SR 24, I-82 TO KEYS ROAD PROJECT

UNDERWATER SOUND LEVELS ASSOCIATED WITH PILE DRIVING ON THE SR 24, I-82 TO KEYS ROAD PROJECT – YAKIMA RIVER

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EXECUTIVE SUMMARY

This technical report describes the data collected during pile driving efforts at the SR 24 bridge replacement project in the Yakima River during the month of June 2005. In addition, data collected using a confined bubble curtain is included. Five 24-inch diameter steel piles were monitored at different water depths in the Yakima River. Piles were driven with a diesel hammer. Table 1 summarizes the results for each pile monitored. The confined bubble curtain was only tested on the last three piles that were in water deep enough to submerge the bubble ring.

Ambient sound levels ranged between 152 dB_{peak} and 155 dB_{peak} without construction equipment and 151 dB_{peak} to 155 dB_{peak} with construction equipment. The maximum sound reduction achieved with the confined bubble curtain was 5 dB. Due to the large rocks and boulders, the outer casing of the confined bubble curtain often did not seat properly on the bottom.

For informational purposes only, results from two piles driven above the river waterline are included in this report.

Table 1: Summary Table of Monitoring Results.

Pile #	Bubble Curtain Scenario	Average Peak (dB ± s.d.)	Average RMS (dB ± s.d.)	SEL (dB re: 1 μPa^2-sec)	Rise Time (msec)
1	Bubbles Off	192 ± 184	171 ± 159	164	9.2
2	Bubbles Off	191 ± 185	171 ± 160	165	9.0
3	Bubbles Off (a)	171 ± 159	153 ± 138	146	5.8
	Bubbles On (b)	177 - 173	161 - 155	159	9.2
4	Bubbles On	193 ± 183	175 ± 165	169	9.3
5	Bubbles On	188 ± 177	171 ± 159	164	2.1

INTRODUCTION

This technical report presents results of underwater sound levels measured during the driving of five 24-inch steel piles at the SR 24 bridge replacement project during June 2005 (Contract Number: 006933). The piles were driven to support the work trestle on the south side of the bridge. Five 24-inch piles were monitored at different water depths in the river channel. The confined bubble curtain was tested during the last three piles when the water depth was deep enough to submerge the bubble ring. Figure 1 shows the locations of monitored piles.

PROJECT DESCRIPTION

This project will replace the existing Yakima River Bridge (bridge number 24/5) over the Yakima River as part of the widening project on SR 24. The project will ensure the safety and continued operaton of traffic on SR 24. As part of the bridge replacement 24-inch steel piles will be driven to support the work trestle next to the existing bridge. This temporary trestle will allow construction equipment to cross, or rest over the river without interrupting traffic on the existing SR 24 Bridge and to allow for the construction of the new bridge in a new alignment.

The project location is on bridge number 24/5 of SR 24 over the Yakima River (Figure 1). Figure 2 shows the approximate pile locations and the respective monitoring locations within the river. Some of the bottom features of the river are also shown in Figure 2. Figure 3 shows the approximate bottom topography through the transect drawn on Figure 2. Water depths at the monitoring locations varied from six inches to two feet deep. Water flow rate also increased with increasing depth.

Figure 1: Location of underwater noise monitoring sites at the SR 24 bridge replacement project on the Yakima River.

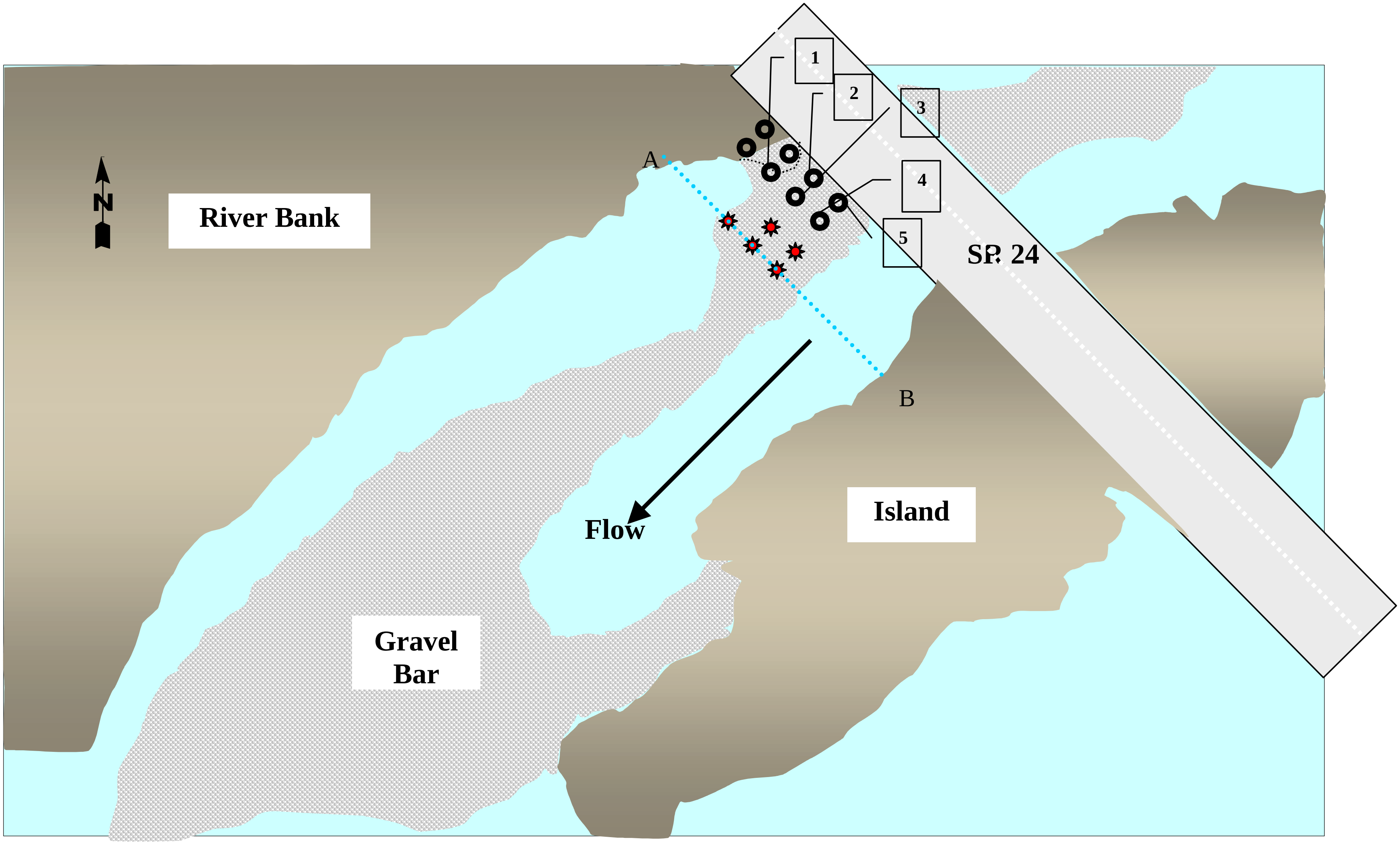


Figure 2: Location of piles (●), monitoring locations (✱), and bottom features within the Yakima River in relation to SR 24. The blue dotted line represents a transect across the river at monitoring locations for Piles 1, 3, and 4 detailed in Figure 3.

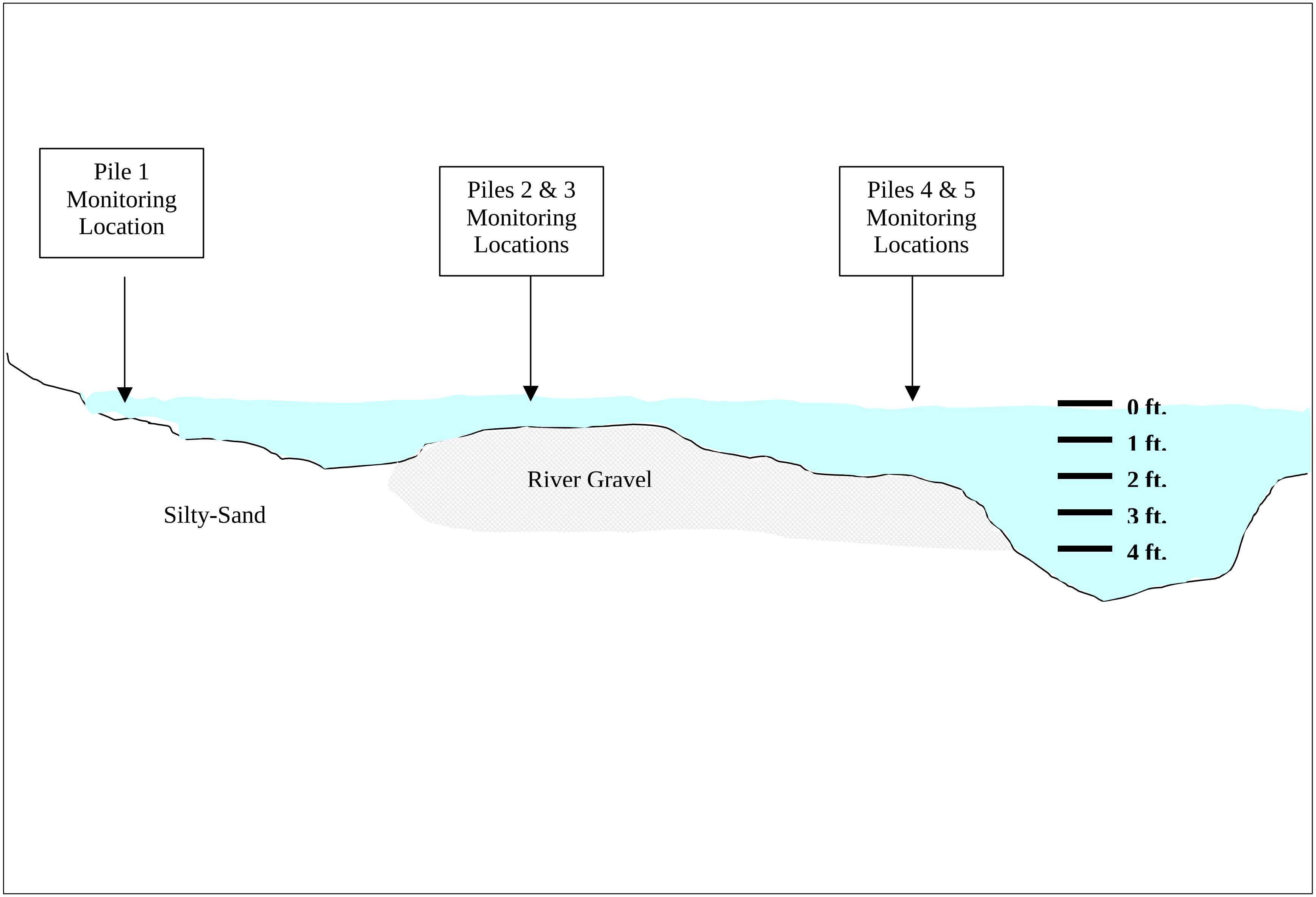


Figure 3: Approximate bottom topography through the transect line (A-B) from Figure 2 looking upriver.

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). Dr. Hastings has abandoned her previous 180 dB_{peak} and 150 dB_{rms} thresholds (Hastings, 2002) and is now, along with Dr. Popper, proposing 194 dB SEL as the new barotrauma threshold for fish. SEL is often used as a metric for a single acoustic event and is often used as an indication of the energy dose. 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.

METHODOLOGY

Underwater sound levels were measured using one Reson TC 4013 hydrophone. One hydrophone was positioned approximately at mid-water level. The hydrophone was located at a distance of 33 feet from the pile and downstream of 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 4). 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 to be acceptable over the study period. A photograph of the system and its components are shown in Figure 4.

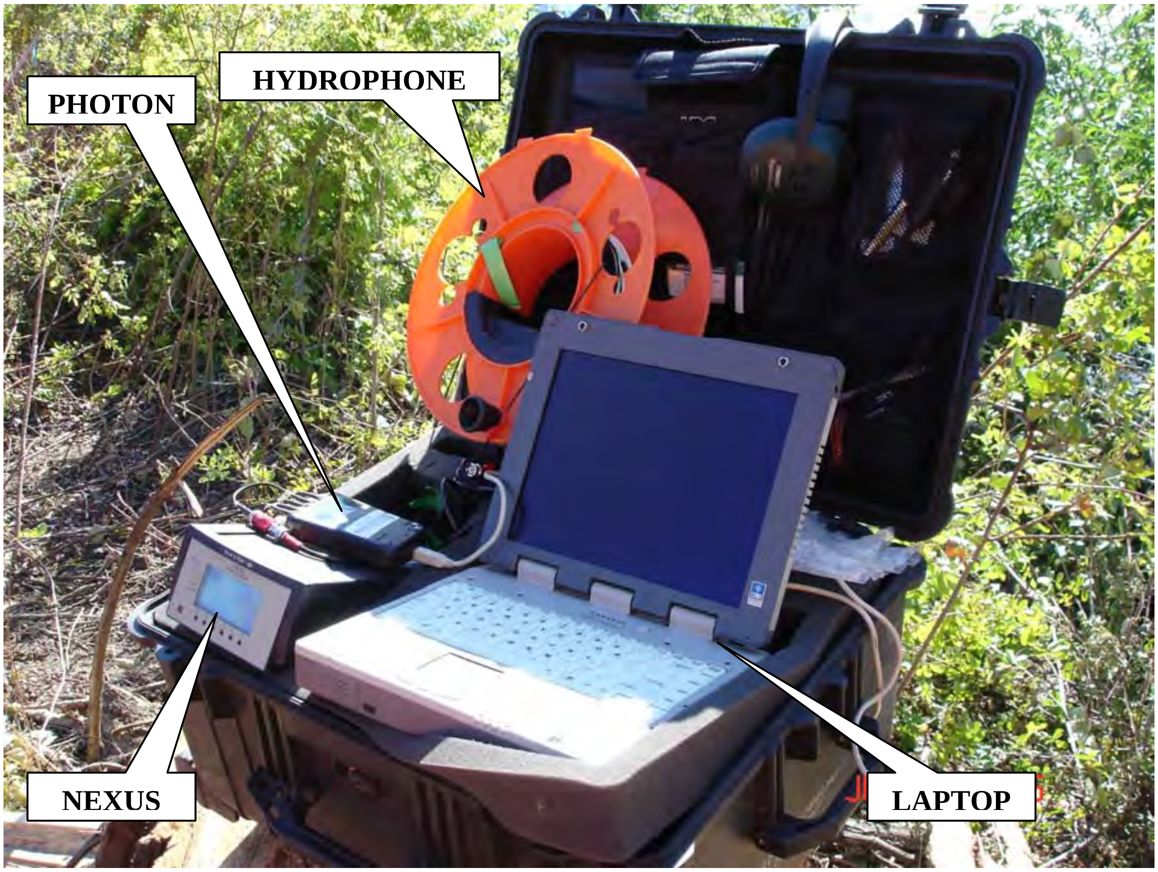


Figure 4: Underwater Sound Level Measurement Equipment

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. No vibratory hammer was used to drive piles. The diesel impact driver was an ICE Model 60S with an energy rating of 60,000 ft-lbs. This is the maximum energy output for the diesel hammer that can only be sustained for a few seconds at a time. Actual operation of the diesel hammer is more likely to be approximately 50% to 70% of this maximum energy for most pile installations.

The substrate consisted of large one to three foot diameter boulders (riprap) at the sediment surface with river rock and gravel below down to about 30-35 feet. Piles driven were open-ended hollow steel piles, 24-inches in diameter with a ½ inch wall thickness. A schedule of sampling conditions for each pile is provided in the Table 1 below. All measurements were made 33 feet from the pile and at mid-water depth.

Table 2: Sampling Conditions Schedule for Each Pile Monitored.

Location	Pile #	Time	Water Depth[1] (ft)	Water Temperature (°F)	Wind Speed (Kts)	Current Speed	Substrate	Pile Diameter (inches)
Shallow Water Depth	1	11:14 am	6-inches	nr	2	~1 ft/sec	Rip Rap, river gravel, sand	24
Intermediate Water Depth	2	10:52 am	1-foot	60°F	1.8	~3 ft/sec	Rip Rap, river gravel, sand	24
	3	3:42 pm	1-foot	64°F	0.8	~3 ft/sec	Rip Rap, river gravel, sand	24
Deep Water Depth	4	10:28 am	2-feet	58°F	0.8	~7 ft/sec	Rip Rap, river gravel, sand	24
	5	2:25 pm	2-feet	nr	0.9	~7 ft/sec	Rip Rap, river gravel, sand	24

nr – not recorded

[1] – Water depth is depth of water at pile location and associated hydrophone location. Hydroacoustic measurements were made at ½ this depth (midwater).

Each measured pile site is described below:

Shallow Water Depth Pile (Pile 1) –

Located near the waters edge on the south side of the bridge and about five feet west of a small gravel bar attached to the shoreline in 6-inches of water. Substrate surface was mostly silty-sand with a few small boulders overlying river gravel.

Intermediate Water Depth Piles (Piles 2 and 3) -

Pile 2 is located 20 feet farther offshore from Pile 1 in one foot of water. Pile 3 is located 20 feet north (upstream) of Pile 2 in one foot of water. Substrate surface was river gravel composed of stones three to six inches across with a few small boulders.

Deep Water Depth Piles (Piles 4 and 5) -

Pile 4 was located 20 feet offshore from Pile 2 in two feet of water. Pile 5 was located 20 feet north (upstream) of Pile 4 in two feet of water. Substrate surface was composed of river gravel with stones three to six inches across with an occasional larger boulder up to two feet across.

The location of the hydrophones is determined by allowing a clear line of sight between the pile and the hydrophone, downstream of the pile, with no other structures nearby. The distance from the pile to the hydrophone location was measured using a Bushnell Yardage Pro rangefinder. In the shallow and intermediate water depths the hydrophone was attached to a weighted nylon cord anchored with a five-pound weight. The cord and hydrophone cables were tied to a static line at the surface 33 feet (10 meters) from the pile (Figure 5).

For the deep water depth, the hydrophone was attached to a 3/8" steel chain anchored by a five-pound weight. High velocity current conditions can cause the nylon cord to which the hydrophones are attached to 'strum' much like a guitar string when plucked. This is caused when the perpendicular component of water flow increases to the point that the flow separates as it goes around the cord. The resulting vortex that sheds has a rotation that causes a reduction in pressure on one side of the cable. This causes the cable to move in that direction and results in the next vortex that sheds to rotate in the opposite direction. The resulting alternate shedding of vortices causes a rapid side-to-side oscillation in the cord in the 2 Hz to 20 Hz frequency range that can be picked up by the hydrophone. At the deep water depth locations, the water current was relatively swift (approximately 7 feet/sec) and caused the nylon cord to strum.

In some cases, fairing or short strips of fabric are attached to the cord to break up the vortices and stop the strumming. For our purposes in relatively shallow water, a simpler method is to use a 3/8" steel chain instead of fairing.

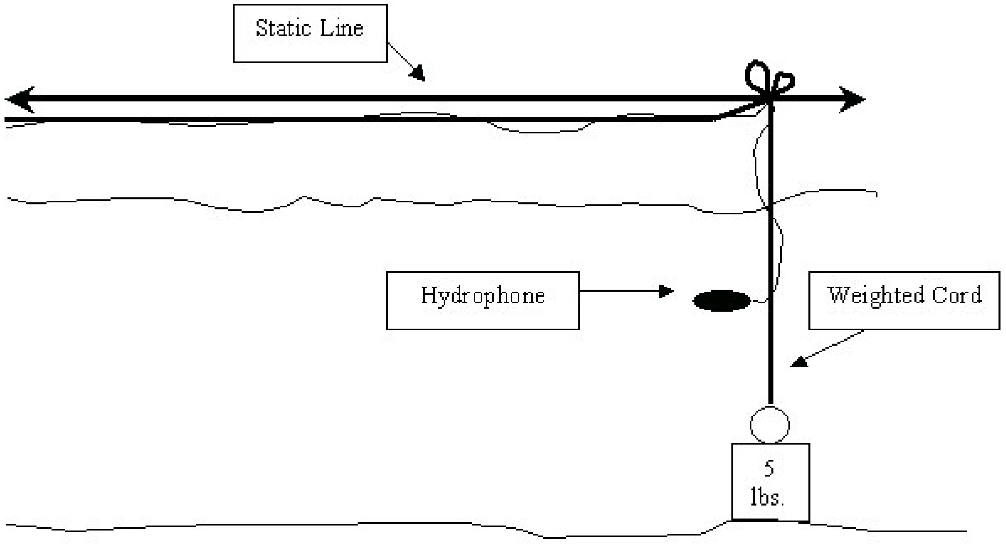


Figure 5: Diagram of hydrophone deployment at each monitoring location. For the two deepest water depths, a chain was substituted for the cord.

RESULTS

UNDERWATER SOUND LEVELS

Pile 1 (Shallow Water)

The first in-water 24-inch steel pile was monitored for underwater sound levels. The pile was driven with a diesel hammer in a water depth of six inches (Figure 6). The pile was only driven to a depth of 2.5 feet, but proper blow count of 17 blows per inch was achieved at that depth. The confined bubble curtain was not used on this pile, in part, because it was necessary to determine if sound levels exceeded the thresholds of 180 dB_{peak} or 150 $dB_{RMS,}$ and because the water depth was not sufficient to submerge the bubble ring and thus it could provide no mitigation.

Figure 6: Location of Pile 1 at waters edge.

Table 3 indicates the results of monitoring for Pile 1. The absolute peak was 199 dB_{peak}, the RMS was 182 dB_{RMS}, and the SEL was 164 dB. As can be seen in Appendix A Figure 14a 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 9.2 milliseconds). This typically indicates a 'ringing' of the pile when the pile encounters a hard substrate such as rock.

In Appendix A Figure 14c, the SEL plot indicates a relatively slow accumulation of energy and a somewhat lower than expected SEL value. Typical SEL values are 20 to 25 dB lower than the absolute peak. The SEL for Pile 1 was 35 dB lower than the peak. This is also an indication of the delay of the absolute peak level mentioned above and somewhat lower sound levels for the waveform peaks overall.

In Appendix A Figure 14b, the frequency spectra indicates that the frequency amplitudes were distributed relatively evenly across all frequencies. This implies that there was no dominant frequency and possibly the increase in amplitudes at the higher frequencies caused by the 'ringing' of the pile.

Pile 2 (Intermediate Water Depth)

The first of two piles driven at a depth of one foot was Pile 2, driven with a diesel hammer. The confined bubble curtain (Figure 7) was deployed for this pile but the bubbles were not turned on because the contractor wanted to see if they could drive the pile and stay under the thresholds set by NMFS. The contractor would start the impact hammer, and as the blows approached and eventually exceeded set thresholds, the contractor was instructed to temporarily cease pile-driving operations. This start-stop process continued until the pile was almost completely driven to depth.

Figure 7: Confined bubble curtain for use in shallow waters with swift currents.

Table 4 indicates the results of monitoring for Pile 2. The absolute peak was 198 dB_{peak}, the RMS was 183 dB_{RMS}, and the SEL was 165 dB. As can be seen in Appendix A Figure 15a 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 9.0 milliseconds). This typically indicates a 'ringing' of the pile when the pile encounters a hard substrate such as rock.

Table 3: Summary of Underwater Sound Level Impacts for Pile 1 (Shallow Water Depth).

Pile #	Date	Hydrophone Depth	Bubble Curtain Rings On	Absolute Peak[2] (dB)	Average Peak (dB ± s.d.)	n[3]	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	% Strikes Exceeding 180 dB_{peak}	% Strikes Exceeding 150 dB_{RMS}
1	6/7/05	3-inches	NO	199	192 ± 184	99	[1]	171 ± 159	164	9.2	96	100

[1] – No bubble curtain used on this pile because water was not deep enough to cover bubble ring.

[2] – Absolute peak value is peak overpressure.

[3] – Number of pile strikes included in the average calculations.

Table 4: Summary of Underwater Sound Level Impacts and Mitigation for Piles 2 and 3 (Intermediate Water Depth).

Pile #	Date	Hydrophone Depth	Bubble Curtain Rings On	Absolute Peak (dB)	Average Peak (dB ± s.d.)	n[6]	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	% Strikes Exceeding 180 dB_{peak}	% Strikes Exceeding 150 dB_{RMS}
2	6/10/05	6-inches	NO	198[2]	191 ± 185	227	[1]	171 ± 160	165	9.0	98	100
3a[4]	6/13/05	6-inches	NO	176[3]	171 ± 159	83	-	153 ± 138	146	5.8	0	98
3b[5]	6/10/05	6-inches	YES	186[3]	177± 173	73	0	161 ± 155	159	9.2	30	96

[1] – No bubble curtain used on this pile because the contractor tried to drive without exceeding threshold limits.

[2] – Absolute peak value is peak overpressure.

[3] – Absolute peak value is peak underpressure.

[4] – Bubbles OFF.

[5] – Bubbles ON.

[6] – Number of pile strikes included in the average calculations.

In Appendix A Figure 15c, the SEL plot indicates a relatively slow accumulation of energy indicated by the rounded ‘shoulder’ at the upper left of the plot.

In Appendix A Figure 15b, the frequency spectrum indicates that the frequency amplitudes contained a dominant frequency at around 900 Hz. This is typical of what is observed for pile driving activities. Frequency spectra for Pile 1 and Pile 2 were plotted together for comparison (Figure 8). Each pile had no bubble curtain operating, however, for Pile 1 you can clearly see that the amplitudes of the upper frequencies are enhanced and for Pile 2 the lower frequencies are higher. Because this was not a controlled test, we cannot be certain that all conditions were the same for each pile. Further research will be needed to identify what might be occurring with the acoustical frequency content for Pile 1.

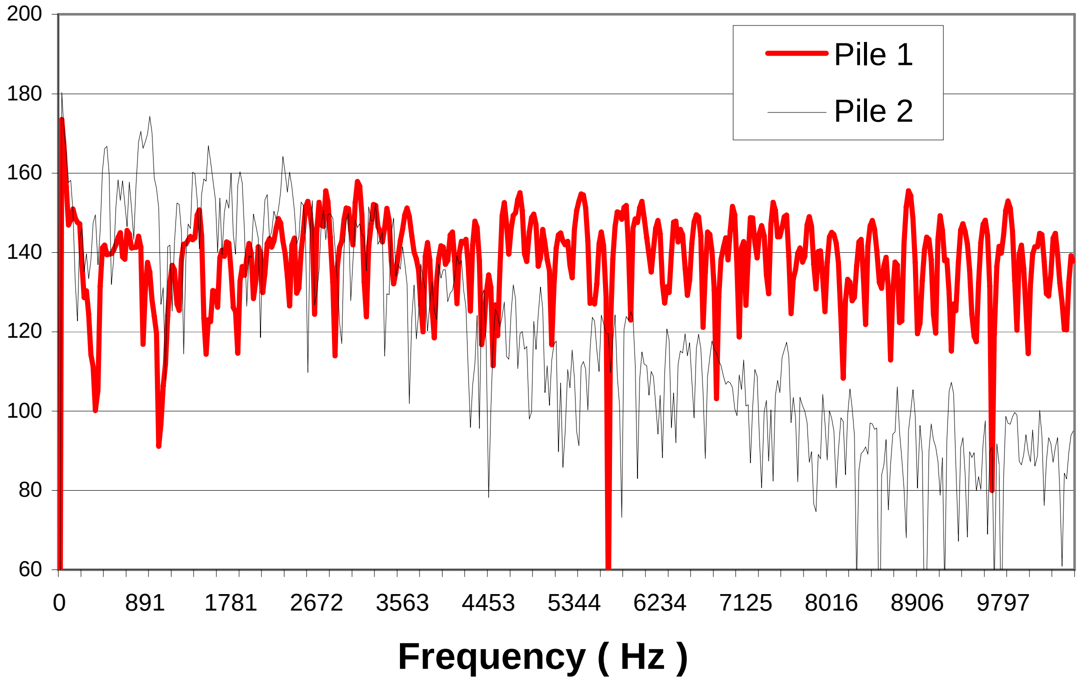


Figure 8: Comparison of Frequency Spectral Plots for Pile 1 and Pile 2 (with NO bubble curtain).

Pile 3 – (Intermediate Water Depth)

Pile 3 was driven with a diesel hammer in a water depth of one foot. The confined bubble curtain was used on this pile. Initially the bubbles were turned off (Table 4 3a) and then the bubbles were turned on (3b) so a comparison of the curtains effectiveness could be determined.

Table 4 indicates the results of monitoring for Pile 3. The absolute peak was 176 dB_{peak} with the bubbles off and 186 dB_{peak} with the bubbles on. The RMS was 159 dB_{RMS} with the bubbles off and 177 dB_{RMS} with the bubbles on. The SEL was 146 dB with the bubbles off and 159 dB with the bubbles on. During the bubbles on condition, the contractor altered the stroke length of the pile driver from seven to five feet in an effort to reduce the peak and RMS values below threshold. This resulted in lower energy going into the pile overall and none of the peak values during this phase exceeded 180 dB_{peak} but 98% of the strikes exceeded 150 dB_{RMS}. It was also likely that large boulders and rip rap where the pile was being driven would not allow the outer casing of the curtain to seat properly on the river bottom. Without a proper seal on the bottom, sound can leak out making the mitigation ineffective. The contractor then modified the air hole configuration to match NMFS's requirements before pile driving continued.

As can be seen in Appendix A Figure 16a, the waveform analysis for Pile 3a (without bubbles) indicates that there was a moderately long delay between the initial onset of the impulse and the absolute peak (rise time of 5.8 milliseconds). This waveform is typical of what is observed for steel piles. For comparison, the waveform in Appendix A Figure 17a for Pile 3b indicates a longer rise time of 9.2 milliseconds indicating a ringing of the pile possibly from the hard substrate.

In Appendix A Figures 16c and 17c, the SEL plots for Piles 3a and 3b indicate a moderately slow accumulation of energy and a somewhat lower than expected SEL value. Typical SEL values are 20 to 25 dB lower than the absolute peak. The SEL for Pile 3a was 30 dB lower than the peak and 3b was 27 dB lower. This is also an indication of the moderate delay of the absolute peak level mentioned above and somewhat lower sound levels for the waveform peaks overall.

In Appendix A Figure 16b, the frequency spectra indicates a dominant frequency around 800 Hz. This is typical of what is observed for most steel piles. Figure 9 compares the spectral frequency plots for the bubbles off and on conditions for Pile 3. As the figure indicates, there is virtually no difference between the plots for either condition suggesting that the bubble curtain was not functioning properly. The higher amplitudes at the lower frequencies without bubbles indicate the higher peak values due to the full stroke length of the hammer measured for this condition.

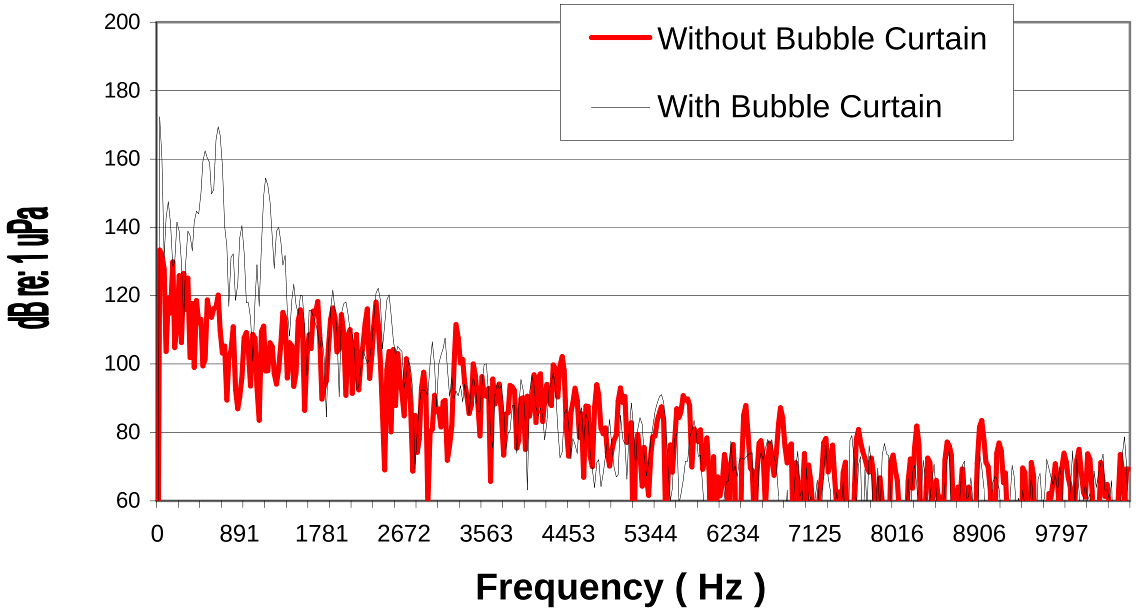


Figure 9: Pile 3 Frequency Spectral Analysis Comparing a Single Pile Strike With Bubbles Off and Bubbles On.

Pile 4 – (Deep Water Depth)

Two piles were driven at this deeper water depth. The first was Pile 4 driven with a diesel hammer in a water depth of two feet. The confined bubble curtain was deployed for this pile and bubbles were on during the entire driving event. However, the outer casing for the bubble curtain indicated that it was tilted slightly to one side. This is likely the result of large rocks or boulders on the bottom not allowing the outer casing to seat properly.

Table 5 indicates the results of monitoring for Pile 4. The absolute peak was 198 dB_{peak}, the RMS was 186 dB_{RMS}, and the SEL was 169 dB. As can be seen in Appendix A Figure 18a, the waveform analysis for Pile 4 indicates that there was a relatively long delay between the initial onset of the impulse and the absolute peak (rise time of 9.3 milliseconds). This typically indicates a 'ringing' of the pile when the pile encounters a hard substrate such as rock. In Appendix A Figure 18c, the SEL plot indicates a moderately slow accumulation of energy indicated by the slightly rounded 'shoulder' at the upper left of the plot.

In Appendix A Figure 18b, the frequency spectrum indicates that the frequency amplitudes contained a dominant frequency between 800 Hz and 900 Hz. This is typical of what is observed for steel pile driving activities.

Pile 5 – (Deep Water Depth)

The second of two piles driven at this depth was Pile 5 driven with a diesel hammer in a water depth of two feet. A large grab was used to pluck the larger boulders ranging from four to five feet across from the site where Pile 5 was to be driven. This would also have the additional benefit of allowing the casing on the bubble curtain to seat properly. The confined bubble curtain was deployed for this pile and bubbles were on during the entire driving event (Figure 10).

Table 5 indicates the results of monitoring for Pile 5. The absolute peak was 192 dB_{peak}, the RMS was 180 dB_{RMS}, and the SEL was 164 dB. As can be seen in Appendix A Figure 20a, the waveform analysis for Pile 5 indicates that there was a moderately short delay between the initial onset of the impulse and the absolute peak (rise time of 2.1 milliseconds). This is a typical waveform observed for steel piles. In Appendix A Figure 20c, the SEL plot indicates a moderately rapid accumulation of energy indicated by the slightly angled 'shoulder' at the upper left of the plot.

In Appendix A Figure 20b, the frequency spectra indicates that the frequency amplitudes contained a dominant frequency around 800 Hz. This is typical of what is observed for steel pile driving activities.

Frequency spectra for Pile 4 and Pile 5 were plotted together for comparison (Figure 11). Each pile had a bubble curtain operating, however, for Pile 4 you can clearly see that the amplitudes of most frequencies are greater and for Pile 5 the amplitudes of most frequencies are lower than for Pile 4. This indicates that the bubble curtain was functioning properly for Pile 5 but not for Pile 4 because the bubble curtain reduced the frequencies in Pile 5. It was also observed in the field that the bubble curtain appeared seated properly on the bottom and foaming bubbles could be seen at the top of the casing for Pile 5 but not for Pile 4.

Figure 10: Pile 5 with Bubble Curtain in Operation.

Table 5: Summary of Underwater Sound Level Impacts and Mitigation for Piles 4 and 5 (Deep Water Depth).

Pile #	Date	Hydrophone Depth	Bubble Curtain Rings On	Absolute Peak (dB)	Average Peak (dB ± s.d.)	n[2]	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	% Strikes Exceeding 180 dB$_{peak}$	% Strikes Exceeding 150 dB$_{RMS}$
4	6/14/05	1-foot	YES	198[1]	193 ± 183	164	-	175 ± 165	169	9.3	96	100
5	6/14/05	1-foot	YES	192[1]	188 ± 177	290	5	171 ± 159	164	2.1	95	100

[1] – Absolute peak value is peak overpressure.

[2] – Number of pile strikes included in the average calculations.

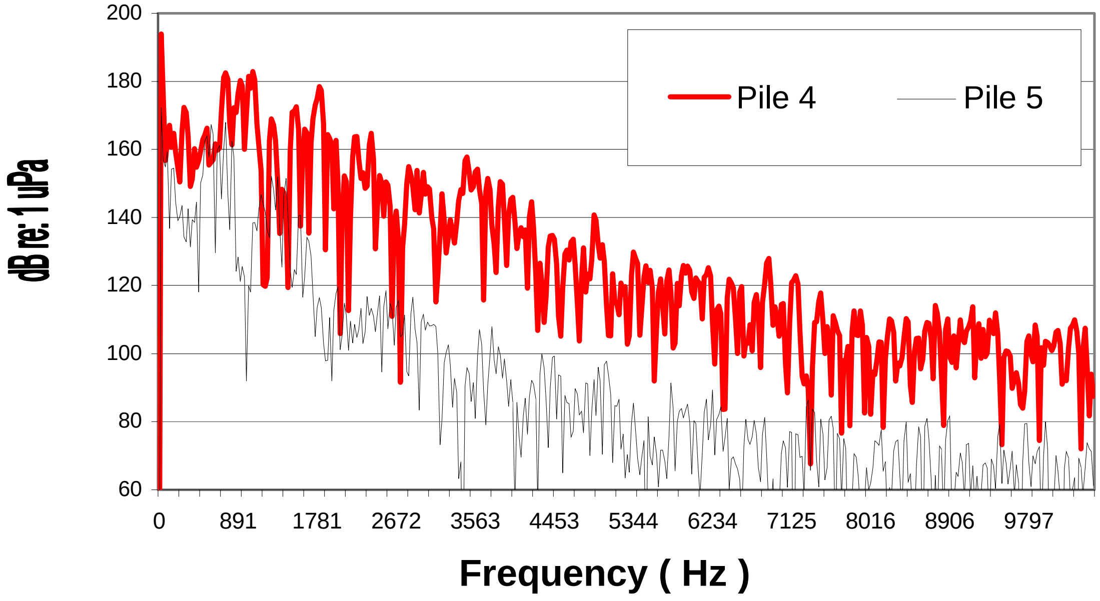


Figure 11: Comparison of Frequency Spectral Analysis for Piles 4 and 5.

Figure 12 shows the average peak underwater sound pressure levels for Piles 1 through 5 (± one standard deviation). The plot indicates the high degree of variability from pile strike to pile strike for each pile. The average values are fairly consistent with the values for Pile 3 being somewhat lower due to the reduced stroke length.

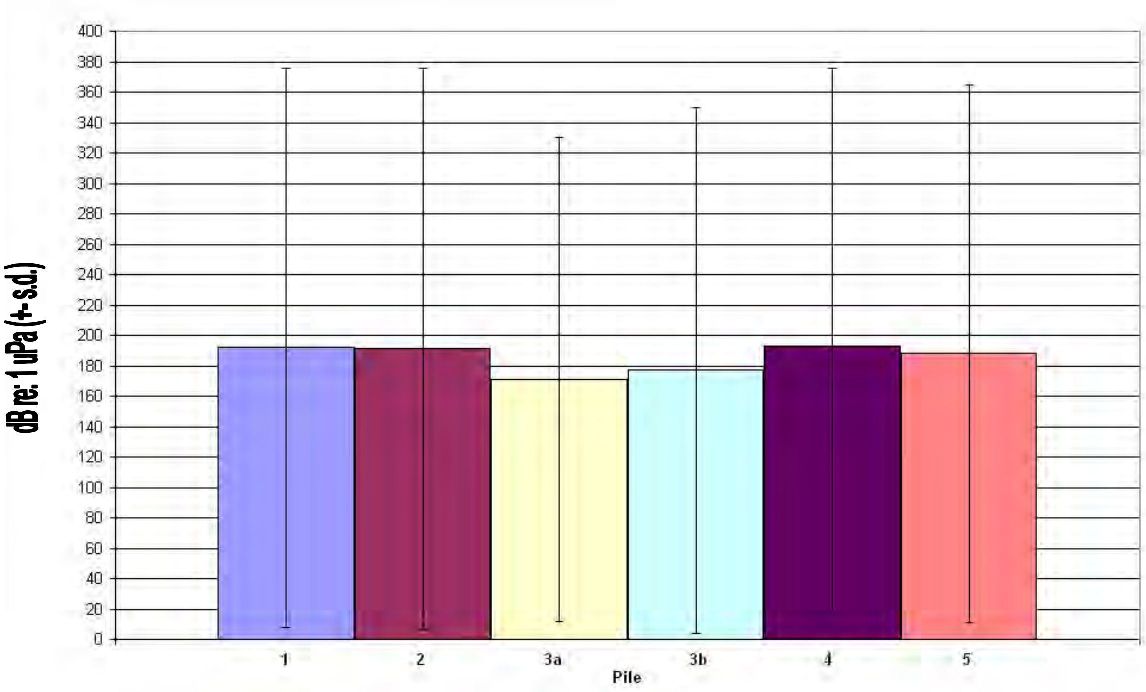


Figure 12: Average dB_{peak} levels (± one standard deviation) for each pile.

Figure 13 shows the average RMS values for Piles 1 through 5 (± one standard deviation). The plot indicates the high degree of variability of RMS values from pile strike to pile strike for each pile. The average values are fairly consistent with the values for Pile 3 being somewhat lower due to the reduced stroke length. There is also no apparent trend observed with increasing water depth.

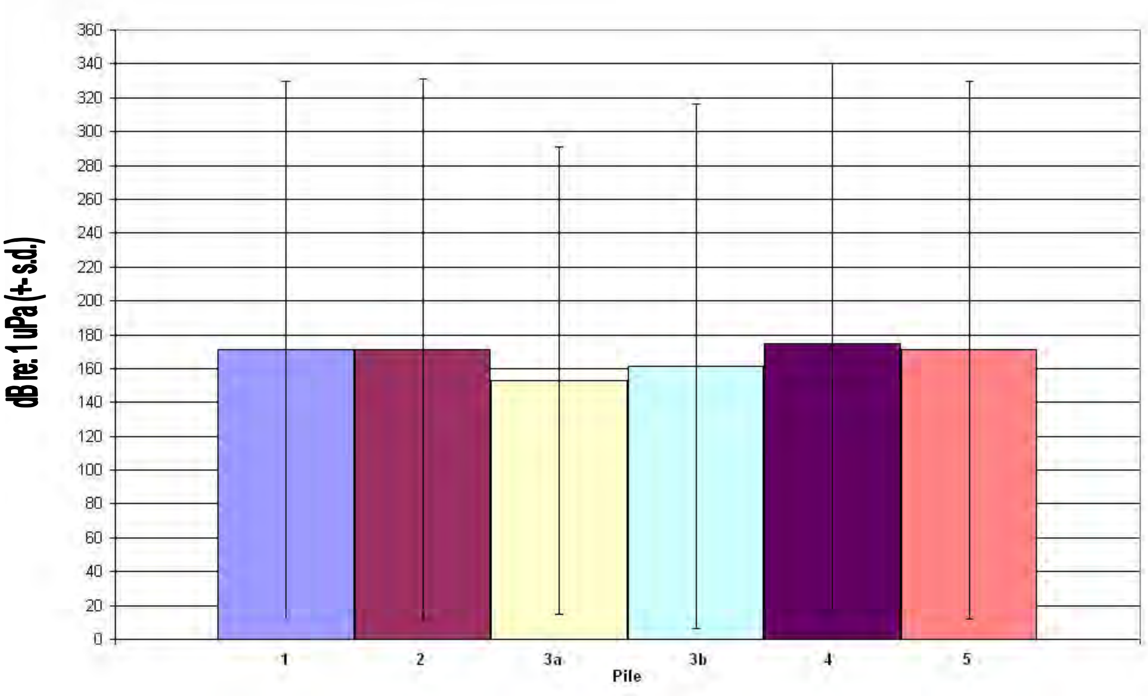


Figure 13: Average dB_{RMS} values (± one standard deviation) for each pile.

SEL

SEL was calculated for each of the absolute peak strikes for each pile. Figure 14 graphically shows that the SEL values for each absolute peak strike for each pile were fairly consistent, the exception being Pile 3 where the contractor reduced the stroke length of the hammer resulting in lower SEL values. None of the SEL values exceeded the proposed threshold of 194 dB SEL from Hastings and Popper (2005). Because decibels are on a logarithmic scale, it would require substantially more energy to exceed this threshold. It would require increasing the energy at least 128 times in order to exceed this threshold. There is also no apparent trend with increasing water depth.

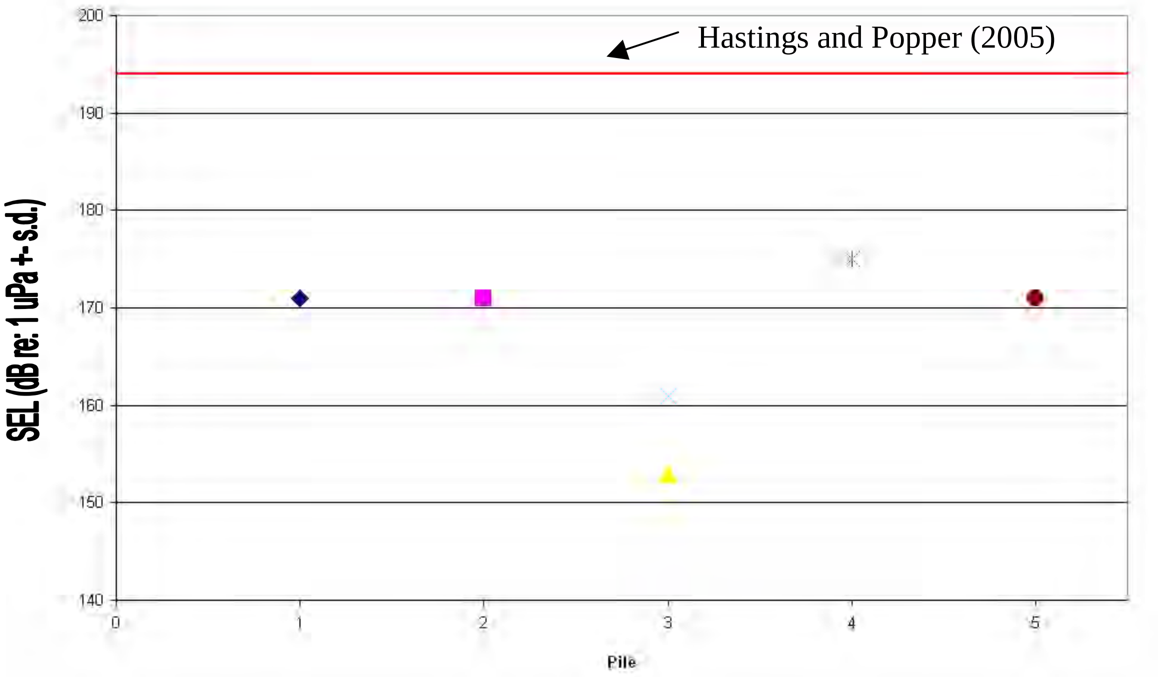


Figure 14: Plot of SEL values for peak pile strike for each pile referenced to the 194 dB SEL threshold proposed by Hastings and Popper (2005).

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 Pile 5, the rise time was relatively long. This could be an indication that the pile was ringing due to the hard substrate or an indication of 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.

Underwater Ambient Noise Levels (No Construction Activity)

Ambient underwater sound levels were measured after construction activity had ceased for the day as well as during construction activity between pile drives. Ambient underwater noise levels with no construction activity ranged between 152 dB_{peak} and 155 dB_{peak}. With construction activity, the ambient underwater noise levels ranged between 151 dB_{peak} and 155 dB_{peak}. This is somewhat higher than has been measured in calmer waters and is due primarily to the flow of the water over the river bottom and small waves created by currents at the surface.

BIOLOGICAL OBSERVATIONS

A few juvenile salmonid fingerlings about two inches in length were observed at the waters edge within the pile driving area. No fish mortality or distress was observed before, during, or after pile driving. No fish were observed in the immediate area around the piles. Swallows and a pair (male and female) of Mallard ducks were observed feeding in the area around the pile driving activity. 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.

DRIVING ‘DRY’ PILES

In addition to monitoring the five required piles that were driven in water the data collection team was able to monitor two additional piles that were driven above the rivers edge. The first pile had a peak value of 165, an RMS value of 150 and an SEL value of 140. These values are typical of piles driven above the waterline but monitored with the hydrophone in water. All of the sound is being transmitted through the ground (sound flanking). The rise time for this pile was 9.1 milliseconds and is similar to what we saw for most of the piles driven in water. The waveform plots for this pile is shown in Appendix B Figure 21.

The second pile had a peak value of 171, an RMS value of 159 and an SEL value of 148. These values are typical of piles driven above the waterline but monitored with the hydrophone in water. All of the sound is being transmitted through the ground (sound flanking). The rise time for this pile was 9.8 milliseconds and is similar to what we saw for most of the piles driven in water. The increased rise times for these two dry piles suggests that most of the sound was not traveling through the water column but through the sediment. However, this relationship is not clearly understood. The waveform plots for this pile is shown in Appendix B Figure 22.

WATER QUALITY

During pile driving operations and operations to remove rip rap from the river, turbidity and water temperature were measured upstream and downstream of the project. Table 6 summarizes the results of these measurements.

Table 6: Summary of Temperature and Turbidity Measurements.

Date	Location	Temperature (°F)	Turbidity (NTU)
6/6/05	Up River	nr	3.76
	Down River	nr	3.74
6/7/05	Up River	nr	3.35
	Down River	nr	4.58
		nr	4.37

Date	Location	Temperature (°F)	Turbidity (NTU)
		nr	3.58
		nr	4.92
		nr	3.13
6/10/05	Up River	55.9	4.52
		60.4	3.72
		63.5	3.43
	Down River	nr	3.65
		nr	7.87
6/13/05	Up River	57.3	3.18
	Down River	nr	4.37
6/14/05	Up River	57.7	3.09
		nr	3.39
	Down River	nr	3.46
		nr	4.88

CONCLUSIONS

All piles with the exception of Pile 3 exceeded the 180 dB_{peak} and 150 dB_{RMS} thresholds set by NMFS. For those piles where the bubble curtain was used, only Pile 5 appeared to have a functioning confined bubble curtain. The bubble curtain on all other piles did not function properly, partly because it did not seat itself completely on the river bottom and partly because the water was too shallow to provide mitigation.

A bubble curtain is very difficult to deploy on a river bottom strewn with boulders and large rocks. A shallow river system may also inhibit harmful sound levels from propagating through the water. The modified waveform exiting the sediment into the water column via sound flanking may be rendered harmless. However, more research will be needed to confirm this possibility.

Mitigation in the form of a bubble curtain in a shallow river system with rocks and boulders is at best difficult to deploy. The large rocks and boulders can render the bubble curtain ineffective. The cost of providing this type of mitigation for these projects may not be reasonable because they are not working effectively.

All piles except for Pile 5 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 SEL values calculated on the absolute peak pile strike exceeded the proposed threshold of 194 dB SEL (Hastings and Popper, 2005). 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.

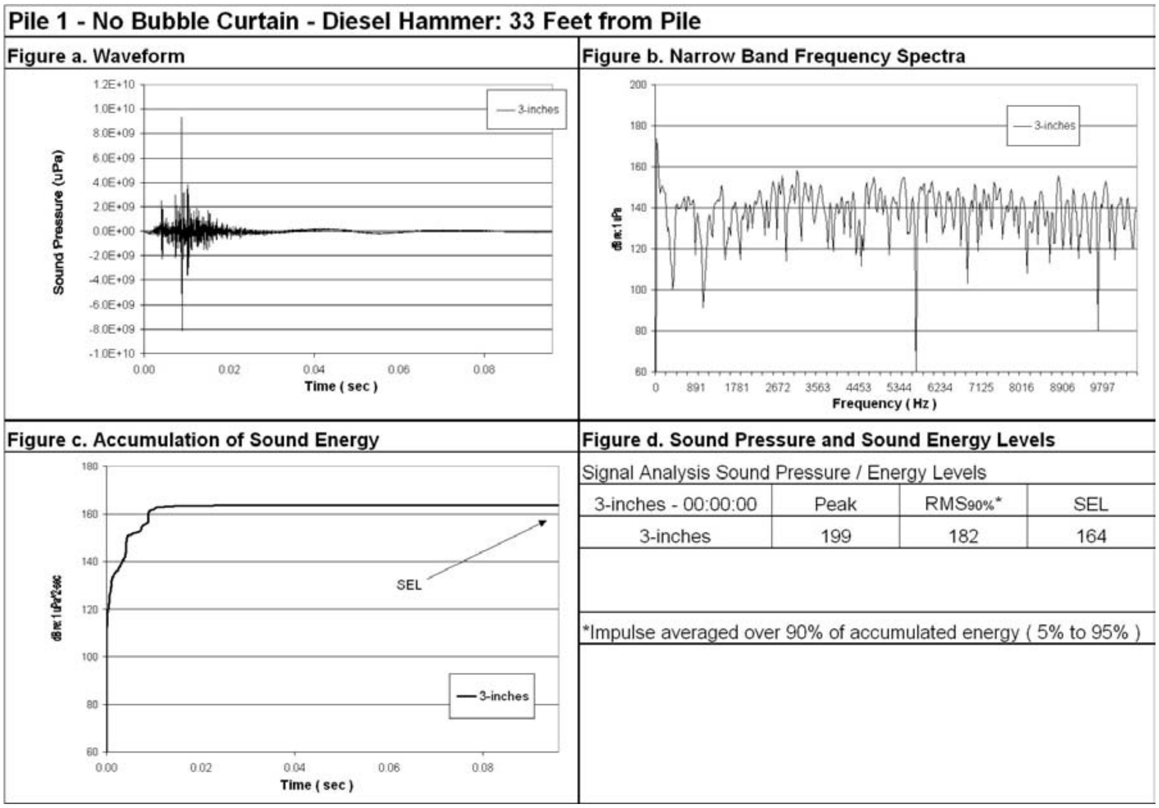
REFERENCES

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.

APPENDIX A– WAVEFORM ANALYSIS FIGURES

PILE 1 – SHALLOW WATER DEPTH – NO BUBBLE CURTAIN



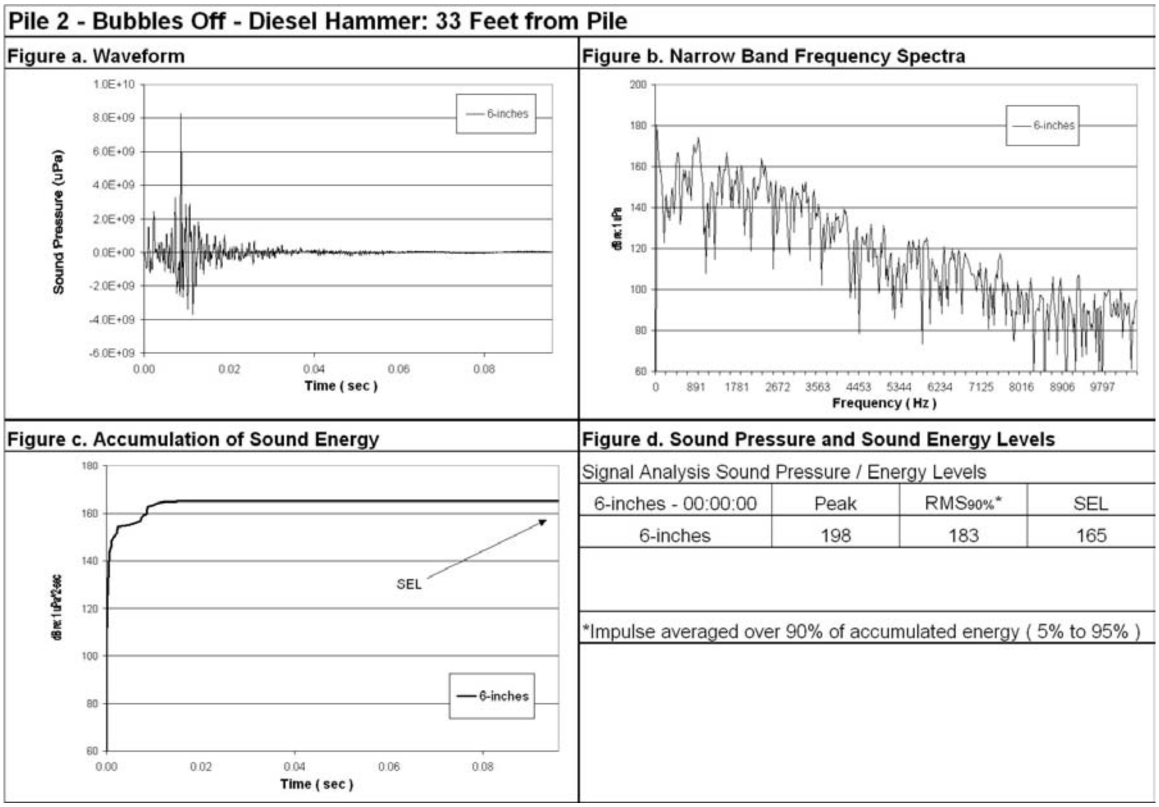
Signal Analysis Sound Pressure / Energy Levels

3-inches - 00:00:00	Peak	RMS90%*	SEL
3-inches	199	182	164

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

Figure 15: Waveform Analysis of Pile 1 Sound Pressure Levels without a Bubble Curtain.

PILE 2 – INTERMEDIATE WATER DEPTH – BUBBLE CURTAIN



Pile 2 - Bubbles Off - Diesel Hammer: 33 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

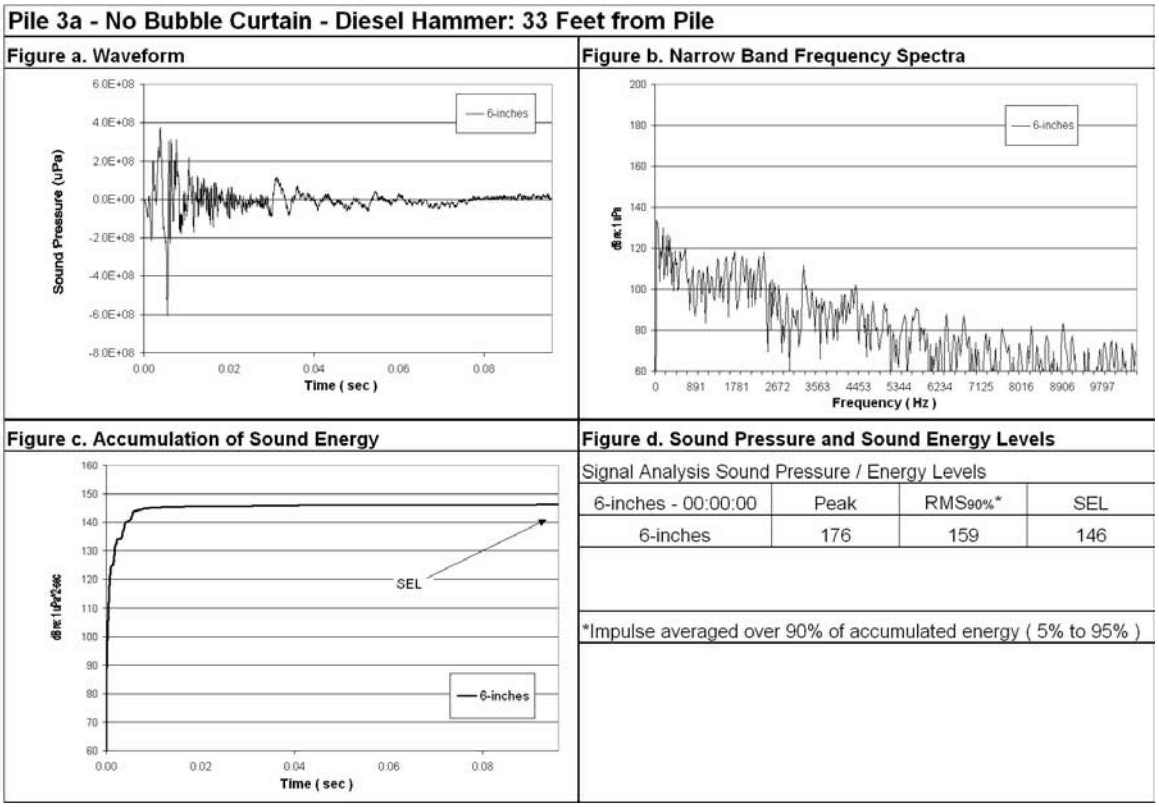
Signal Analysis Sound Pressure / Energy Levels

6-inches - 00:00:00	Peak	RMS90%*	SEL
6-inches	198	183	165

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

Figure 16: Waveform Analysis of Pile 2 Sound Pressure Levels with Bubble Curtain.

PILE 3 – INTERMEDIATE WATER DEPTH – WITH AND WITHOUT BUBBLE CURTAIN



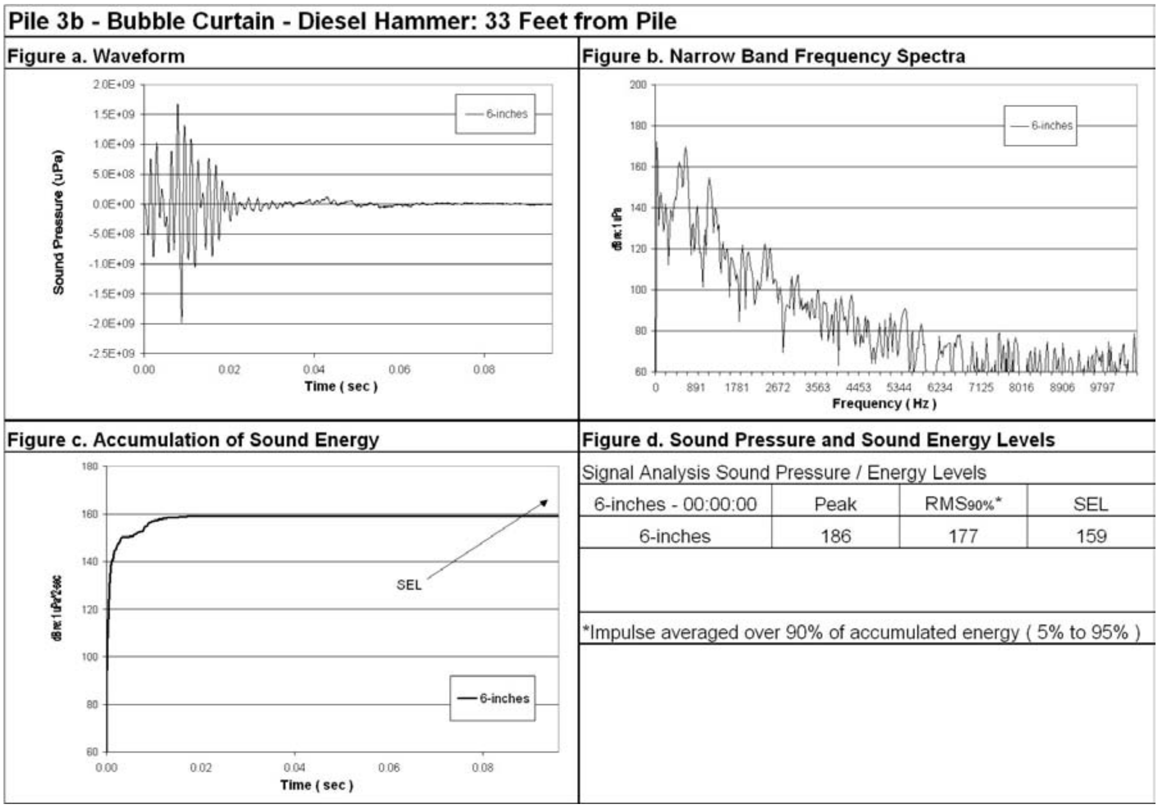
Pile 3a - No Bubble Curtain - Diesel Hammer: 33 Feet from Pile

Signal Analysis Sound Pressure / Energy Levels

6-inches - 00:00:00	Peak	$\text{RMS}_{90\%}$*	SEL
6-inches	176	159	146

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

Figure 17: Waveform Analysis of Pile Number 3 with Bubbles Turned Off.



Pile 3b - Bubble Curtain - Diesel Hammer: 33 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

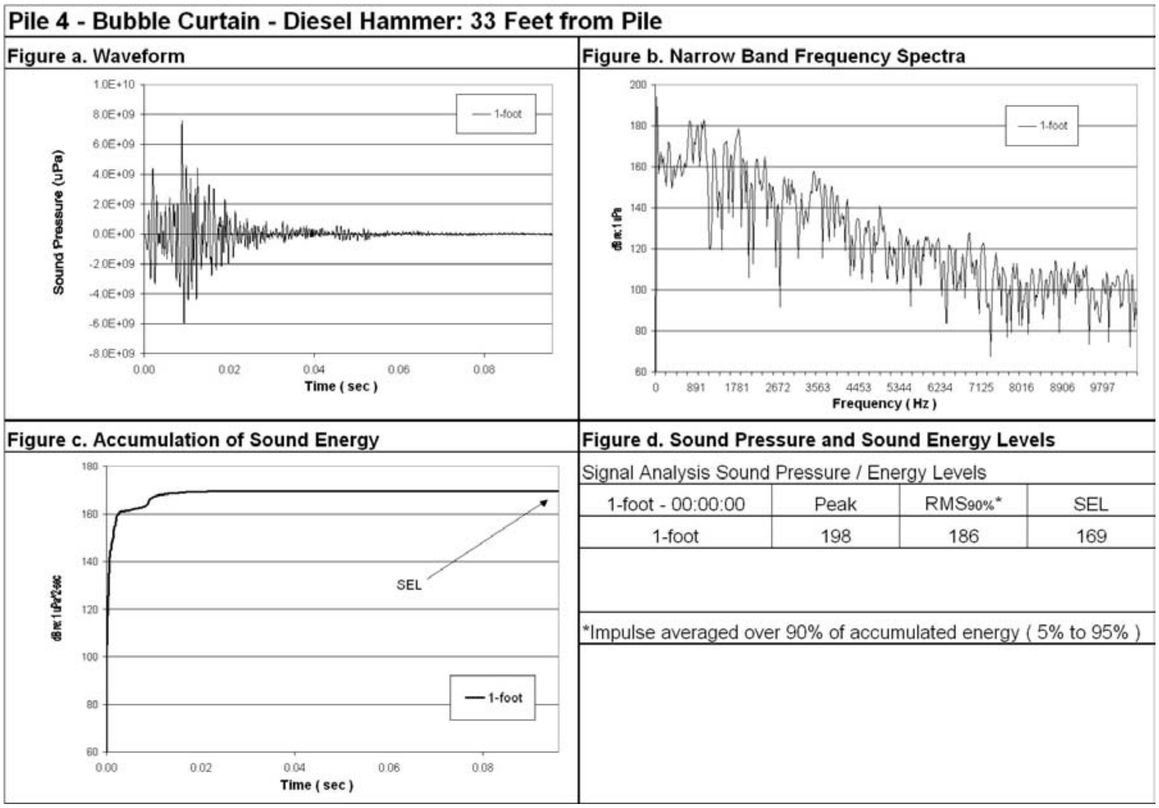
Signal Analysis Sound Pressure / Energy Levels

6-inches - 00:00:00	Peak	RMS90%*	SEL
6-inches	186	177	159

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

Figure 18: Waveform Analysis of Pile Number 3 with Bubbles Turned On.

PILE 4 – INTERMEDIATE WATER DEPTH – WITH AND WITHOUT BUBBLE CURTAIN



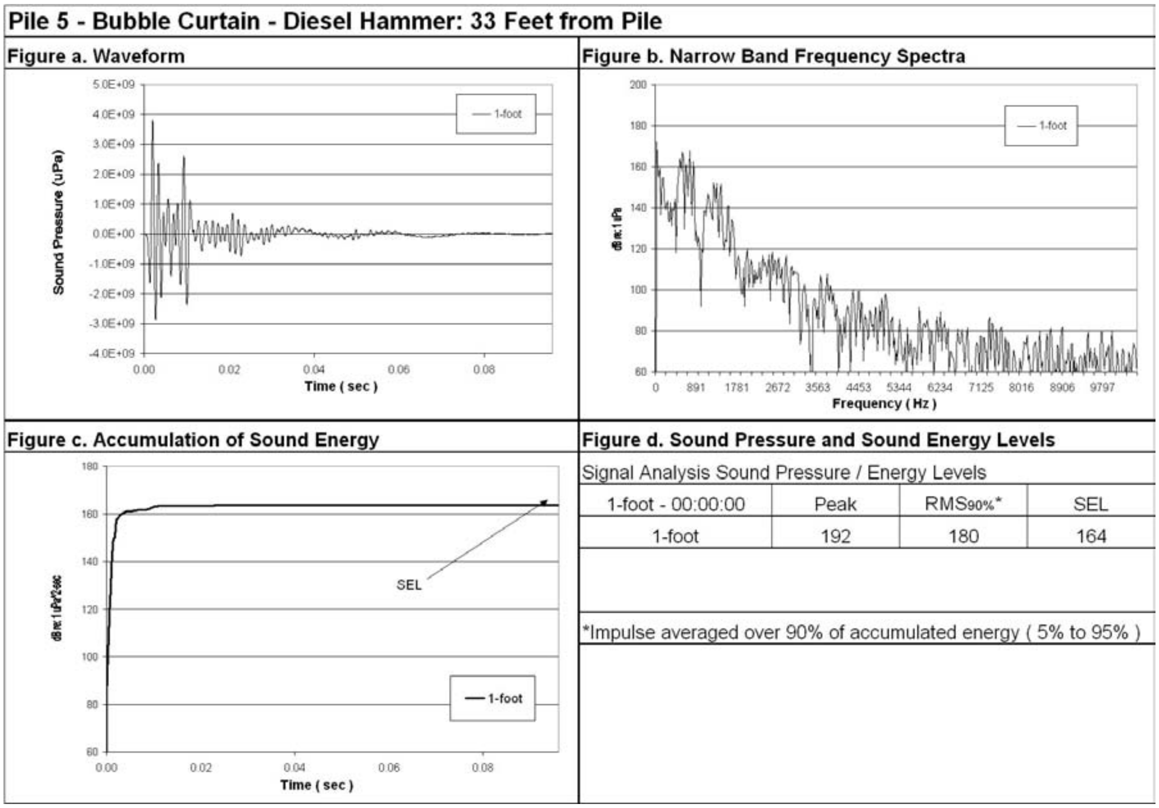
Signal Analysis Sound Pressure / Energy Levels

1-foot - 00:00:00	Peak	RMS90%*	SEL
1-foot	198	186	169

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

Figure 19: Waveform Analysis of Pile Number 3 with Bubbles Turned On.

PILE 5 – INTERMEDIATE WATER DEPTH – WITH AND WITHOUT BUBBLE CURTAIN



Pile 5 - Bubble Curtain - Diesel Hammer: 33 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

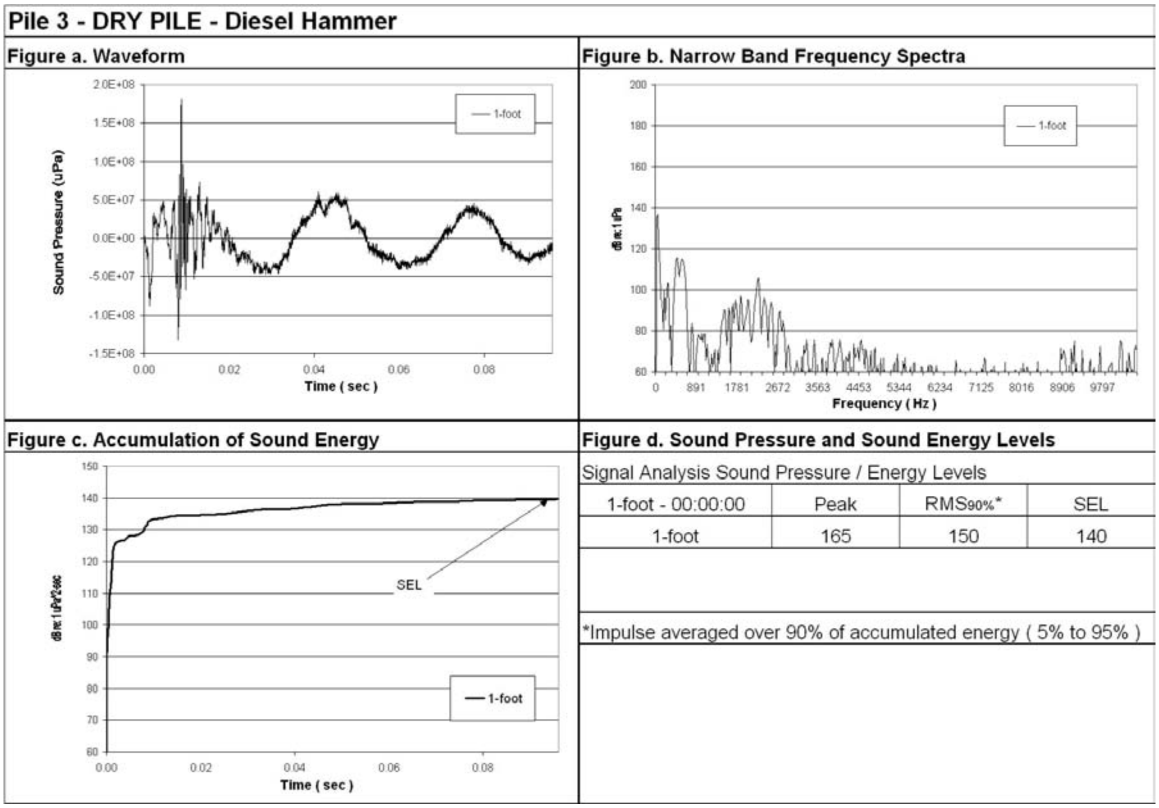
1-foot - 00:00:00	Peak	$RMS_{90\%}$*	SEL
1-foot	192	180	164

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

Figure 20: Waveform Analysis of Pile Number 5 with Bubbles Turned On.

APPENDIX B– WAVEFORM ANALYSIS FIGURES

DRY PILE 1



Pile 3 - DRY PILE - Diesel Hammer

Figure a. Waveform

Figure b. Narrow Band Frequency Spectra

Figure c. Accumulation of Sound Energy

Figure d. Sound Pressure and Sound Energy Levels

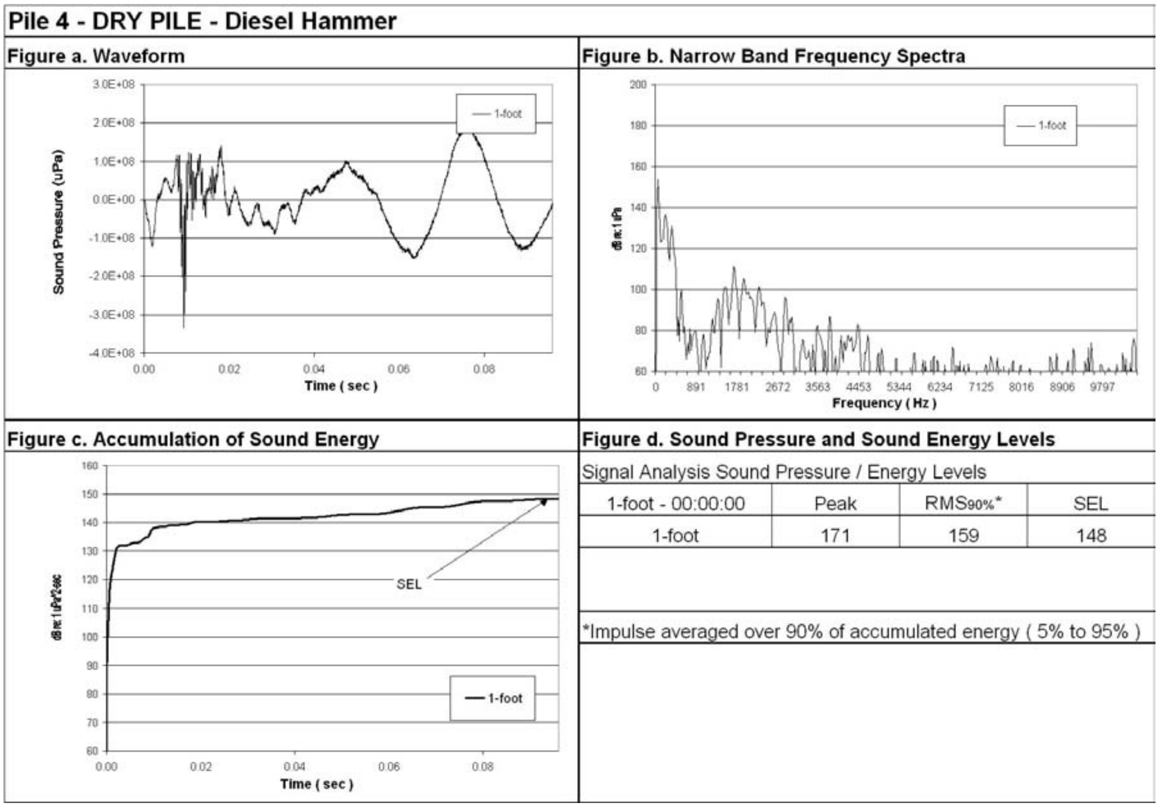
Signal Analysis Sound Pressure / Energy Levels

1-foot - 00:00:00	Peak	RMS90%*	SEL
1-foot	165	150	140

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

Figure 21: Waveform Analysis of a 'Dry' Pile Driven Outside the Water.

DRY PILE 2



Pile 4 - DRY PILE - Diesel Hammer

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	171	159	148

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

Figure 22: Waveform Analysis of a 'Dry' Pile Driven Outside the Water.