Bridge 154, Pile 4

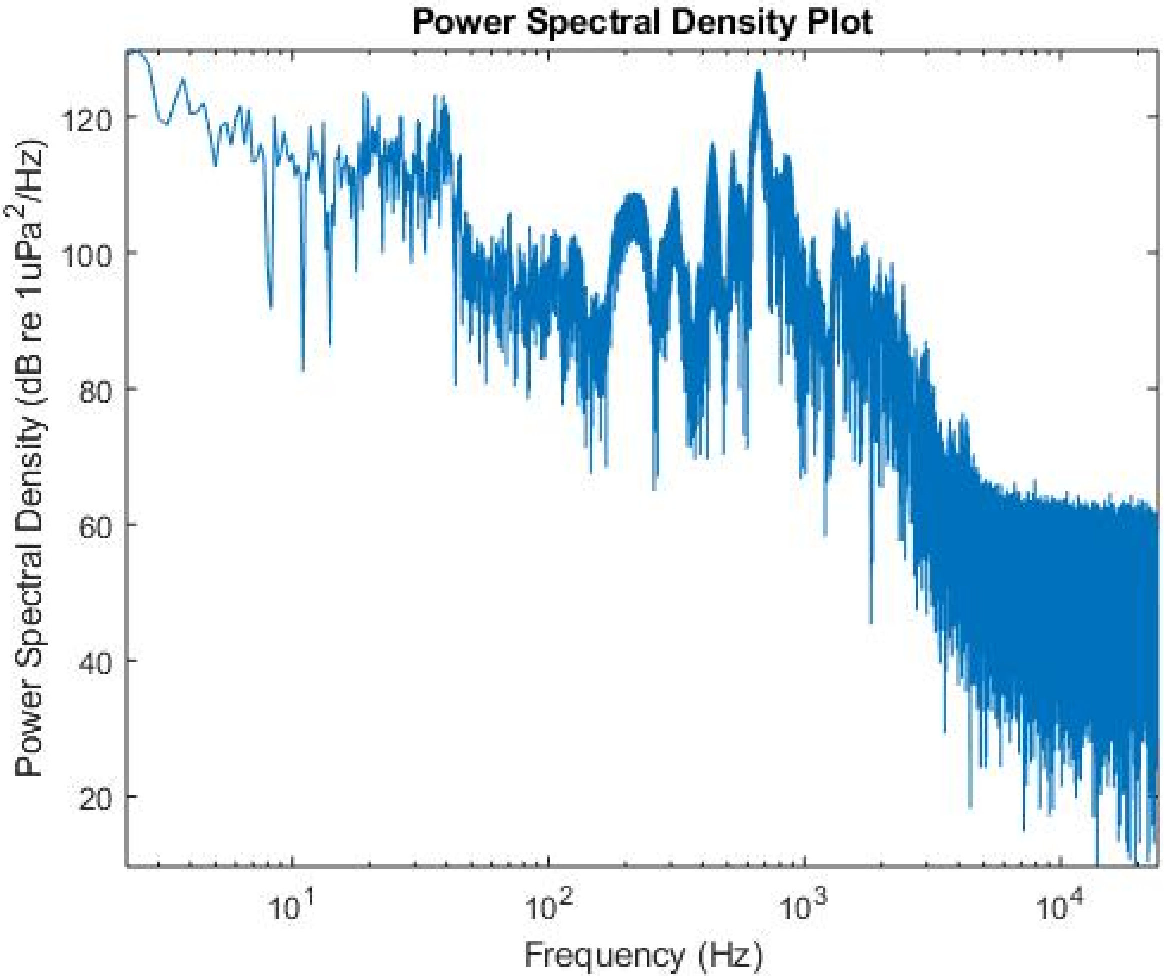
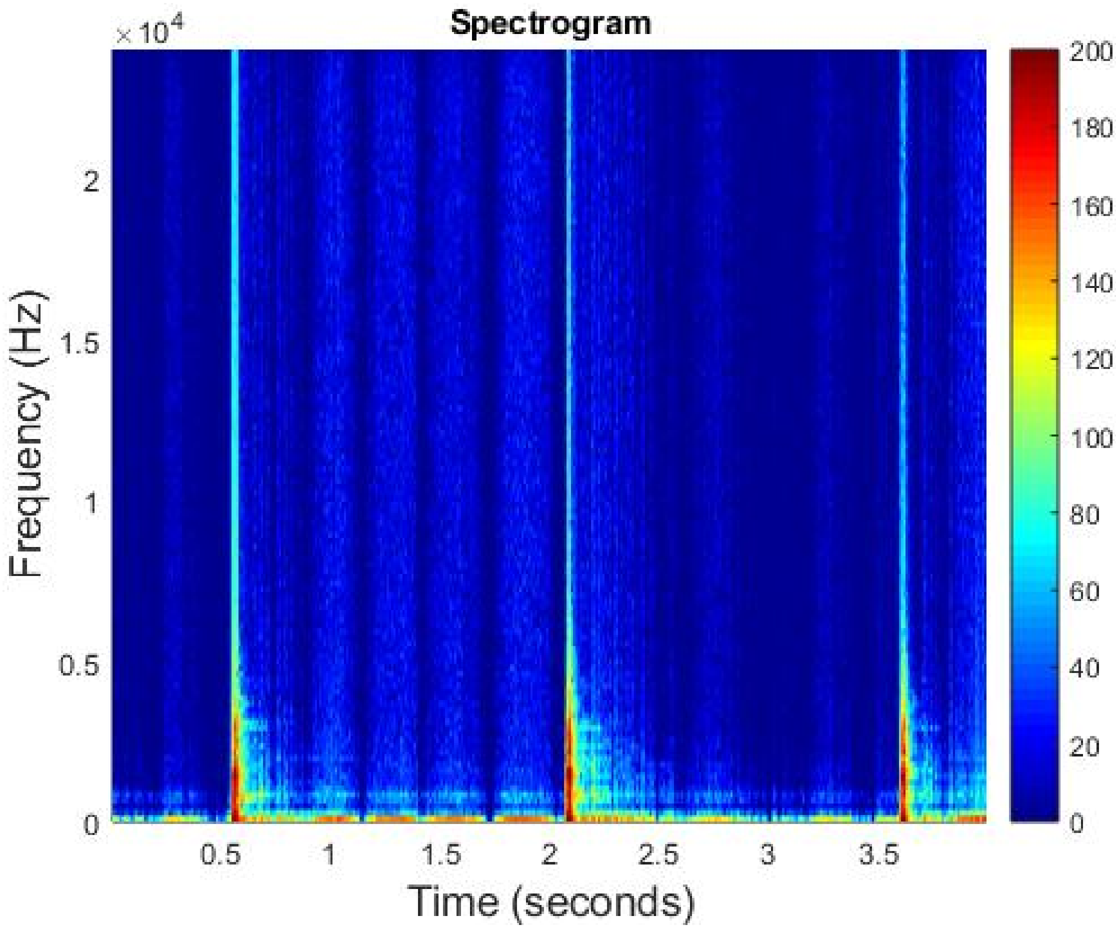


Figure 9 shows the Spectrogram plot for Pile 4. The spectrogram shows that there is substantially more energy (red color) in the pile strikes for this pile below approximately 250 Hz. It appears that the bubble curtain was performing normally for this pile with estimated noise reductions in the range of about 12 dB to 13 dB.

Figure 9: Spectrogram Plot for Bridge 154, Pile 4



Tables 3 and 4 summarize the results of underwater noise monitoring at Bridge 154.

Table 3: 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	12/19/18 1:45 PM	1.5	360	194	-	179*	169*	195
2	12/19/18 2:10 PM		231	191	186	171	162	186
3	12/19/18 2:38 PM		224	195	-	180*	170*	194
4	12/19/18 2:54 PM		230	194	191	175	166	186

*-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

Since all four piles were impact driven on the same day the daily cSEL's were calculated using an actual $SEL_{90\%}$ for each individual pile strike for Piles 2 and 4. Then the estimated cSEL for Piles 1 and 3 were estimated using 10*LOG(number of strikes) and logarithmically added to the cSEL value for Piles 2 and 4 to get an estimated daily cSEL of 198 dB_{cSEL}. The distance from the 10 meter measurement location to the daily cSEL to the interim cSEL threshold of 187 dB_{cSEL} is 54 meters (177 feet).

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7 SUMMARY

A total of four, 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 slightly in a range between 191 dB_{Peak} and 195 dB_{Peak} with the peak L_{50} ranging between 186 dB_{peak} to 191 dB_{peak}.
- The measured $RMS_{90\%}$ L_{50} levels ranged between 171 $dB_{RMS90\%}$ and 180 $dB_{RMS90\%}$.
- Cumulative Sound Exposure Levels (cSEL) for all piles driven on the same day, ranged between 186 dB_{cSEL} and 195 dB_{cSEL}.
- For Piles 1 and 3 due to equipment malfunction the recordings were not saved and the calculated values of RMS and SEL are estimates.
- Only Piles 1 and 3 exceeded the cSEL interim threshold for fish. For the daily cSEL the distance to the 187 dB_{cSEL} interim threshold is 177 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 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.