SR 202, SR 520 TO SAHALEE WAY PROJECT

UNDERWATER SOUND LEVELS ASSOCIATED WITH 'DRY' PILE DRIVING AT THE EVANS CREEK BRIDGE ON SR 202

Prepared by:
Jim Laughlin
Washington State Department of Transportation
Office of Air Quality and Noise
15700 Dayton Avenue North, P.O. Box 330310
Seattle, WA 98133-9710

September 2006

Table of Contents

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

This technical report describes the data collected during pile driving efforts over Evans Creek as part of the SR 202, SR 520 to Sahalee Way Project in Redmond Washington during the month of August 2006. Five 16-inch diameter steel piles were driven at various distances from the Evans Creek channel. Sound levels were monitored underwater in Evans Creek during pile driving activities for five piles. Piles were driven with a diesel hammer. Table 1 summarizes the results for each pile monitored. No bubble curtain was used since none of the piles were driven in water.

Ambient sound levels averaged approximately 137 dB_{RMS} to 141 dB_{RMS} with construction equipment.

Table 1: Summary Table of Monitoring Results.

Pile #	Hydrophone Depth	Absolute Peak (dB)	RMS (peak) (dB)	SEL (dB)	Rise Time (msec)
1	1-foot (midwater)	179	174	164	18.4
2	1-foot (midwater)	172	164	151	7.3
3	1-foot (midwater)	172	164	151	15.3
4	1-foot (midwater)	174	164	150	7.1
5	1-foot (midwater)	172	164	150	7.6

INTRODUCTION

This technical report presents results of underwater sound levels measured during the driving of five 16-inch steel piles near Evans Creek as part of the SR 202, SR 520 to Sahalee Way Project in Redmond, Washington during August 2006 (Contract Number: 007030). The piles were driven to support the bridge replacement over Evans Creek. Five 16-inch piles were monitored at different distances from the Evans Creek water channel.

PROJECT DESCRIPTION

This project will widen almost three miles of SR 202. The project begins in the commercial area of Redmond at SR 520, travels through a small portion of the City of Sammamish near 192nd Place NE, and ends in the rural area of King County at Sahalee Way NE.

The first stage of this project adds an additional lane in each direction between SR 520 and East Lake Sammamish Parkway and improves the intersection of SR 202 and East Lake Sammamish Parkway. Other work includes bicycle lanes, sidewalks, drainage, landscaped median, signing upgrades, signal revisions at the SR 520 off-ramp and at NE 70th Street.

The second stage includes two new lanes, retaining walls, noise walls, bicycle lanes, sidewalks, replacement of the bridges at 196th Avenue NE and at Evans Creek. From 196th Avenue NE to Sahalee Way, crews will raise the roadway 14 feet to accommodate an ancient landslide.

The pile driving monitoring work was conducted as part of the bridge replacement at Evans Creek.

Figure 1: Location of underwater noise monitoring sites at the Evans Creek for the SR 202, SR 520 to Sahalee Way project. Piles are not to scale.

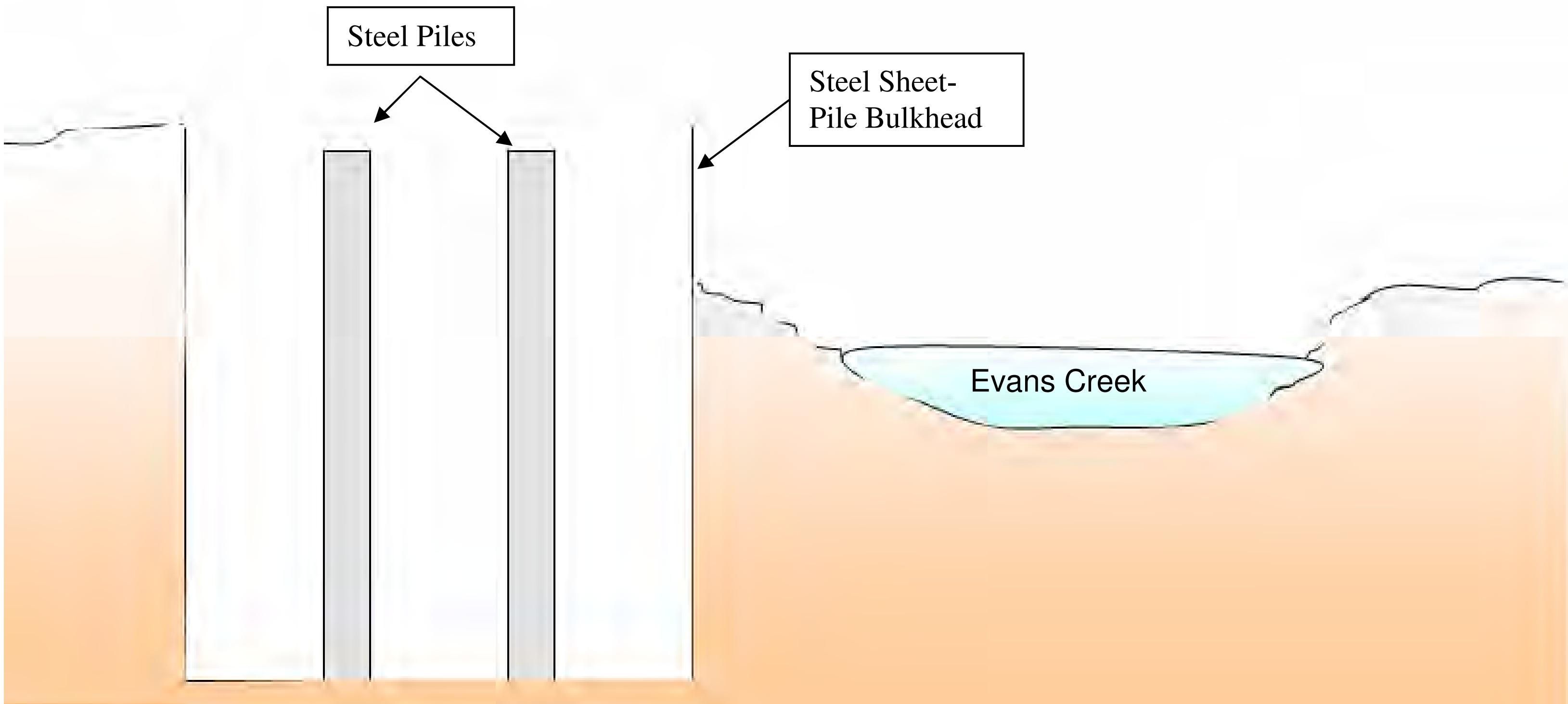

Figure 2: Cross section of pile locations relative to Evans Creek in the monitoring area.

UNDERWATER SOUND LEVELS

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, which are sometimes referred to as the SPL and RMS level respectively. The peak pressure is the instantaneous maximum or minimum overpressure observed during each pulse and can be presented in Pascals (Pa) or decibels (dB) referenced to a pressure of 1 micropascal (μPa). Since water and air are two distinctly different media, a different sound pressure 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 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)*

For comparison, an underwater sound level of equal perceived loudness would be 62 dB higher to a comparable sound level in air.

The RMS level is the square root of the energy divided by the impulse duration. This level, presented in dB re: 1 μPa, is the mean square pressure level of the pulse. It has been used by National Marine Fisheries Service (NMFS) in criteria for judging impacts to marine mammals from underwater impulse-type sounds. The majority of literature uses peak sound pressures to evaluate barotraumas injuries to fish. Except where otherwise noted, sound levels reported in this report are expressed in dB re: 1 μPa.

Rise time is another descriptor used in waveform analysis to describe the characteristics of underwater impulses. Rise time is the time in microseconds (ms) it takes the waveform to go from background levels to absolute peak level.

Sound Exposure Level (SEL), frequently used for human noise exposures, has recently been suggested as a possible metric to quantify impacts to fish (Hastings and Popper 2005). SEL is calculated by summing the cumulative pressure squared (p^2), integrating over time, and normalizing to one second. This metric accounts for both negative and positive pressures because p^2 is positive for both and thus both are treated equally in the cumulative sum of p^2 (Hastings and Popper, 2005). The units for SEL are dB re: 1 micropascal^2-sec.

Popper et al. (2006) recommend a dual criteria of 208 dB_{peak} and 187 dB_{SEL} as a very conservative interim guidance to protect fish from physical injury and mortality for a single pile driving impact. Because SEL is a metric based on energy, sound exposure for a single strike can be summed to estimate the total energy exposure from multiple strikes, which can then be compared to the recommended interim guidance. Some recovery of the tissue will take place during the interval between strikes that is not taken into account, so this approach should be conservative.

Alternatively, if the sound intensity or total energy exposure for an observed effect is known, a safe SEL per strike can be estimated by using the pressure-particle velocity relationships for a plane wave. As an example, the total energy exposures for Hastings (1995) “worst case” injury and mortality were for 3- to 4-inch long blue gouramis (*Trichogaster trichopterus*) with a mass of 10-15 grams. One was stunned (i.e., became unconscious) after only 10 minutes exposure and others died after only 30 minutes exposure (50% mortality based on 6 fish), both to a 400-Hz tone at 192 dB re 1 μPa (peak). In contrast, the worst case (25% mortality based on 12 fish) for 6-inch long goldfish, about 100 grams each, was mortality after a one-hour exposure to 204 dB re 1 μPa (peak) at 250 Hz.

Comparing an energy dose or energy flux density, E_f, in J/ m^2 with an allowable SEL an approximation for a plane wave is used. The relationship between sound pressure (*p*) and particle velocity (*v*) is $p = (\rho c)v$, where ρ (kg/m^3) is the density of the fluid and *c* (m/s) is the speed of sound in the fluid is also used. The product, ρc is called the characteristic impedance and its value is about 1.6×10^6 (kg/m^2-s) for seawater and 1.5×10^6 (kg/m^2-s) for freshwater. Using these values an allowable SEL can be calculated for a given number of pile strikes and a given time duration (in seconds) for the sound pulse generated by each strike. For example,

$$\text{SEL per Strike} = 10 \log [\rho c\ E_f / 10^{-12} / (\#\ \text{strikes})].$$

This approximation is used to calculate the SEL per strike that would give an equivalent total sound energy dose. Calculated values are for seawater with $\rho c = 1.6 \times 10^6$ (kg/m^2-s) and time per strike = 0.075 s. Comparisons made by Hastings and Popper (2005) indicate that the recommended guidance is conservative based on the worst-case data for injury and mortality from Hastings (1995).

METHODOLOGY

Underwater sound levels were measured using one Reson TC 4013 hydrophone positioned at mid-water level. The hydrophones were located at a varying distances from the pile being monitored. 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 Dactron Photon 4-channel signal spectrum analyzer that is attached to an Itronix GoBook II laptop computer. The waveform of the pile strikes along with the number of strikes, overpressure minimum and maximum, absolute peak values, and RMS sound levels, integrated over 90% of the duration of the pulse, were captured and stored on the laptop hard drive for subsequent signal analysis. The system and software calibration is checked annually against a NIST traceable standard. The operation of the hydrophone was checked in the field using a GRAS type 42AC high-level pistonphone with a hydrophone adaptor. The pistonphone signal was 146 dB re: 1 µPa. The pistonphone signal levels produced by the pistonphone and measured by the measurement system were within 1 dB and the operation of the system was judged acceptable over the study period. A photograph of the system and its components are shown in Figure 3.

Figure 3: Underwater Sound Level Measurement Equipment

Signal analysis software provided with the Photon was set at a sampling rate of one sample every 41.7 µs (9,500 Hz). This sampling rate is more than sufficient for the bandwidth of interest for underwater pile driving impact sound and gives 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.

Due to the high degree of variability between the absolute peaks for each pile strike an average peak and RMS value is computed along with the standard deviation (s.d.) giving an indication of the amount of variation around the average for each pile.

All piles were driven to bearing depth with a diesel hammer. The diesel impact driver was a Berminghammer B-4505 with a rated energy of 75,900 ft/lbs. This is the maximum energy output for the diesel hammer that can only be sustained for a few seconds at a time. The actual transferred energy was more likely 55,000 - 60,000 ft./lbs for most pile installations.

The substrate consisted of a mix of sand and fist-sized rocks with occasional rocks of one-foot in diameter. Piles driven were closed end hollow steel piles, 16-inches in diameter with a one-inch wall thickness. All measurements were made at varying distances from the pile and at mid-water depth.

The location of the hydrophone was determined by placing the hydrophone in the deepest (center) part the creek channel and at midwater depth since there were no piles being driven in the water. The hydrophone was attached to a weighted nylon cord anchored with a five-pound weight. The cord and hydrophone cables were attached to a float at the surface (Figure 4).

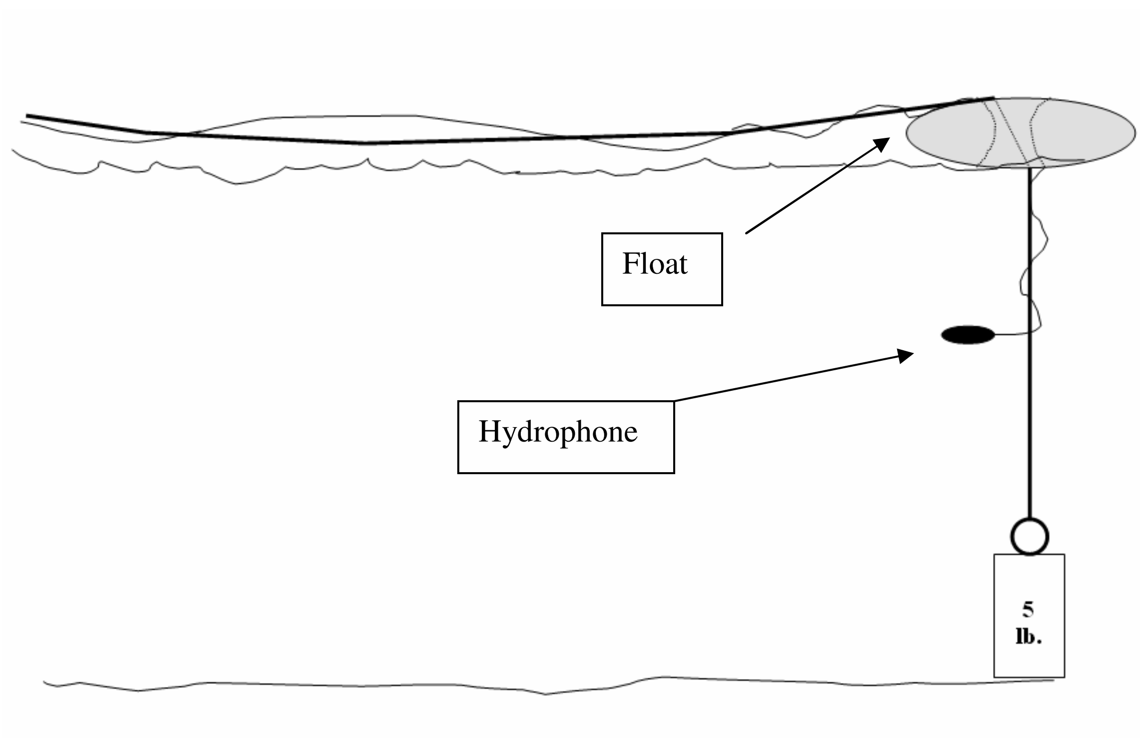

Figure 4: Diagram of hydrophone deployment at the monitoring location.

RESULTS

UNDERWATER SOUND LEVELS

Pile 1

Pile 1 was driven with a diesel hammer 9 meters (30 feet) from the waters edge. Table 2 indicates the results of monitoring for Pile 1. The highest absolute peak is 179 dB_{peak}. The highest RMS was 174 dB_{RMS}. The SEL for the peak strike was 164 dB_{SEL}.

As can be seen in Appendix A Figure 6 the waveform analysis for Pile 1 indicates that there was a relatively long delay between the initial onset of the impulse and the absolute peak (rise time of 13.9 milliseconds) followed by a rather large swing in the amplitude of the waveform. This is indicative of sound flanking through the sediments. None of the pile strikes exceeded peak values of 180 dB_{peak} and almost all RMS values exceeded 150 dB_{RMS}.

Pile 2

Pile 2 was driven 8 meters (26 feet) from the waters edge. Table 3 indicates the results of monitoring for Pile 2. The highest absolute peak from the midwater hydrophone is 172 dB_{peak} and the highest midwater RMS is 164 dB_{RMS} for the entire driving event. The midwater SEL for the peak strike is 151 dB_{SEL}. None of the pile strikes exceeded 180 dB_{peak} and almost all of the strikes exceeded 150 dB_{RMS}.

Pile 3

Pile 3 was driven 8 meters (30 feet) from the waters edge. Table 4 indicates the results of monitoring for Pile 3. The highest absolute peak from the midwater hydrophone is 172 dB_{peak} and the highest midwater RMS is 164 dB_{RMS} for the entire driving event. The midwater SEL for the peak strike is 151 dB_{SEL}. None of the pile strikes exceeded 180 dB_{peak} and almost all of the strikes exceeded 150 dB_{RMS}.

Pile 4

Pile 4 was driven 8 meters (26 feet) from the waters edge. Table 5 indicates the results of monitoring for Pile 4. The highest absolute peak from the midwater hydrophone is 174 dB_{peak} and the highest midwater RMS is 164 dB_{RMS} for the entire driving event. The midwater SEL for the peak strike is 150 dB_{SEL}. None of the pile strikes exceeded 180 dB_{peak} and almost all of the strikes exceeded 150 dB_{RMS}.

Pile 5

Pile 5 was driven 7 meters (23 feet) from the waters edge. Table 6 indicates the results of monitoring for Pile 5. The highest absolute peak from the midwater hydrophone is 172 dB_{peak} and the highest midwater RMS is 164 dB_{RMS} for the entire driving event. The midwater SEL for the peak strike is 150 dB_{SEL}. None of the pile strikes exceeded 180 dB_{peak} and almost all of the strikes exceeded 150 dB_{RMS}.

Table 2: Summary of Underwater Sound Levels for Pile 1.

Pile #	Date	Hydrophone Depth	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (dB ± s.d.)	n[2]	% of Strikes Over 180 dBpeak	Average RMS (dB ± s.d.)	% of Strikes Over 150 dBrms	SEL (dB)	Rise Time (msec)
1	8/11/06	1-foot (midwater)	179[1]	174	166 ± 294	35	0%	42 ± 297	93%	164	18.4

[1] – Absolute peak value is peak underpressure.
[2] – Number of pile strikes included in the average calculations.

Table 3: Summary of Underwater Sound Levels for Pile 2.

Pile #	Date	Hydrophone Depth	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (dB ± s.d.)	n[2]	% of Strikes Over 180 dBpeak	Average RMS (dB ± s.d.)	% of Strikes Over 150 dBrms	SEL (dB)	Rise Time (msec)
2	8/11/06	1-foot (midwater)	172	164	287 ± 62	246	0%	65 ± 20	93%	151	7.3

[1] – Absolute peak value is peak underpressure.
[2] – Number of pile strikes included in the average calculations.

Table 4: Summary of Underwater Sound Levels for Pile 3.

Pile #	Date	Hydrophone Depth	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (dB ± s.d.)	n[2]	% of Strikes Over 180 dBpeak	Average RMS (dB ± s.d.)	% of Strikes Over 150 dBrms	SEL (dB)	Rise Time (msec)
3	8/11/06	1-foot (midwater)	172[1]	164	250 ± 53	295	0%	61 ± 20	92%	151	15.3

[1] – Absolute peak value is peak underpressure.
[2] – Number of pile strikes included in the average calculations.

Table 5: Summary of Underwater Sound Levels for Pile 4.

Pile #	Date	Hydrophone Depth	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (dB ± s.d.)	n[2]	% of Strikes Over 180 dBpeak	Average RMS (dB ± s.d.)	% of Strikes Over 150 dBrms	SEL (dB)	Rise Time (msec)
4	8/11/06	1-foot (midwater)	174	164	364 ± 90	289	0%	82 ± 27	93%	150	7.1

[1] – Absolute peak value is peak underpressure.
[2] – Number of pile strikes included in the average calculations.

Table 6: Summary of Underwater Sound Levels for Pile 5.

Pile #	Date	Hydrophone Depth	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (dB ± s.d.)	n[2]	% of Strikes Over 180 dBpeak	Average RMS (dB ± s.d.)	% of Strikes Over 150 dBrms	SEL (dB)	Rise Time (msec)
5	8/11/06	1-foot (midwater)	172	164	299 ± 84	293	0%	71 ± 25	92%	150	7.6

[1] – Absolute peak value is peak underpressure.
[2] – Number of pile strikes included in the average calculations.

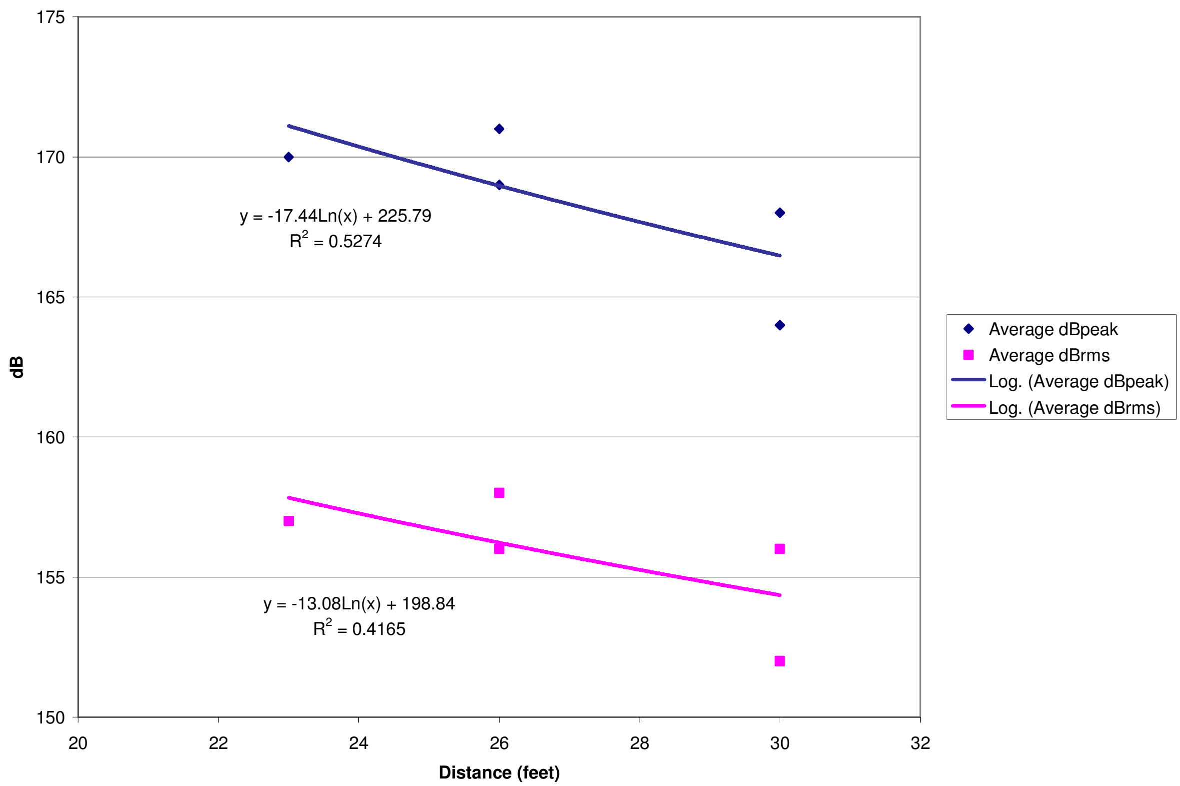

Figure 5: Plot of the average dBpeak and average dBrms versus distance from pile for all piles.

SEL

SEL was calculated for each of the absolute peak strikes for each pile. None of the SEL values exceeded the proposed threshold of 187 dB SEL proposed by Popper et al. (2006). Because decibels are on a logarithmic scale, it would require substantially more energy to exceed this threshold.

Rise Time

Yelverton (1973) indicated rise time was the cause of injury. According to Yelverton (1973), the closer the peak is to the front of the impulse wave the greater the chance for injury. In other words, the shorter the rise time the higher the likelihood for effects on fish.

In all piles, except for the end of the drive of Pile 1, the rise times were relatively long. This could be an indication that the pile was driven out of water and the sound was being attenuated through sound flanking where most of the energy was not traveling directly through the water but through the sediment up to the hydrophone. However, this relationship is not entirely clear.

BIOLOGICAL OBSERVATIONS

No fish mortality or distress was observed before, during, or after pile driving. None of the birds observed indicated signs of distress or abnormal behavior.

Future studies should identify a “control” area that is biologically similar. Biological observations in the control area could be compared to those in the study (treatment) area to help identify biological impacts of construction activity. The control area could be the study area but with observations made before construction and following. Without this type of comparison between control (or “no” treatment areas) and treatment areas it is very hard to evaluate the significance (if any) of the biological observation presented.

CONCLUSIONS

All piles had relatively long rise times. The longer rise times may relate to sound flanking through the sediment and may be somewhat protective to fish injury. However, these relationships are not clearly identified at this time.

None of the of the peak values exceeded the 180 dBpeak threshold that is currently being implemented by U. S. Fish and Wildlife and NMFS. None of the SEL values calculated on the absolute peak pile strike exceeded the proposed threshold of 187 dB SEL (Popper et al., 2006). Therefore, it is unlikely that any of the piles driven with an impact hammer for this project would have caused physical injury or mortality to fish and none were observed.

REFERENCES

Hastings, M. C. (1995). "Physical effects of noise on fishes." Proceedings of INTER-NOISE 95, The 1995 International Congress on Noise Control Engineering, vol. II, pp. 979–984.

Hastings, Mardi C., 2002. Clarification of the Meaning of Sound Pressure Levels and the Known Effects of Sound on Fish. White Paper. August 2002.

Hastings, Mardi C.; and Arthur N. Popper. 2005. Effects of Sound on Fish. White Paper. January 2005.

Popper, Arthur N., Thomas J. Carlson, Brandon L. Southall, and Roger L. Gentry. Interim Criteria for Injury of Fish Exposed to Pile Driving Operations: A White Paper. 2-24-06.

APPENDIX A– WAVEFORM ANALYSIS FIGURES

PILE 1

Pile 1 - Out of Water - 30 feet from pile

Figure a. Waveform

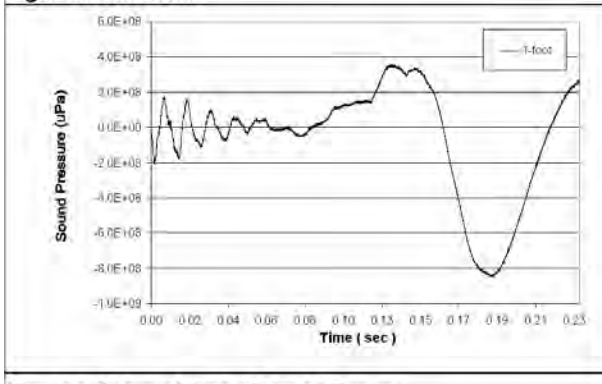

Figure b. Narrow Band Frequency Spectra

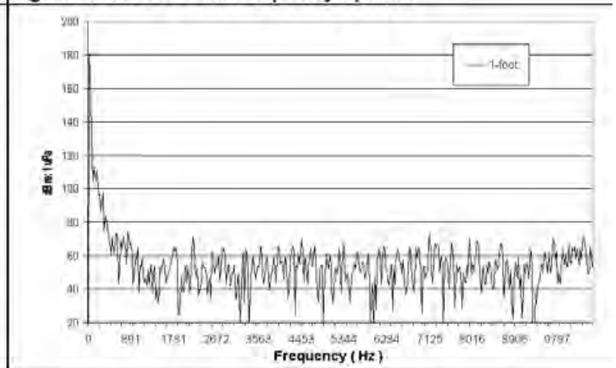

Figure c. Accumulation of Sound Energy

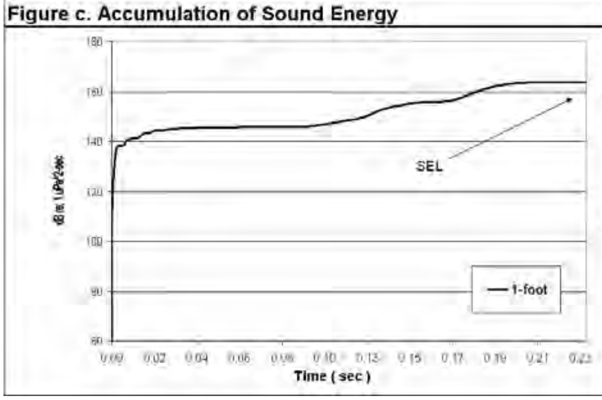

Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

1-foot - 00:00:00	Peak	$RMS_{90\%}$*	SEL
1-foot	179	174	164

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

Figure 6: Waveform Analysis of Pile 1 Underwater Sound Pressure Levels 30-feet from the pile driven outside the water channel.

PILE 2

Pile 2 - Out of Water - 26 feet from pile

Figure a. Waveform

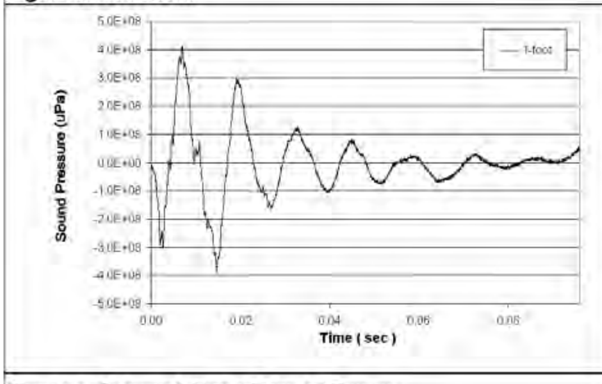

Figure b. Narrow Band Frequency Spectra

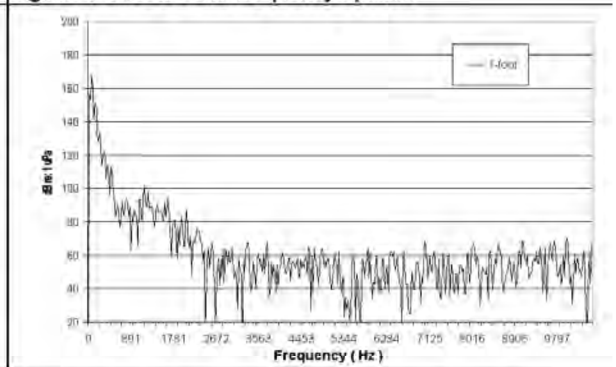

Figure c. Accumulation of Sound Energy

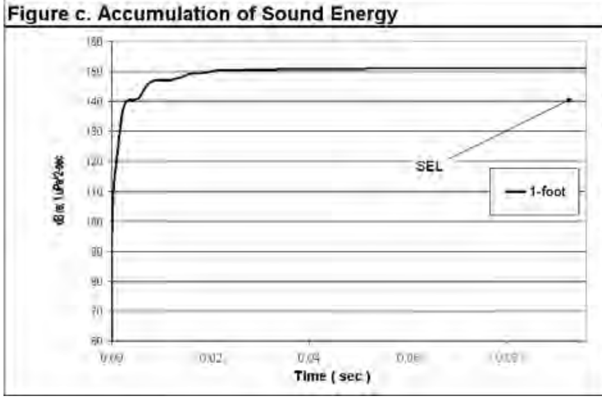

Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

1-foot - 00:00:00	Peak	RMS90%*	SEL
1-foot	172	164	151

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

Figure 7: Waveform Analysis of Pile 2 Underwater Sound Pressure Levels 26-feet from the pile driven outside the water channel.

PILE 3

Pile 3 - Out of Water - 30 feet from pile

Figure a. Waveform

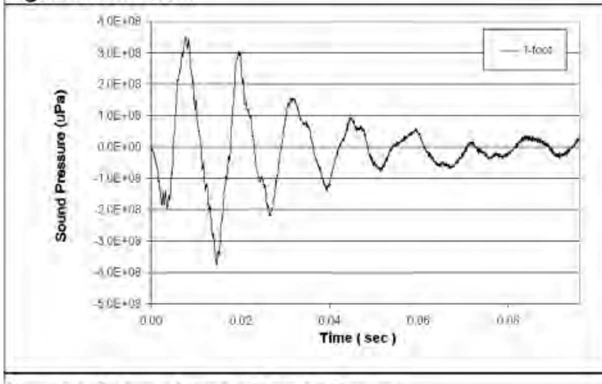

Figure b. Narrow Band Frequency Spectra

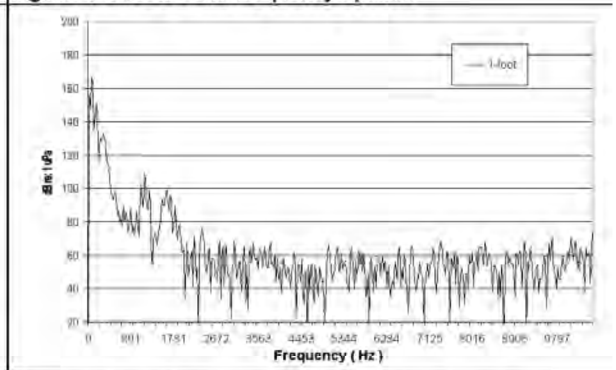

Figure c. Accumulation of Sound Energy

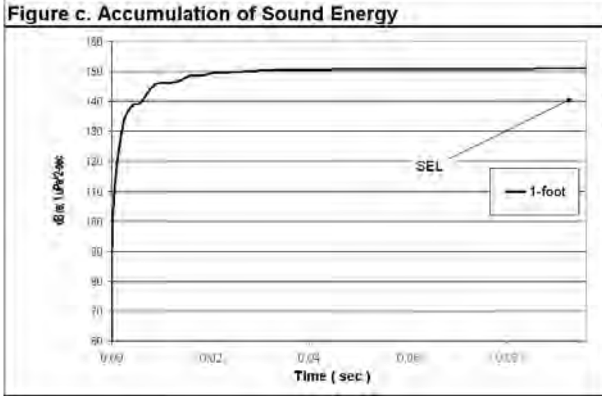

Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

1-foot - 00:00:00	Peak	RMS90%*	SEL
1-foot	172	164	151

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

Figure 8: Waveform Analysis of Pile 3 Underwater Sound Pressure Levels 30-feet from the pile driven outside the water channel.

PILE 4

Pile 4 - Out of Water - 26 feet from pile

Figure a. Waveform

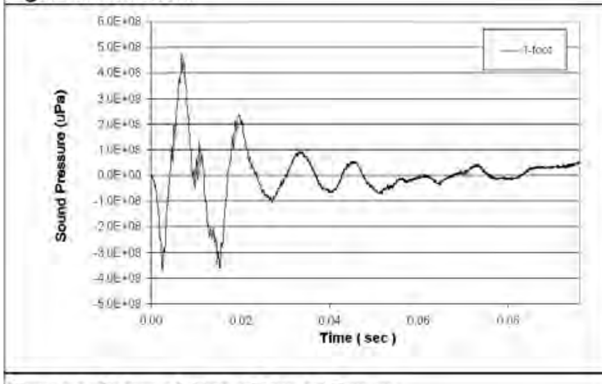

Figure b. Narrow Band Frequency Spectra

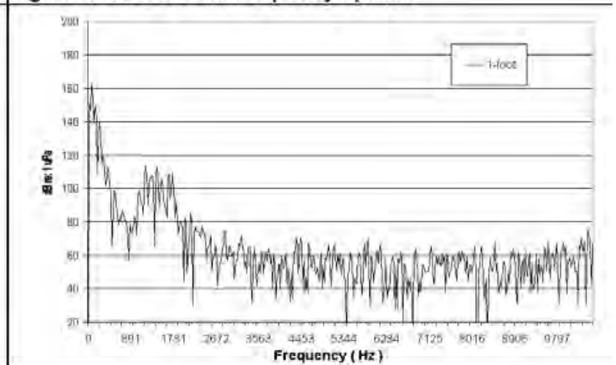

Figure c. Accumulation of Sound Energy

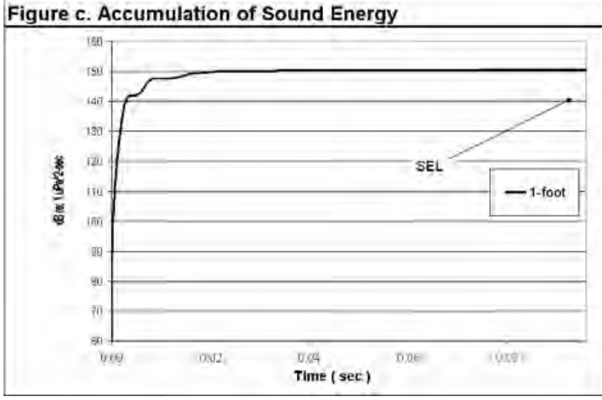

Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

1-foot - 00:00:00	Peak	RMS90%*	SEL
1-foot	174	164	150

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

Figure 9: Waveform Analysis of Pile 4 Underwater Sound Pressure Levels 26-feet from the pile driven outside the water channel.

PILE 5

Pile 5 - Out of Water - 23 feet from pile

Figure a. Waveform

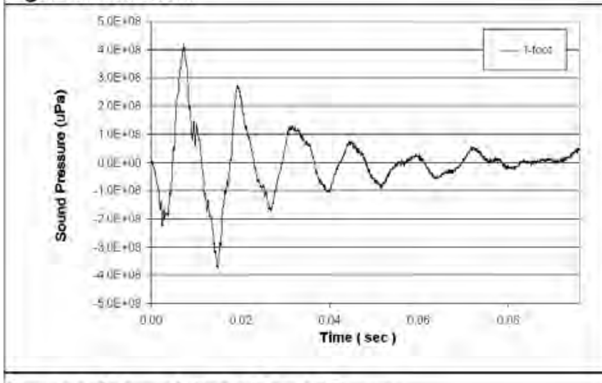

Figure b. Narrow Band Frequency Spectra

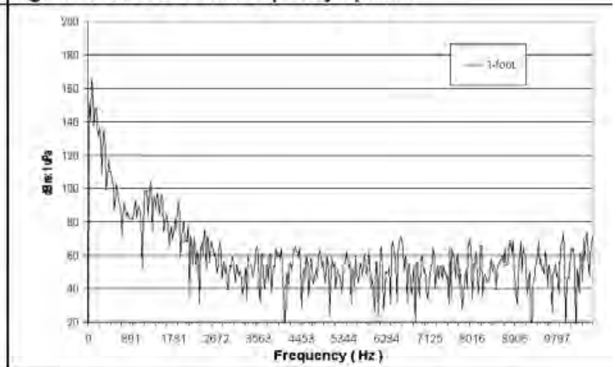

Figure c. Accumulation of Sound Energy

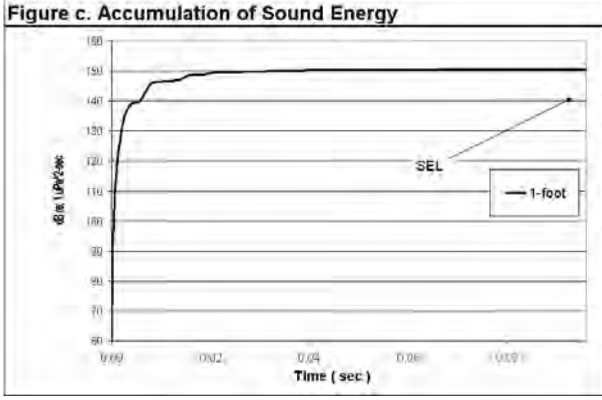

Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

1-foot - 00:00:00	Peak	RMS90%*	SEL
1-foot	172	164	150

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

Figure 10: Waveform Analysis of Pile 5 Underwater Sound Pressure Levels 23-feet from the pile driven outside the water channel.