WASHINGTON STATE PARKS CAPE DISAPPOINTMENT WAVE BARRIER PROJECT

UNDERWATER SOUND LEVELS ASSOCIATED WITH PILE DRIVING AT THE CAPE DISAPPOINTMENT BOAT LAUNCH FACILITY, WAVE BARRIER PROJECT

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EXECUTIVE SUMMARY

This technical report describes the data collected during pile driving efforts at the Cape Disappointment boat launch facility near Ilwaco, Washington during the month of December 2005. One 12-inch diameter standard steel pile and four 12-inch piles with 1.5-foot wide interlocking steel 'wings' on two sides were monitored at different water depths at the Cape Disappointment boat launch facility.

Piles were driven using different pile cap materials and monitored to look for differences (in sound pressure?). The pile cap materials tested were wood (plywood), Conbest, Micarta, and Nylon. Piles were driven with an air hammer. Table 1 summarizes the results for each pile monitored. The bubble curtain was tested with the bubbles off and then on during the pile driving events.

Micarta achieved the best sound level reductions, with the exception of wood, while retaining hammer efficiencies and minimizing safety hazards.

Ambient sound levels averaged approximately 148 dB_{peak} to 155 dB_{peak} with construction equipment. The maximum sound reduction achieved using a pile cap was 27 dB with the wood pile cap. The maximum sound reduction achieved with the bubble curtain was 17 dB.

Table 1: Summary Table of Monitoring Results.

Pile #	Date	Hydrophone Depth	Pile Cap Material	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (Pascals ± s.d.)	Average Decibel Reduction from Bubble Curtain	SEL (dB)	Rise Time (msec)
1	12/13/05	13 feet (midwater)	Conbest	OFF	207	189	8667± 5225	-	173	11.7
				ON	198	181	5215 ± 1515	5	166	4.4
			Wood	OFF	180[1]	165	812 ± 168	-	154	37.7
				ON	181	170	707 ± 209	1	157	14.4
			None	OFF	208	191	16174 ± 4625	-	175	1.8
				ON	199	183	4625 ± 2564	11	168	1.9
		25 feet (bottom)	Conbest	OFF	205	188	8861 ± 4338	-	173	11.7
				ON	206	187	9533 ± 3961	5	173	10.7
			Wood	OFF	181	168	910 ± 165	-	157	34.8
				ON	181	169	712 ± 191	2	157	36.6
			None	OFF	205[1]	185	9550 ± 5370	-	171	1.5
				ON	193	176	2243 ± 845	13	164	2.7
2	12/14/05	8 feet (midwater)	None	OFF	203	188	7696 ± 4044	-	175	3.7
				ON	195	176	1665 ± 258	14	165	12.6
		16 feet (bottom)	None	OFF	202	189	6771 ± 4226	-	176	4.6
				ON	195	179	1956 ± 787	11	166	12.6
3	12/14/05	8 feet (midwater)	Micarta	OFF	195[1]	182	554 ± 138	-	169	7.8
				ON	183	169	164 ± 26	11	157	12.7
		16 feet (bottom)	Micarta	OFF	194[1]	182	3054 ± 1292	-	169	13.1
				ON	186[1]	175	1345 ± 209	7	161	21.2

Pile #	Date	Hydrophone Depth	Pile Cap Material	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (Pascals ± s.d.)	Average Decibel Reduction from Bubble Curtain	SEL (dB)	Rise Time (msec)
4	12/14/05	8 feet (midwater)	Nylon	OFF	196[1]	183	5247 ± 709	-	169	12.4
				ON	184	169	681 ± 241	17	157	5.4
		16 feet (bottom)	Nylon	OFF	194[1]	181	4176 ± 598	-	168	7.8
				ON	188[1]	176	1800 ± 167	7	161	2.9
5	12/14/05	8 feet (midwater)	Wood	OFF	188[1]	175	1677 ± 544	-	162	6.8
				ON	182	171	807 ± 226	6	157	16.9
		16 feet (bottom)	Wood	OFF	190	176	2092 ± 601	-	165	22.1
				ON	186	179	1592 ± 277	2	163	17.1

[1] – Absolute peak value is peak underpressure.

INTRODUCTION

This technical report presents results of underwater sound levels measured during the driving of one 12-inch standard steel pile and four 12-inch steel piles with 1.5 foot steel interlocking ‘wings’ on two sides at the Cape Disappointment boat launch facility in December 2005 (Interagency Agreement GCA4755). The environmental review and permitting effort led to a negotiated 'mitigated determination of non-significance' (MDNS) where a framework of successive mitigation decisions were made by an interagency team with the goal to achieve the greatest protection for listed species.

The piles were driven to replace the existing wood wave barrier. The five piles were monitored while being driven with different pile cap materials at different water depths at the facility. The pile cap materials used were wood (plywood), Conbest, Micarta, and Nylon (Figure 1). The Conbest material is not shown in Figure 1 but is similar to Micarta in size and thickness but looks like a layered aluminum disk in composition. The bubble curtain was tested with on/off cycles during each pile driving event. Figure 2 shows the piles with ‘wings’ and Figure 3 shows the locations of monitored piles.

PROJECT DESCRIPTION

This project is removing old rotting sections of the boat launch wave barrier and replaced it with a steel pile wave barrier. The project location is on the north side of the Cape Disappointment boat launch facility near Ilwaco, Washington (Figure 3). Figure 3 shows the approximate pile locations. Monitoring for pile 1 was 33 feet southwest of the pile and for piles 2-5 33 feet northwest of each pile between the pile and the barge. Water depths at the monitoring locations varied from 12 to 26 feet deep. There was a substantial tidal current in the area during the monitoring of the piles.

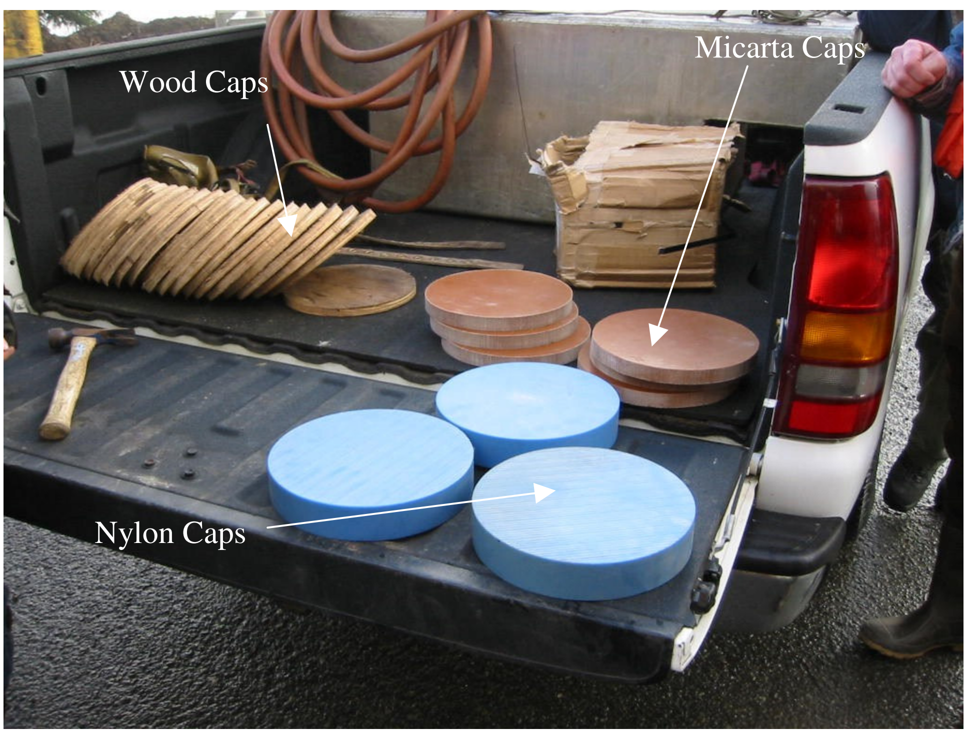

Figure 1: Pile cap types tested in this monitoring project (Conbest pile cap not shown).

Figure 2: 12-inch diameter steel piles with interlocking ‘wings’ used to create the wave barrier (photo courtesy of Washington State Parks and Recreation, R. Johnson).

Figure 3: Location of underwater noise monitoring sites at the Cape Disappointment Wave Barrier project. Note: Piles are not to scale.

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 peak 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 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 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.

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.

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/m3) 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,

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

METHODOLOGY

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

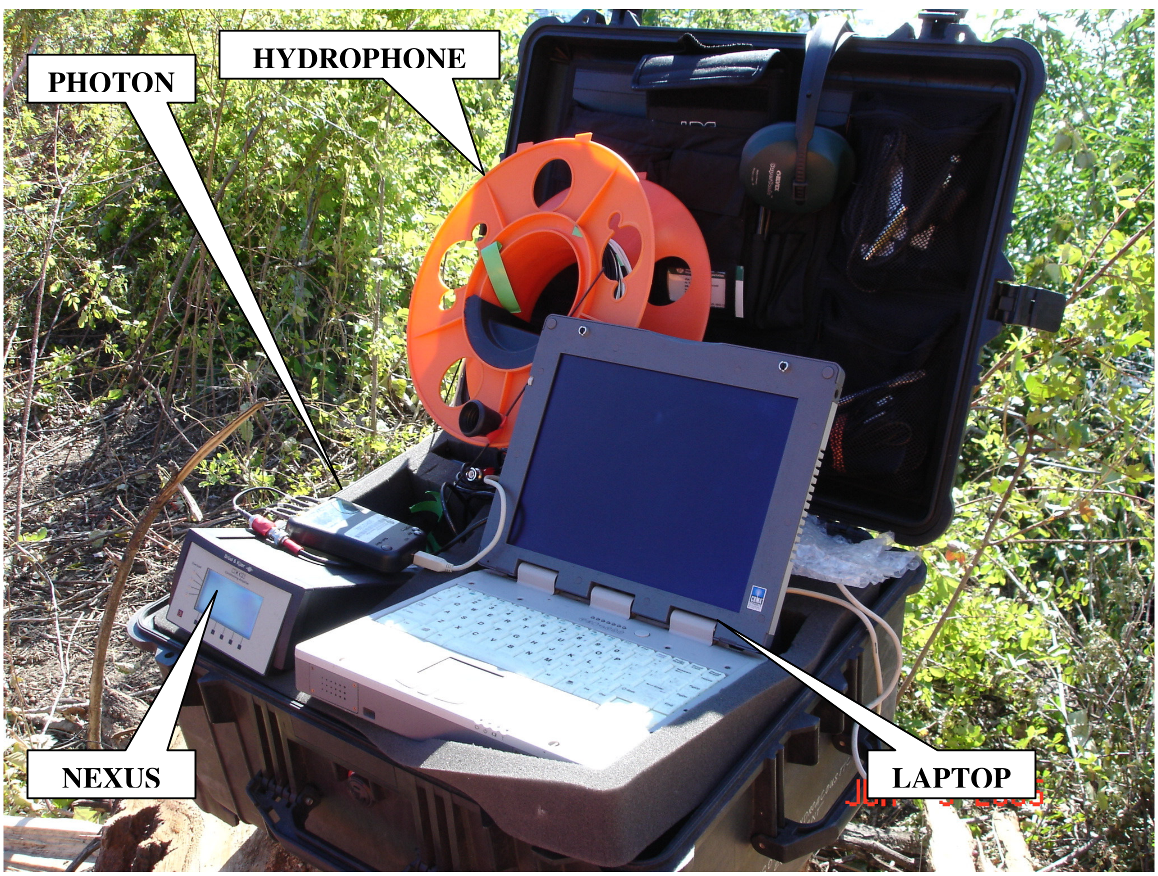

Figure 4: Underwater Sound Level Measurement Equipment

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.

A vibratory hammer was used to drive the first two piles initially. Then all piles were driven to appropriate depth with an air hammer. The Vulcan air impact hammer with an energy rating of 52,000 ft.-lbs. was used for this project. This is the maximum energy output for the air hammer that can only be sustained for a few seconds at a time. Actual operation of the air hammer is more likely to be approximately 50% to 70% of this maximum energy for most pile installations.

The substrate consisted of a mix of silt and mud with a harder glacial till layer below. Piles driven were one open-ended hollow steel pile, 12-inches in diameter with a 3/8-inch wall thickness. Four additional open-ended hollow steel piles 12-inches in diameter with 1.5 foot interlocking ‘wings’ on two sides were driven to form the wave barrier. All measurements were made 33 feet from the pile, at mid-water depth and one foot from the bottom.

Each measured pile site is described below:

Pile 1 –

Located approximately 150 feet offshore at the farthest end of the new wave barrier (See Figure 1). The pile is located in 26 feet of water.

Piles 2 – 5

Piles 2 through 5 were driven while interlocked with three or more other piles starting approximately 10 feet inshore of pile 1. These piles ranged in depth between 16 and 12 feet of water dependent on tidal level.

The location of the hydrophones is determined by allowing a clear line of sight between the pile and the hydrophone, with no other structures nearby. The distance from the pile to the hydrophone location was measured using a Bushnell Yardage Pro rangefinder. The hydrophone was attached to a weighted nylon cord anchored with a five-pound weight. The cord and hydrophone cables were attached to surface floats that kept the hydrophones at the proper location in the water column (Figure 5). For pile 1, the hydrophones were in a location with no other obstructions near it. For piles 2 through 5, the hydrophones were located between the pile and the barge.

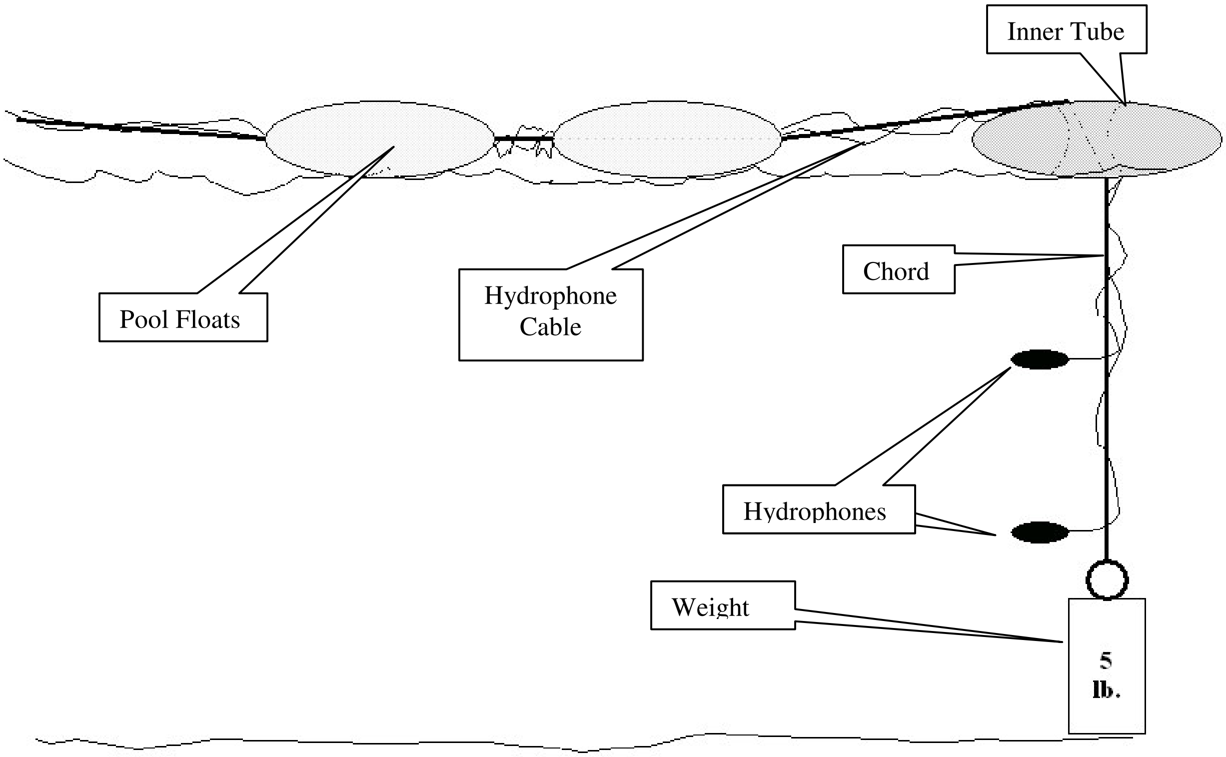

Figure 5: Diagram of hydrophone deployment.

BUBBLE CURTAIN DESIGN

Two bubble curtain designs were used by the contractor at the Cape Disappointment Boat Launch facility. The first was a standard single ring placed at the bottom of pile 1 based on the design of Longmuir and Lively (2001). The second bubble curtain was a "U" shaped design that enabled the curtain to be fitted around the base of several piles that were interlocked together in a wall design (Figure 6).

It is important to note that during the use of the "U" shaped bubble curtain on piles 2 through 5 the tidal current swept some of the bubble curtain away from the pile being driven. This happened after high tide as water began to recede rapidly. However, as can be seen in the analysis that follows it had little or no impact on the effectiveness of the bubble curtain.

Figure 6: "U" shaped bubble curtain for use on wave barrier piles.

RESULTS

UNDERWATER SOUND LEVELS

Pile 1

Pile 1 was driven with an air hammer in a water depth of 26 feet. The bubble curtain was off at the start of the drive and then 22 seconds into the drive the bubble curtain was turned on. Pile 1 was tested first using a pile cap material of Conbest and then restruck with a wood pile cap and then finally restruck with no pile cap. Tables 2 and 3 indicate the results of monitoring for Pile 1.

CONBEST

The highest absolute peak from the midwater hydrophone is 207 dB_{peak} and the absolute highest peak from the bottom hydrophone is 206 dB_{peak} for Conbest. The highest midwater and bottom RMS were both 189 dB_{RMS} and 188 dB_{RMS} respectively. The highest midwater and bottom SEL for the peak strike were both 173 dB_{SEL}. Rise time for the Conbest pile cap was relatively long indicating a reduction of the transfer of energy from the hammer. Virtually all of the peak values exceed 180 dB_{peak} and the RMS values exceeded 150 dB_{RMS} for both the midwater and bottom hydrophones.

Typical SEL values are 20 to 30 dB lower than the absolute peak. The SEL for Conbest averaged around 33 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.

The SEL per strike estimates in Tables 2 and 3 indicate that none of the calculated SEL values for a single strike (peak strike) exceeded the estimated summed SEL per strike thresholds.

The average sound reductions achieved with Conbest is 5 dB. The average peak sound reduction achieved with the bubble curtain was 5 dB. This indicates that the bubble curtain was providing a sound level reduction that is typical of most bubble curtains.

WOOD

The highest absolute peak from the midwater and bottom hydrophones is 181 dB_{peak} for wood. The highest midwater RMS was 170 dB_{RMS} and bottom RMS was 169 dB_{RMS}. The highest midwater and bottom SEL for the peak strike were both 157 dB_{SEL}. Rise times for the wood pile cap were quite long indicating a substantial reduction of the transfer of energy from the hammer. Figure 7 shows a wood pile cap that has been compressed and shattered after use on only three piles.

Figure 7: Fractured and compressed wood pile cap after being used on piles 5, 6, and 7 (photo courtesy of Washington State Parks and Recreation, R. Johnson)

Five peak strikes (11%) exceed 180 dB_{peak} at the midwater hydrophone and six peak strikes (13%) at the bottom hydrophone. All the RMS values exceeded 150 dB_{RMS} for both the midwater and bottom hydrophones.

The SEL for the wood pile cap averaged around 25 dB lower than the peak. None of the calculated SEL values for a single strike (peak strike) exceeded the estimated summed SEL per strike thresholds.

The average sound reductions achieved with wood is 24 db. The average peak sound reduction achieved with the bubble curtain was 2 dB. This indicates that the bubble curtain was not functioning as well as anticipated.

Table 2: Summary of Underwater Sound Level Impacts for Pile 1, Midwater.

Pile #	Date	Hydrophone Depth	Pile Cap Material	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (Pascals ± s.d.)	n[2]	Average Decibel Reduction from Bubble Curtain	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
1	12/13/05	13 feet (midwater)	Conbest	OFF	207	189	8667± 5225	46	-	179 ± 171	173	11.7	204
				ON	198	181	5215 ± 1515	56	5	175 ± 160	166	4.4	203
			Wood	OFF	180[1]	165	812 ± 168	6	-	163 ± 148	154	37.7	213
				ON	181	170	707 ± 209	41	1	165 ± 149	157	14.4	204
			None	OFF	208	191	16174 ± 4625	12	-	184 ± 177	175	1.8	210
				ON	199	183	4625 ± 2564	30	11	175 ± 164	168	1.9	206
							Total:	**191**				**Total:**	**186**

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

Table 3: Summary of Underwater Sound Level Impacts for Pile 1, Bottom.

Pile #	Date	Hydrophone Depth	Pile Cap Material	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (Pascals ± s.d.)	n[2]	Average Decibel Reduction from Bubble Curtain	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
1	12/13/05	25 feet (bottom)	Conbest	OFF	205	188	8861 ± 4338	46	-	178 ± 171	173	11.7	204
				ON	206	187	9533 ± 3961	56	5	175 ± 160	173	10.7	203
			Wood	OFF	181	168	910 ± 165	6	-	165 ± 151	157	34.8	213
				ON	181	169	712 ± 191	41	2	166 ± 152	157	36.6	204
			None	OFF	205[1]	185	9550 ± 5370	12	-	180 ± 173	171	1.5	210
				ON	193	176	2243 ± 845	30	13	172 ± 158	164	2.7	206
							Total:	**191**				**Total:**	**186**

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

Pile 2

Pile 2 was driven with an air hammer in a water depth of 16 feet. The bubble curtain was off at the start of the drive and then 166 seconds into the drive the bubble curtain was turned on. Pile 2 was tested using no pile cap material. Tables 4 and 5 indicate the results of monitoring for Pile 2.

The highest absolute peak from the midwater hydrophone is 203 dB_{peak} and the absolute highest peak from the bottom hydrophone is 202 dB_{peak}. The highest midwater RMS was 188 dB_{RMS} and bottom RMS was both and 189 dB_{RMS} respectively. The highest midwater SEL was 175 dB_{SEL} and bottom SEL was 176 dB_{SEL} for the peak strikes. Rise times with no pile cap were relatively short with the bubble curtain turned off but then lengthened when the bubbles were turned on. 137 peak pile strike (71%) values exceeded 180 dB_{peak} for the midwater and bottom hydrophones with the bubble curtain on. Virtually all the RMS values exceeded 150 dB_{RMS} for both the midwater and bottom hydrophones.

Typical SEL values are 20 to 30 dB lower than the absolute peak. The SEL with no pile cap averaged around 28 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.

The SEL per strike estimates in Tables 4 and 5 calculated using the formula given in the 'Characteristics of Sound' chapter above indicate that none of the calculated SEL values for a single strike (peak strike) exceeded the estimated summed SEL per strike thresholds.

The average peak sound reductions achieved with the bubble curtain ranged between 11 and 14 dB. This indicates that the bubble curtain was providing sound reduction better than a typical bubble curtain.

Table 4: Summary of Underwater Sound Level Impacts for Pile 2, Midwater.

Pile #	Date	Hydrophone Depth	Pile Cap Material	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (Pascals ± s.d.)	n[2]	Average Decibel Reduction from Bubble Curtain	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
2	12/14/05	8 feet (midwater)	None	OFF	203	188	7696 ± 4044	14	-	181 ± 175	175	3.7	209
				ON	195	176	1665 ± 258	180	14	169 ± 161	165	12.6	198
							Total:	**194**				**Total:**	**198**

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

Table 5: Summary of Underwater Sound Level Impacts for Pile 2, Bottom.

Pile #	Date	Hydrophone Depth	Pile Cap Material	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (Pascals ± s.d.)	n[2]	Average Decibel Reduction from Bubble Curtain	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
2	12/14/05	16 feet (bottom)	None	OFF	202	189	6771 ± 4226	14	-	181 ± 175	176	4.6	209
				ON	195	179	1956 ± 787	180	11	171 ± 160	166	12.6	198
							Total:	**194**				**Total:**	**198**

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

Pile 3

Pile 3 was driven with an air hammer in a water depth of 16 feet. The bubble curtain was off at the start of the drive and then 91 seconds into the drive the bubble curtain was turned on. Pile 3 was tested using a Micarta pile cap material. Tables 6 and 7 indicate the results of monitoring for Pile 3.

MICARTA

The highest absolute peak from the midwater hydrophone is 195 dB_{peak} and the absolute highest peak from the bottom hydrophone is 194 dB_{peak} for Micarta. The highest midwater and bottom RMS were both 189 dB_{RMS} and 188 dB_{RMS} respectively. The highest midwater and bottom SEL for the peak strike were both 169 dB_{SEL}. Rise time for the Micarta pile cap is relatively long indicating a reduction of the transfer of energy from the hammer. The highest midwater SEL for the peak strike was 178 dB_{SEL} and 180 dB_{SEL} for the bottom. Only 55 midwater pile strike peak values (37%) exceeded 180 dB_{peak} with the bubble curtain on. All but five bottom pile strike peak values exceeded 180 dB_{peak}. Virtually all pile strike RMS values exceeded 150 dB_{RMS} for both the midwater and bottom hydrophones.

Typical SEL values are 20 to 30 dB lower than the absolute peak. The SEL for Micarta averaged around 26 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.

The SEL per strike estimates in Tables 6 and 7 indicate that none of the calculated SEL values for a single strike (peak strike) exceeded the estimated summed SEL per strike thresholds.

The average peak sound reductions achieved with the bubble curtain ranged between 7 and 11 dB. This can be seen visually in Figure 8. This indicates that the bubble curtain was functioning slightly better than anticipated.

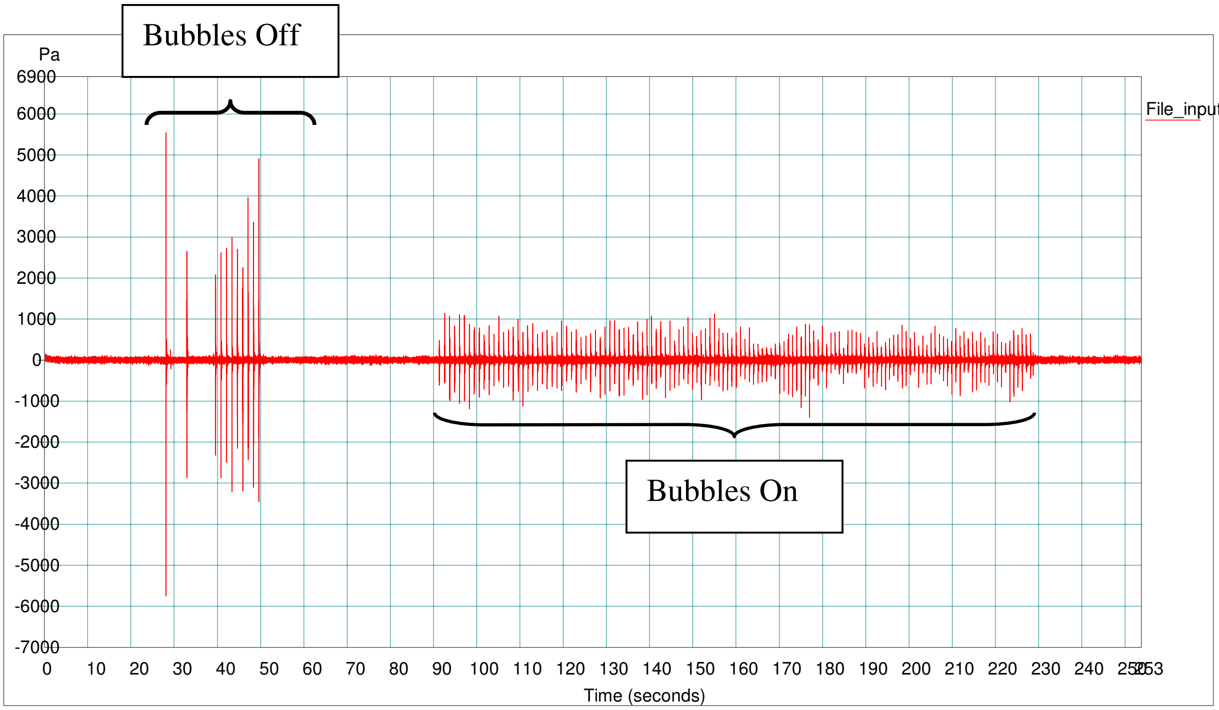

Figure 8: Waveform recording indicating the effects on amplitude with bubble curtain on versus bubble curtain off for pile 3.

Table 6: Summary of Underwater Sound Level Impacts for Pile 3, Midwater.

Pile #	Date	Hydrophone Depth	Pile Cap Material	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (Pascals ± s.d.)	n[2]	Average Decibel Reduction from Bubble Curtain	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
3	12/14/05	8 feet (midwater)	Micarta	OFF	195[1]	182	554 ± 138	13	-	175 ± 163	169	7.8	209
				ON	183	169	164 ± 26	134	11	164 ± 148	157	12.7	199
							Total:	**147**				**Total:**	**199**

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

Table 7: Summary of Underwater Sound Level Impacts for Pile 3, Bottom.

Pile #	Date	Hydrophone Depth	Pile Cap Material	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (Pascals ± s.d.)	n[2]	Average Decibel Reduction from Bubble Curtain	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
3	12/14/05	16 feet (bottom)	Micarta	OFF	194[1]	182	3054 ± 1292	13	-	176 ± 162	169	13.1	209
				ON	186[1]	175	1345 ± 209	134	7	169 ± 153	161	21.2	199
							Total:	**147**				**Total:**	**199**

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

Pile 4

Pile 4 was driven with an air hammer in a water depth of 15 feet. The bubble curtain was off at the start of the drive and then 52 seconds into the drive the bubble curtain was turned on. Pile 4 was tested using a Nylon pile cap material. Tables 8 and 9 indicate the results of monitoring for Pile 4.

NYLON

The highest absolute peak from the midwater hydrophone is 196 dB_{peak} and the absolute highest peak from the bottom hydrophone is 194 dB_{peak} for Nylon. The highest midwater RMS is 183 dB_{RMS} and bottom RMS is 181 dB_{RMS}. The highest midwater and bottom SEL for the peak strike is 168 and 169 dB_{SEL} respectively. Rise time for the Nylon pile cap is relatively long indicating a reduction of the transfer of energy from the hammer although there seems to be a shortening of the rise time when the bubble curtain was turned on. It is not clear why this happened. Only 29 midwater pile strike peak values (11%) exceeded 180 dB_{peak} with the bubble curtain on. All bottom pile strike peak values exceeded 180 dB_{peak} with the bubble curtain on. All pile strike RMS values exceeded 150 dB_{RMS} for both the midwater and bottom hydrophones.

Typical SEL values are 20 to 30 dB lower than the absolute peak. The SEL for Nylon averaged around 27 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.

The SEL per strike estimates in Tables 8 and 9 indicate that none of the calculated SEL values for a single strike (peak strike) exceeded the estimated summed SEL per strike thresholds.

The average peak sound reductions achieved with the bubble curtain ranged between 7 and 11 dB. This can be seen visually in Figure 7. This indicates that the bubble curtain was operating slightly better than a typical bubble curtain.

Table 8: Summary of Underwater Sound Level Impacts for Pile 4, Midwater.

Pile #	Date	Hydrophone Depth	Pile Cap Material	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (Pascals ± s.d.)	n[2]	Average Decibel Reduction from Bubble Curtain	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
4	12/14/05	8 feet (midwater)	Nylon	OFF	196[1]	183	5247 ± 709	15	-	178 ± 162	169	12.4	209
				ON	184	169	681 ± 241	256	17	164 ± 146	157	5.4	196
							Total:	**271**				**Total:**	**196**

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

Table 9: Summary of Underwater Sound Level Impacts for Pile 4, Bottom.

Pile #	Date	Hydrophone Depth	Pile Cap Material	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (Pascals ± s.d.)	n[2]	Average Decibel Reduction from Bubble Curtain	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
4	12/14/05	16 feet (bottom)	Nylon	OFF	194[1]	181	4176 ± 598	15	-	177 ± 162	168	7.8	209
				ON	188[1]	176	1800 ± 167	256	7	171 ± 150	161	2.9	196
							Total:	**271**				**Total:**	**196**

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

Pile 5

Pile 5 was driven with an air hammer in a water depth of 12 feet. The bubble curtain was off at the start of the drive and then 112 seconds into the drive the bubble curtain was turned on. Pile 5 was tested using a wood pile cap material. Tables 10 and 11 indicate the results of monitoring for Pile 5.

WOOD

The highest absolute peak from the midwater hydrophone is 188 dB_{peak} and the absolute highest peak from the bottom hydrophone is 190 dB_{peak} for wood. The highest midwater RMS is 175 dB_{RMS} and bottom RMS is 176 dB_{RMS}. The highest midwater and bottom SEL for the peak strike is 162 and 165 dB_{SEL} respectively. Rise time for the wood pile cap is the longest of all pile cap materials tested indicating a reduction of the transfer of energy from the hammer. Fifteen midwater pile strike peak values (88%) exceeded 180 dB_{peak} with the bubble curtain off. Fourty-three midwater pile strike peak values (23%) exceeded 180 dB_{peak} with the bubble curtain on. All pile strike RMS values exceeded 150 dB_{RMS} for both the midwater and bottom hydrophones.

Typical SEL values are 20 to 30 dB lower than the absolute peak. The SEL for the wood pile cap averaged around 26 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.

The SEL per strike estimates in Tables 10 and 11 indicate that none of the calculated SEL values for a single strike (peak strike) exceeded the estimated summed SEL per strike thresholds.

The average peak sound reductions achieved with the bubble curtain ranged between 7 and 11 dB. This can be seen visually in Figure 7. This indicates that the bubble curtain was functioning slightly better than anticipated.

Table 10: Summary of Underwater Sound Level Impacts for Pile 5, Midwater.

Pile #	Date	Hydrophone Depth	Pile Cap Material	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (Pascals ± s.d.)	n[2]	Average Decibel Reduction from Bubble Curtain	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
5	12/14/05	8 feet (midwater)	Wood	OFF	188[1]	175	1677 ± 544	18	-	169 ± 158	162	6.8	208
				ON	182	171	807 ± 226	186	6	166 ± 151	157	16.9	189
							Total:	**204**				**Total:**	**197**

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

Table 11: Summary of Underwater Sound Level Impacts for Pile 5, Bottom.

Pile #	Date	Hydrophone Depth	Pile Cap Material	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (Pascals ± s.d.)	n[2]	Average Decibel Reduction from Bubble Curtain	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
5	12/14/05	16 feet (bottom)	Wood	OFF	190	176	2092 ± 601	18	-	171 ± 160	165	22.1	208
				ON	186	179	1592 ± 277	186	2	172 ± 157	163	17.1	189
							Total:	**204**				**Total:**	**197**

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

Pile Cap Comparisons

Sound level reduction comparisons were made for the different pile cap materials without the influence of the bubble curtain. Using wood as a pile cap clearly has the greatest sound level reductions ranging from 11 to 26 dB. Wood also had the highest rise time and the lowest SEL values for the piles tested. Unfortunately, wood compresses easily with each pile strike and does not transfer the energy from the hammer to the pile efficiently enough to warrant regular use. Wood also has a tendency to catch fire after being used as a pile cap so safety is also an issue.

Conbest had sound level reductions between 7 and 8 dB, Nylon had sound level reductions between 4 and 5 dB, and Micarta had sound level reductions between 1 and 5 dB. Rise times for these three pile cap materials were very similar as were the SEL levels. These three materials, although more expensive than wood, can be reused on several piles before they need to be changed out, do not catch fire, and have minimal compression or breakage.

Based on these results it appears that Micarta would be the best choice for pile cap material. This still allows the operator to achieve the best sound level reductions while still maintaining an efficient drive of the pile and remaining safe.

Table 12: Sound Reductions Achieved with the Different Pile Cap Materials (bubble curtain off).

Pile #	Pile Type	Hydrophone Depth	Pile Cap Material	Average Peak (Pascals ± s.d.)	Average Decibel Reduction from Pile Cap	SEL (dB)	Rise Time (msec)
1	Single	Midwater	None	16174 ± 4625	-	175	1.8
			Conbest	8667± 5225	5	173	11.7
			Wood	812 ± 168	26	154	37.7
		Bottom	None	9550 ± 5370	-	171	1.5
			Conbest	8861 ± 4338	1	173	11.7
			Wood	910 ± 165	21	157	34.8
2	Winged	Midwater	None	7696 ± 4044	-	175	3.7
		Bottom		6771 ± 4226	-	176	4.6
3	Winged	Midwater	Micarta	554 ± 138	8	169	7.8
		Bottom		3054 ± 1292	7	169	13.1
4	Winged	Midwater	Nylon	5247 ± 709	4	169	12.4
		Bottom		4176 ± 598	5	168	7.8
5	Winged	Midwater	Wood	1677 ± 544	14	162	6.8
		Bottom		2092 ± 601	11	165	22.1

Spectral Frequency Analysis

A spectral frequency analysis was conducted on the peak pile strike (Figures 9 and 10). Figure 9 indicates that for the single pile the wood pile cap as having the greatest effect of lowering the sound levels of all frequencies even with the bubble curtain off. The Conbest pile cap was able to reduce only the higher frequencies above approximately 600 Hz with the bubble curtain off. With the bubble curtain on the frequencies for Conbest were lowered from approximately 190 Hz and above. With no pile cap there was little change in frequency levels with or without the bubble curtain.

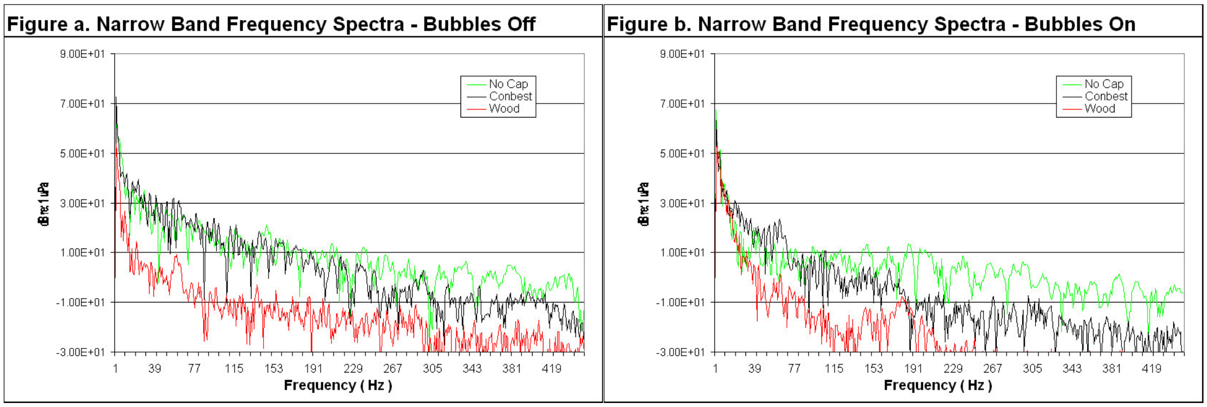

Figure 9: Spectral Frequency Analysis comparing Conbest and wood pile caps versus no caps with bubble curtain on and off.

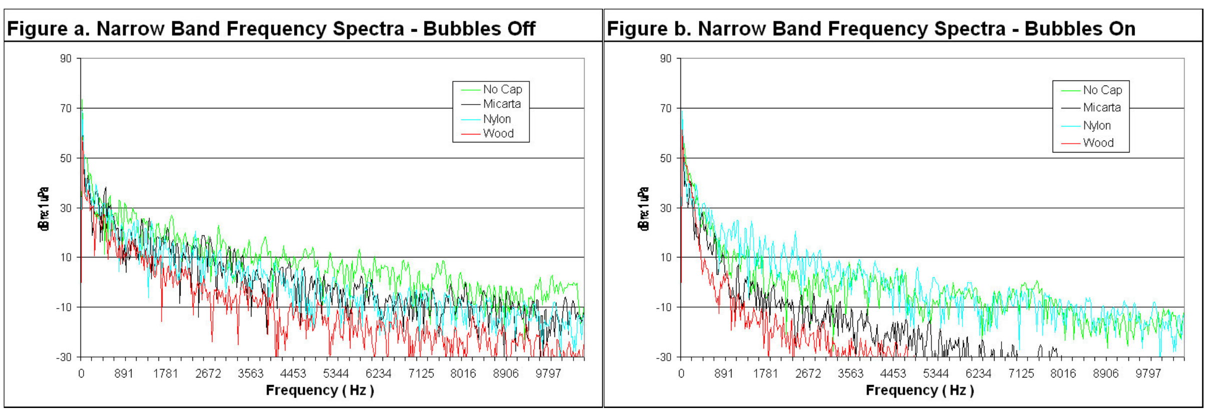

Figure 10: Spectral Frequency Analysis comparing Micarta, Nylon, and wood pile caps versus no caps with bubble curtain on and off.

Figure 10 indicates that for the piles with 'wings' when the bubble curtain is off the wood pile cap was able to reduce frequency levels at all frequencies. Nylon and Micarta were able to reduce frequencies above approximately 600 Hz, similarly to Conbest above. When the bubble curtain was turned on the performance of the wood and Micarta pile caps were enhanced whereas only a slight improvement was observed for Nylon. Micarta is able to reduce frequencies above approximately 450 Hz with the bubble curtain on. Nylon actually exhibited sound levels higher than with no cap at frequencies between approximately 900 and 3500 Hz and then no difference when compared to no cap with all other frequencies.

SEL

SEL was calculated for each of the absolute peak strikes for each pile. None of the SEL values exceeded 177 $dB_{SEL.}$

Rise Time

Yelverton (1973) indicated rise time was an important factor of the mechanism of injury. According to Yelverton , 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 those piles that did not use a pile cap, the rise times were relatively long. This could be 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.

Airborne Noise Measurements

Maximum airborne noise levels using A-weighting were measured at three different locations around the project location (Figure 11). Figure 11 indicates the L_{max} or maximum noise level recorded during a pile driving event at each location. Each location represents a different pile driving event. L_{max} values ranged from 76 dBA to 89 dBA dependent mostly on distance from the source.

Biological Observations

No fish mortality or distress was observed before, during, or after pile driving. No fish were observed in the immediate area around the piles. A great blue heron flushed and flew out of the area when pile driving started on 12/13/05. A few common goldeneyes and horned grebes that were foraging adjacent to the boat ramp moved behind the small island in the embayment when pile driving started.

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.

Figure 11: Airborne measurement locations (✹) with A-weighted maximum values.

CONCLUSIONS

The pile cap material Micarta achieved the best sound level reductions, with the exception of wood. In most cases both bubble curtain designs, standard ring and “U” shaped curtain, performed as well as expected or better.

All piles, with the exception of the piles with no pile caps, 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). None of the calculated SEL values exceeded the estimated SEL per strike thresholds based on the total number of pile strikes. 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.

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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.

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Longmuir, C., and T. Lively. 2001. Bubble curtain systems for use during marine pile driving. Fraser River Pile & Dredge Ltd., New Westminster, BC, Canada.

Yelverton, J. T., D. R. Richmond, E. R. Fletcher, and R. K. Jones. 1973. Safe distance from underwater explosions for mammals and birds. Technical Report DNA 3114 T. Defense Nuclear Agency, Department of Defense, Washington, D.C.

A ENDIX A– WAVEFORM ANALY I FIGURE

ILE 1 – CONBE T - BUBBLE CURTAIN OFF

Figure 6a

Pile 1, Conbest, Midwater, Bubbles Off: 33 Feet from Pile

Figure a. Waveform

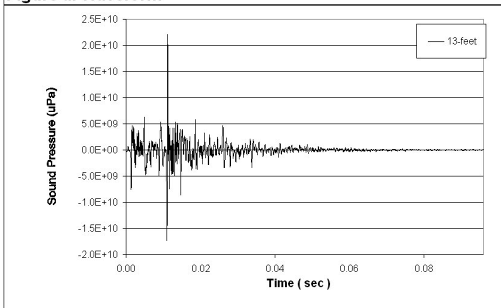


Figure b. Narrow Band Frequency Spectra

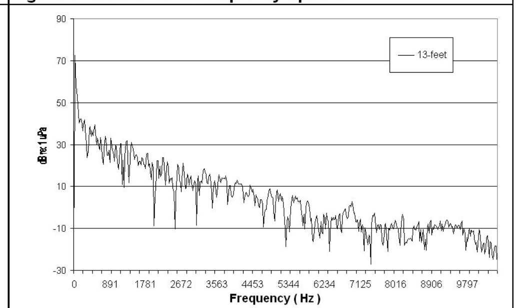


Figure c. Accumulation of Sound Energy

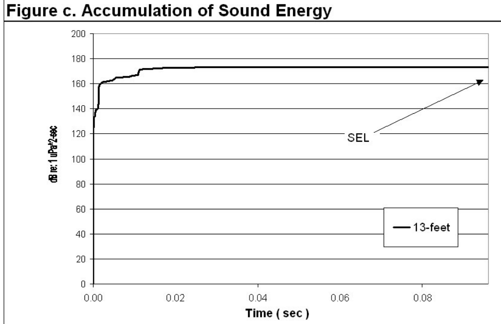


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
13-feet	207	189	173

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

Figure 6b

Pile 1, Conbest, Bottom, Bubbles Off: 33 Feet from Pile

Figure a. Waveform

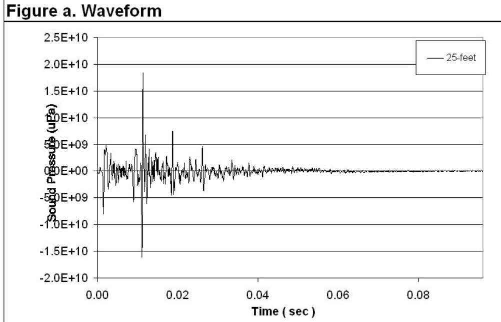


Figure b. Narrow Band Frequency Spectra

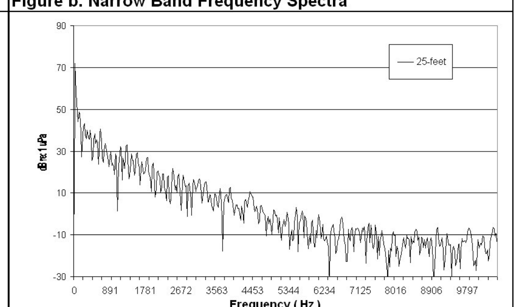


Figure c. Accumulation of Sound Energy

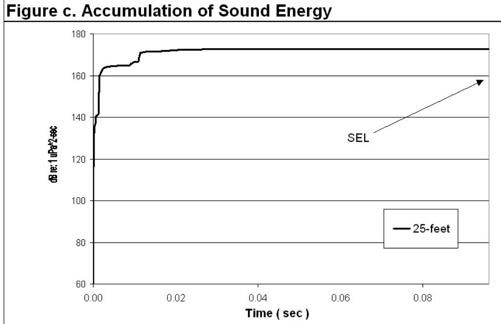


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
25-feet	205	188	173

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

Figure 12: Waveform Analysis of Pile 1 Sound Pressure Levels with Conbest pile cap and Bubble Curtain Off, Midwater and Bottom.

ILE 1 – CONBE T BUBBLE CURTAIN ON

Figure 7a

Pile 1, Conbest, Midwater, Bubbles On: 33 Feet from Pile

Figure a. Waveform

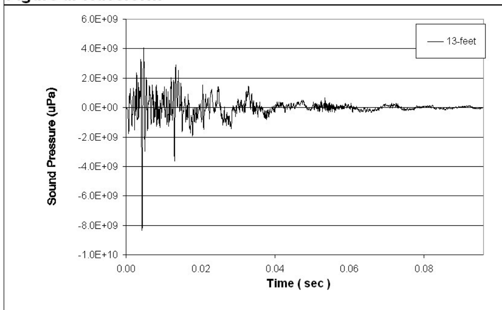


Figure b. Narrow Band Frequency Spectra

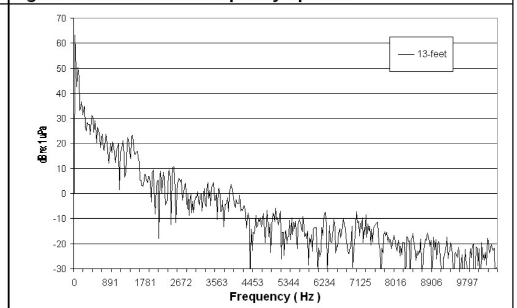


Figure c. Accumulation of Sound Energy

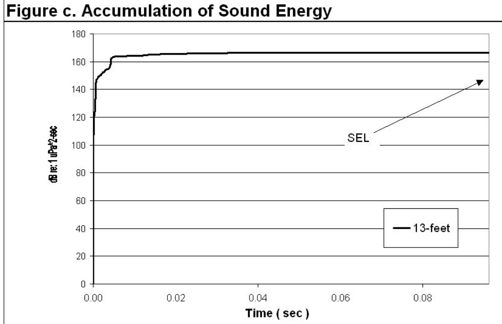


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
13-feet	198	181	166

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

Figure 7b

Pile 1, Conbest, Bottom, Bubbles On: 33 Feet from Pile

Figure a. Waveform

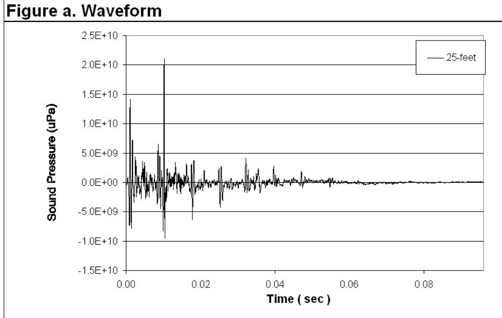


Figure b. Narrow Band Frequency Spectra

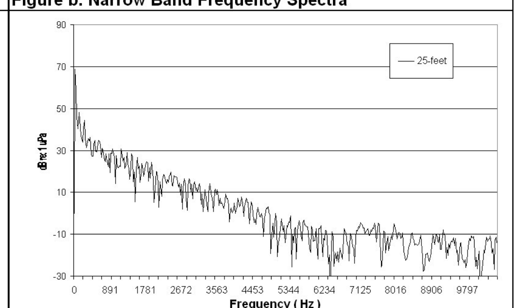


Figure c. Accumulation of Sound Energy

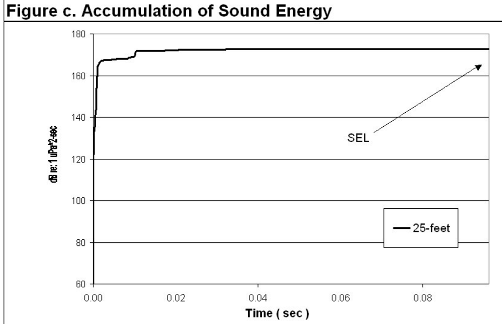


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

feet from pile - 00:00:(	Peak	RMS90%*	SEL
25-feet	206	187	173

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

Figure 13: Waveform Analysis of Pile 1 Sound Pressure Levels with Conbest Pile Cap and Bubble Curtain On, Midwater and Bottom.

ILE 1 – WOOD BUBBLE CURTAIN OFF

Figure 8a

Pile 1, Wood, Midwater, Bubbles Off: 33 Feet from Pile

Figure a. Waveform

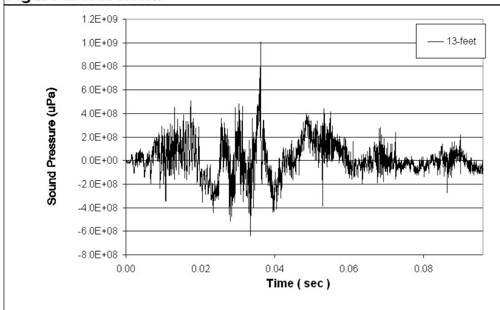


Figure b. Narrow Band Frequency Spectra

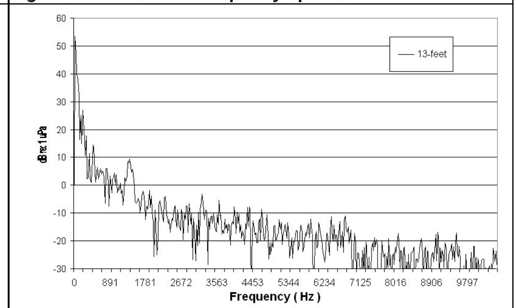


Figure c. Accumulation of Sound Energy

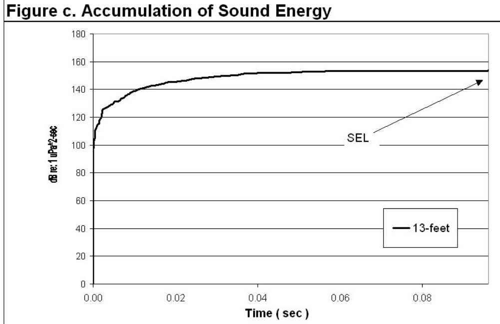


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
13-feet	180	165	154

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

Figure 8b

Pile 1, Wood, Bottom, Bubbles Off: 33 Feet from Pile

Figure a. Waveform

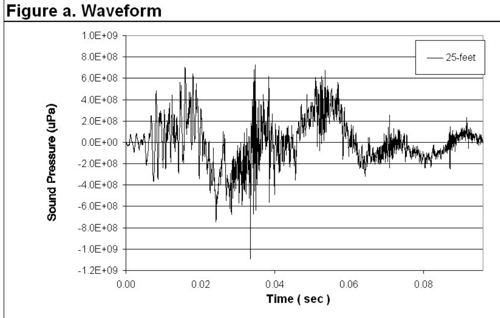


Figure b. Narrow Band Frequency Spectra

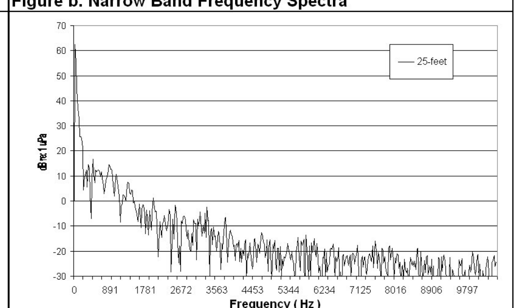


Figure c. Accumulation of Sound Energy

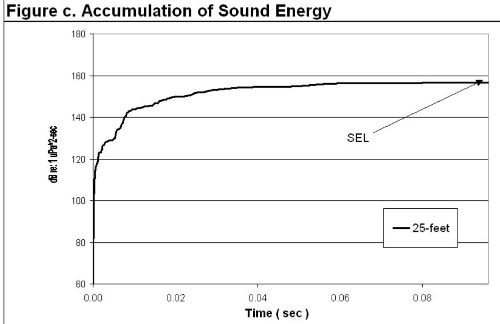


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
25-feet	181	168	157

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

Figure 14: Waveform Analysis of Pile 1 Sound Pressure Levels with Wood Pile Cap and Bubble Curtain Off, Midwater and Bottom.

ILE 1 – WOOD BUBBLE CURTAIN ON

Figure 9a

Pile 1, Wood, Midwater, Bubbles On: 33 Feet from Pile

Figure a. Waveform

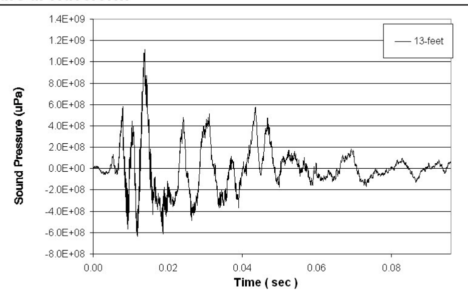


Figure b. Narrow Band Frequency Spectra

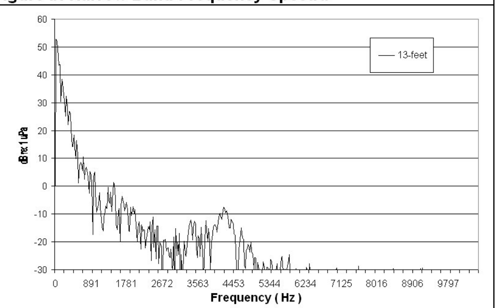


Figure c. Accumulation of Sound Energy

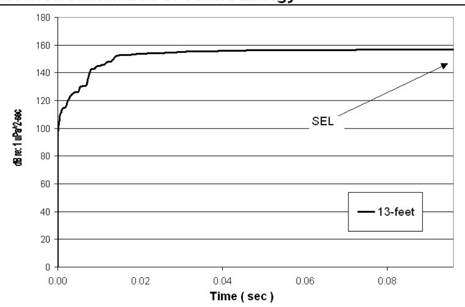


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
13-feet	181	170	157

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

Figure 9b

Pile 1, Wood, Bottom, Bubbles On: 33 Feet from Pile

Figure a. Waveform

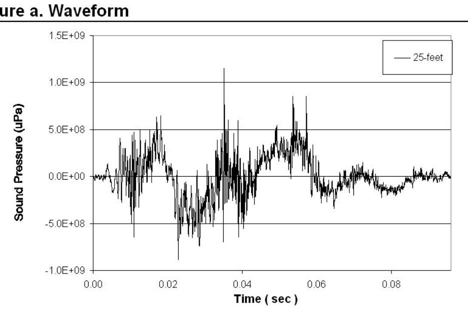


Figure b. Narrow Band Frequency Spectra

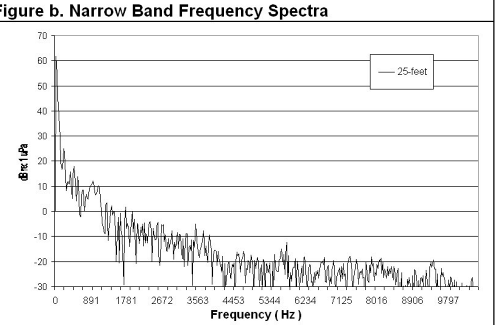


Figure c. Accumulation of Sound Energy

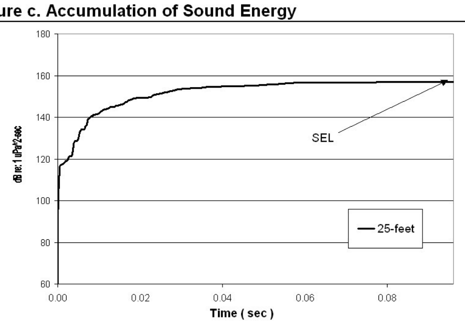


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
25-feet	181	169	157

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

Figure 15: Waveform Analysis of Pile 1 Sound Pressure Levels with Wood Pile Cap and Bubble Curtain On, Midwater and Bottom.

ILE 1 – NO ILE CA BUBBLE CURTAIN OFF

Figure 10a

Pile 1, No Pile Cap, Midwater, Bubbles Off: 33 Feet from Pile

Figure a. Waveform

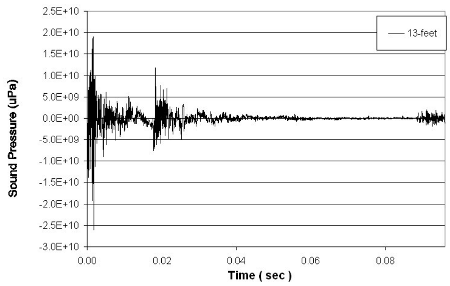


Figure b. Narrow Band Frequency Spectra

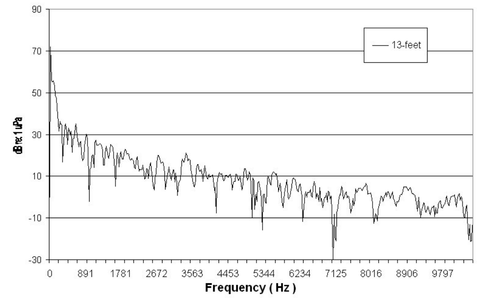


Figure c. Accumulation of Sound Energy

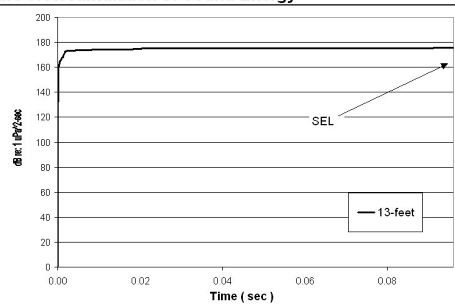


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
13-feet	208	191	175

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

Figure 10b

Pile 1, No Pile Cap, Bottom, Bubbles Off: 33 Feet from Pile

Figure a. Waveform

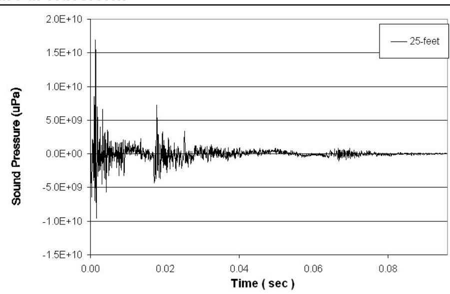


Figure b. Narrow Band Frequency Spectra

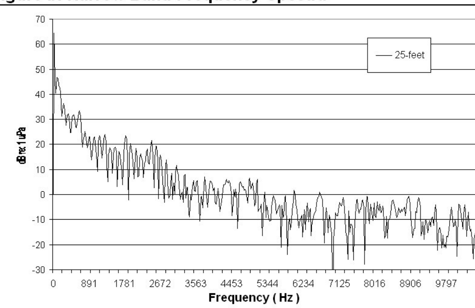


Figure c. Accumulation of Sound Energy

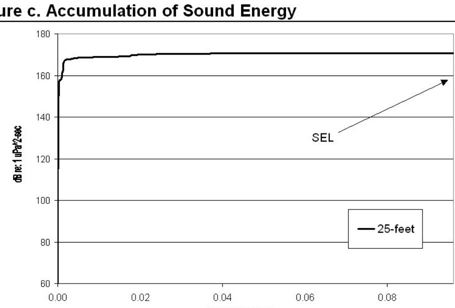


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
25-feet	205	185	171

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

Figure 16: Waveform Analysis of Pile 1 Sound Pressure Levels with No Pile Cap and Bubble Curtain Off, Midwater and Bottom.

ILE 1 – NO ILE CA BUBBLE CURTAIN ON

Figure 11a

Pile 1, No Pile Cap, Midwater, Bubbles On: 33 Feet from Pile

Figure a. Waveform

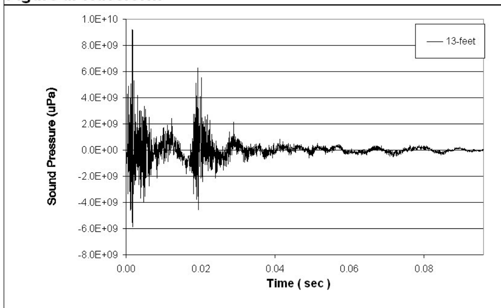


Figure b. Narrow Band Frequency Spectra

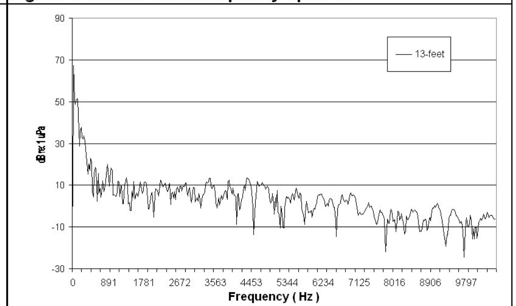


Figure c. Accumulation of Sound Energy

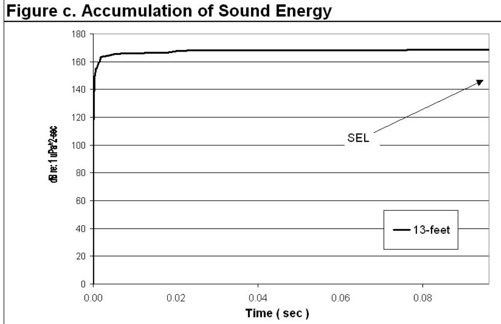


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
13-feet	199	183	168

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

Figure 11b

Pile 1, No Pile Cap, Bottom, Bubbles On: 33 Feet from Pile

Figure a. Waveform

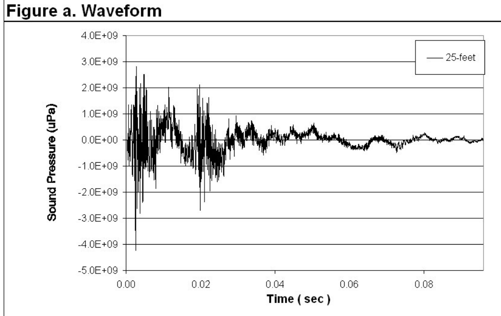


Figure b. Narrow Band Frequency Spectra

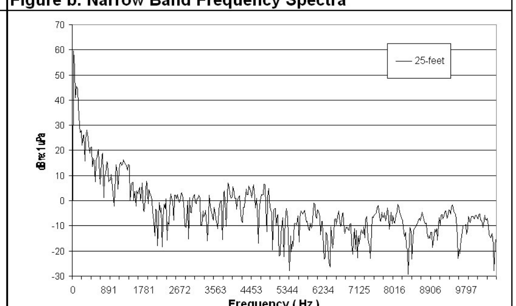


Figure c. Accumulation of Sound Energy

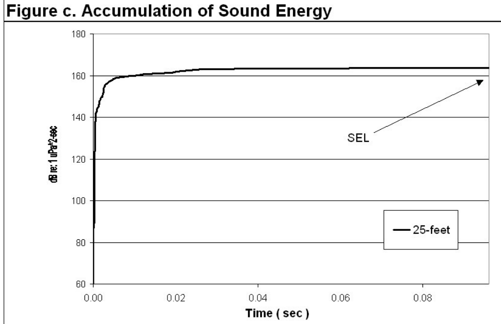


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
25-feet	193	176	164

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

Figure 17: Waveform Analysis of Pile 1 Sound Pressure Levels with No Pile Cap and Bubble Curtain On, Midwater and Bottom.

ILE 2 – NO ILE CA , BUBBLE CURTAIN OFF

Figure 12a

Pile 2, No Pile Cap, Midwater, Bubbles Off: 33 Feet from Pile

Figure a. Waveform

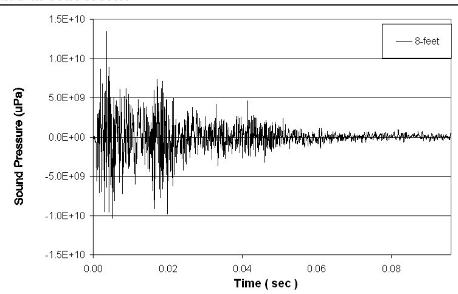


Figure b. Narrow Band Frequency Spectra

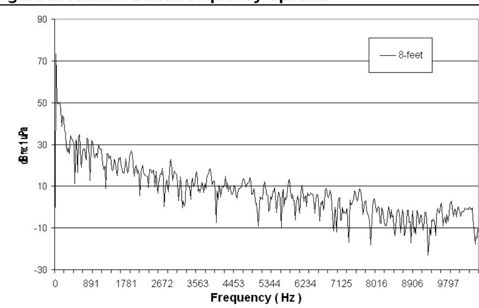


Figure c. Accumulation of Sound Energy

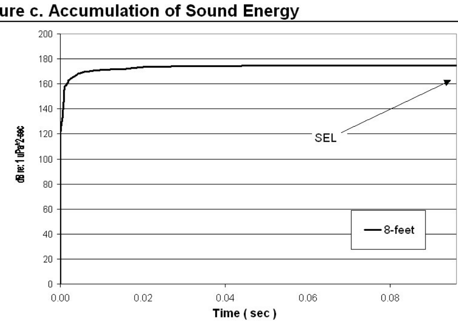


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
8-feet	203	188	175

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

Figure 12b

Pile 2, No Pile Cap, Bottom, Bubbles Off: 33 Feet from Pile

Figure a. Waveform

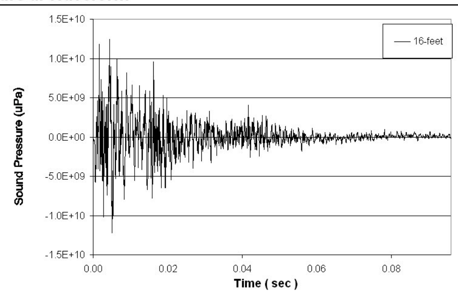


Figure b. Narrow Band Frequency Spectra

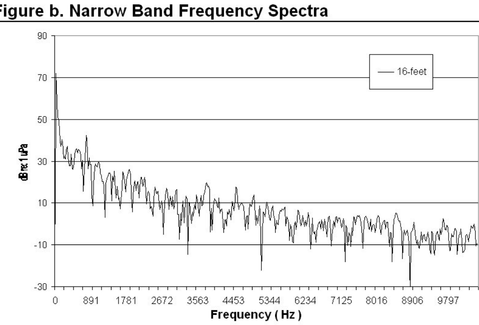


Figure c. Accumulation of Sound Energy

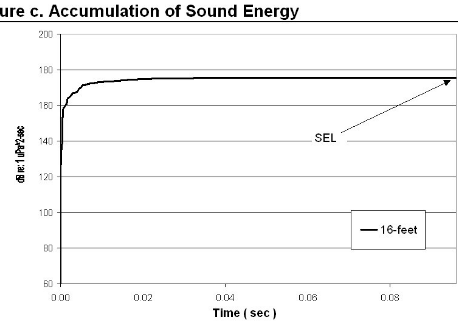


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
16-feet	202	189	176

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

Figure 18: Waveform Analysis of Pile 2 Sound Pressure Levels with No Pile Cap and Bubble Curtain Final Off, Midwater and Bottom.

ILE 2 – NO ILE CA , BUBBLE CURTAIN ON

Figure 13a

Pile 2, No Pile Cap, Midwater, Bubbles On: 33 Feet from Pile

Figure a. Waveform

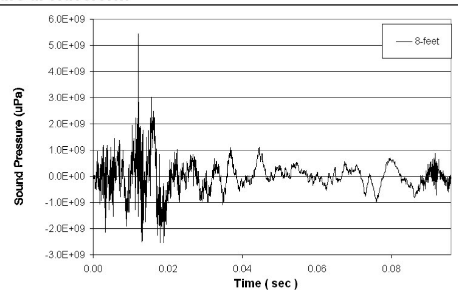


Figure b. Narrow Band Frequency Spectra

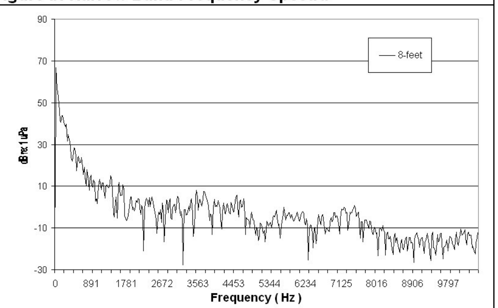


Figure c. Accumulation of Sound Energy

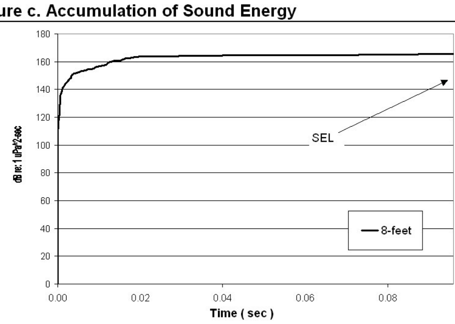


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
8-feet	195	176	165

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

Figure 13b

Pile 2, No Pile Cap, Bottom, Bubbles On: 33 Feet from Pile

Figure a. Waveform

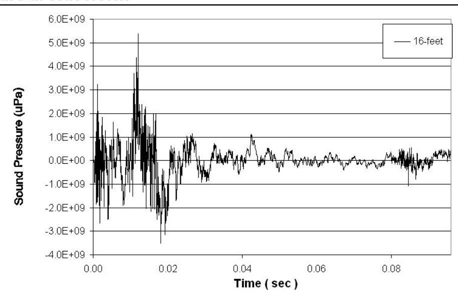


Figure b. Narrow Band Frequency Spectra

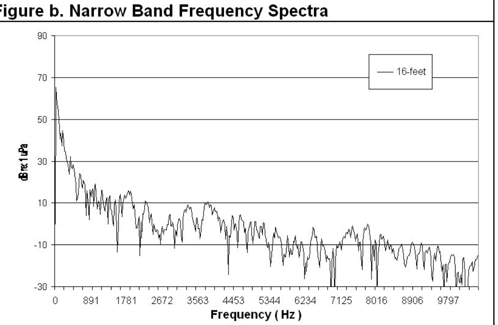


Figure c. Accumulation of Sound Energy

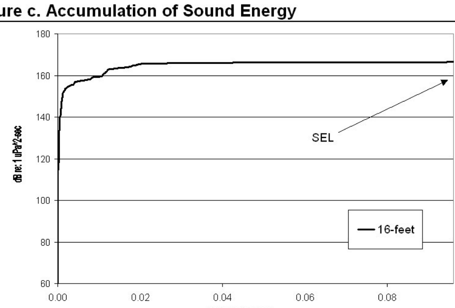


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
16-feet	195	179	166

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

Figure 19: Waveform Analysis of Pile Number 2 Sound Pressure Levels with No Pile Cap and Bubble Curtain On, Midwater and Bottom.

ILE 3 – MICARTA ILE CA , BUBBLE CURTAIN OFF

Figure 14a

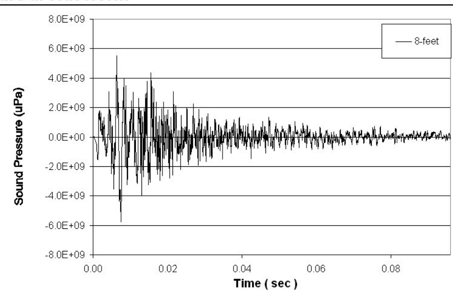
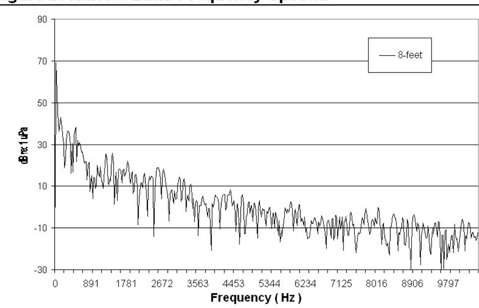
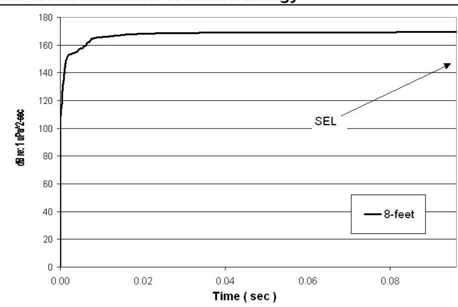
Pile 3, Micarta, Midwater, Bubbles Off: 33 Feet from Pile	
Figure a. Waveform	Figure b. Narrow Band Frequency Spectra
	

Figure c. Accumulation of Sound Energy	Figure d. Sound Pressure and Sound Energy Levels
	Signal Analysis Sound Pressure / Energy Levels (see table below)

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
8-feet	195	182	169

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

Figure 14b

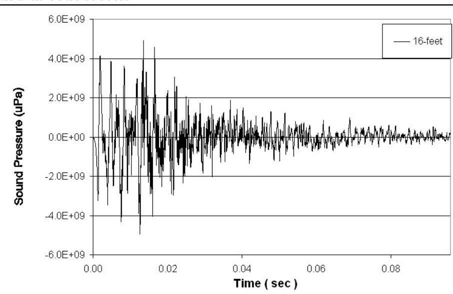
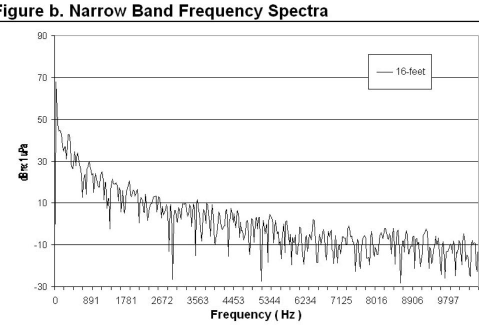
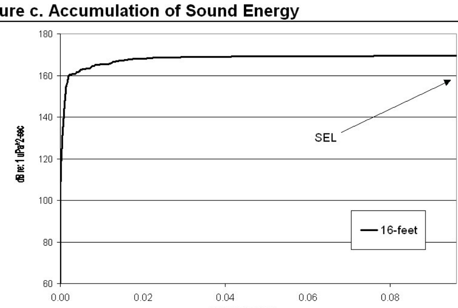
Pile 3, Micarta, Bottom, Bubbles Off: 33 Feet from Pile	
Figure a. Waveform	Figure b. Narrow Band Frequency Spectra
	

Figure c. Accumulation of Sound Energy	Figure d. Sound Pressure and Sound Energy Levels
	Signal Analysis Sound Pressure / Energy Levels (see table below)

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
16-feet	194	182	169

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

Figure 20: Waveform Analysis of Pile Number 3 Sound Pressure Levels with Micarta Pile Cap and Bubble Curtain Off, Midwater and Bottom.

ILE 3 – MICARTA ILE CA , BUBBLE CURTAIN ON

Figure 15a

Pile 3, Micarta, Midwater, Bubbles On: 33 Feet from Pile

Figure a. Waveform

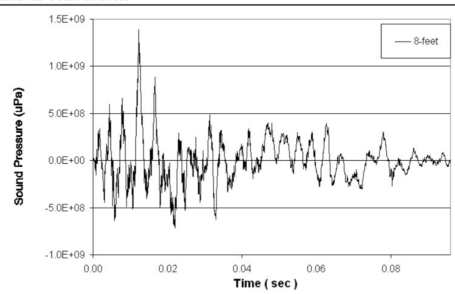


Figure b. Narrow Band Frequency Spectra

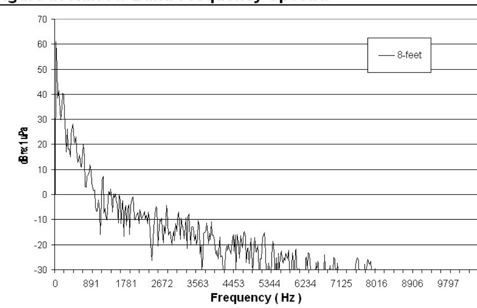


Figure c. Accumulation of Sound Energy

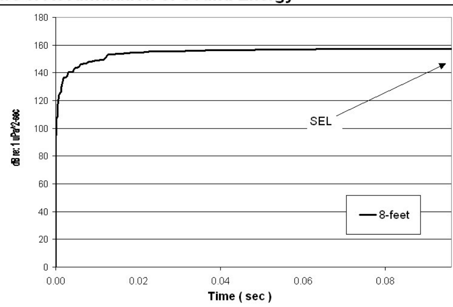


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
8-feet	183	169	157

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

Figure 15b

Pile 3, Micarta, Bottom, Bubbles On: 33 Feet from Pile

Figure a. Waveform

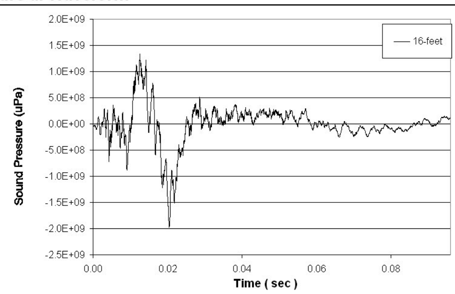


Figure b. Narrow Band Frequency Spectra

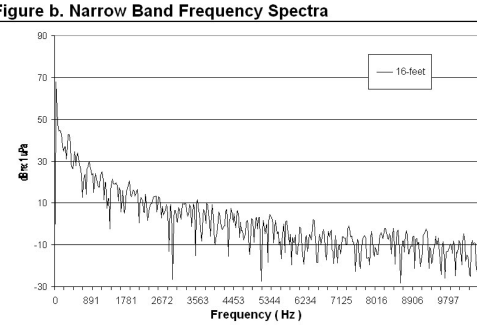


Figure c. Accumulation of Sound Energy

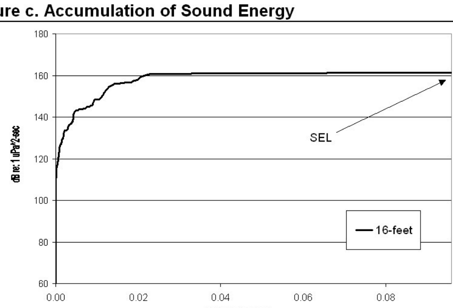


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
16-feet	186	175	161

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

Figure 21: Waveform Analysis of Pile Number 3 Sound Pressure Levels with Bubble Curtain Second Off, Midwater and Bottom.

ILE 4 – NYLON ILE CA , BUBBLE CURTAIN OFF

Figure 16a

Pile 4, Nylon, Midwater, Bubbles Off: 33 Feet from Pile

Figure a. Waveform

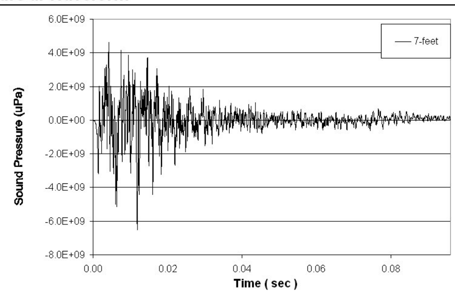


Figure b. Narrow Band Frequency Spectra

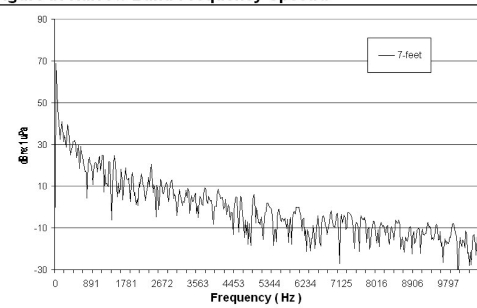


Figure c. Accumulation of Sound Energy

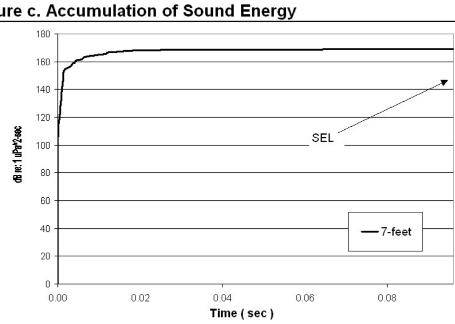


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
7-feet	196	183	169

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

Figure 16b

Pile 4, Nylon, Bottom, Bubbles Off: 33 Feet from Pile

Figure a. Waveform

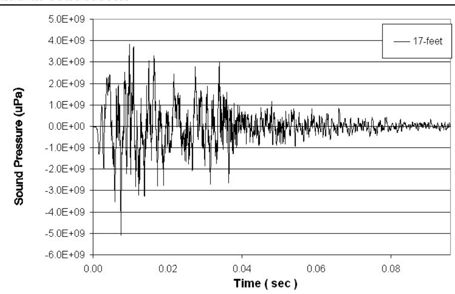


Figure b. Narrow Band Frequency Spectra

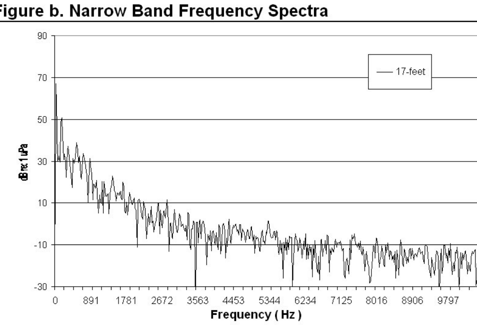


Figure c. Accumulation of Sound Energy

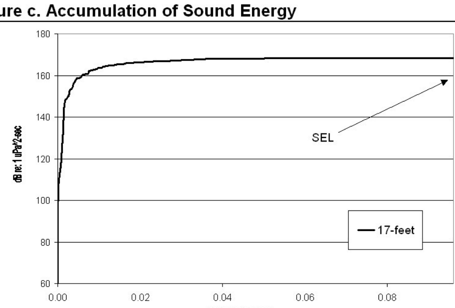


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
17-feet	194	181	168

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

Figure 22: Waveform Analysis of Pile Number 4 Sound Pressure Levels with Nylon Pile Cap and Bubble Curtain Off, Midwater and Bottom.

ILE 4 – NYLON ILE CA , BUBBLE CURTAIN ON

Figure 17a

Pile 4, Nylon, Midwater, Bubbles On: 33 Feet from Pile

Figure a. Waveform

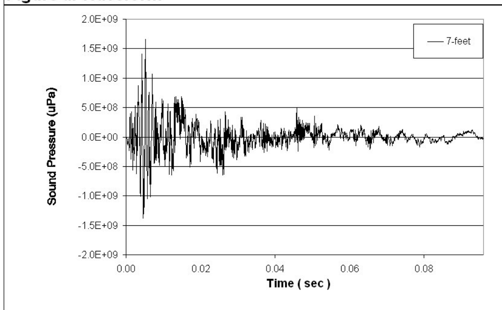


Figure b. Narrow Band Frequency Spectra

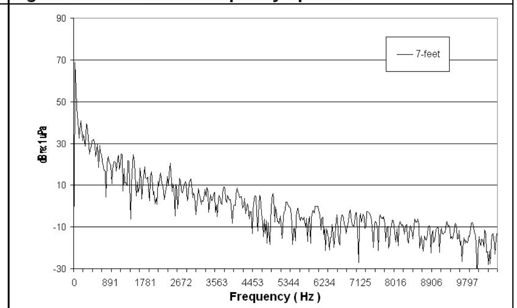


Figure c. Accumulation of Sound Energy

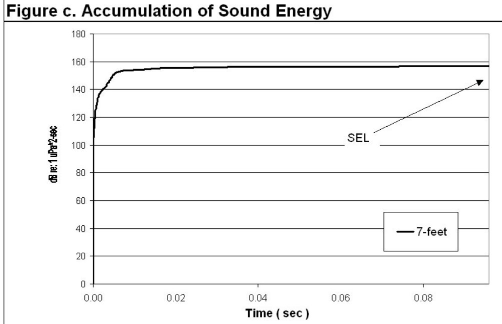


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
7-feet	184	169	157

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

Figure 17b

Pile 4, Nylon, Bottom, Bubbles On: 33 Feet from Pile

Figure a. Waveform

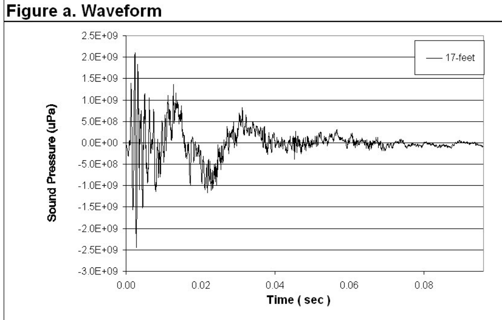


Figure b. Narrow Band Frequency Spectra

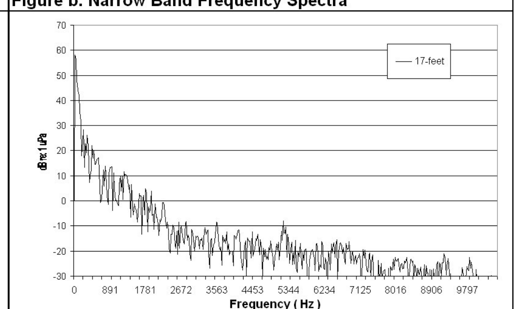


Figure c. Accumulation of Sound Energy

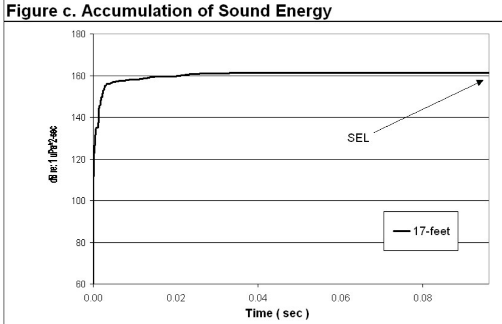


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
17-feet	188	176	161

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

Figure 23: Waveform Analysis of Pile Number 4 Sound Pressure Levels with Nylon Pile Cap and Bubble Curtain On, Midwater and Bottom.

ILE 5 – WOOD ILE CA , BUBBLE CURTAIN OFF

Figure 18a

Pile 5, Wood, Midwater, Bubbles Off: 33 Feet from Pile

Figure a. Waveform

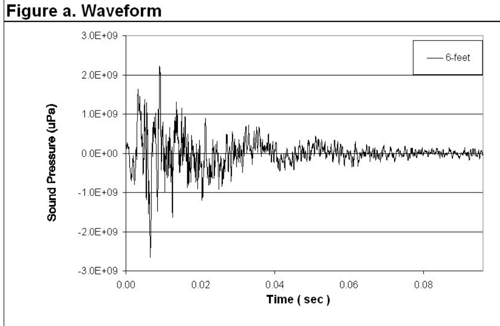


Figure b. Narrow Band Frequency Spectra

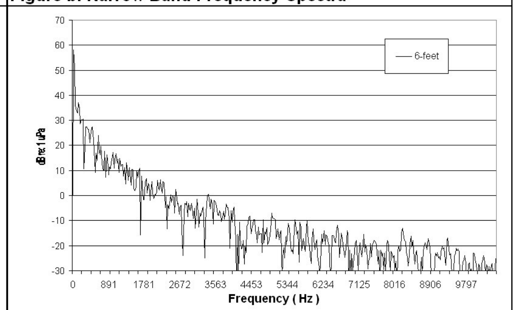


Figure c. Accumulation of Sound Energy

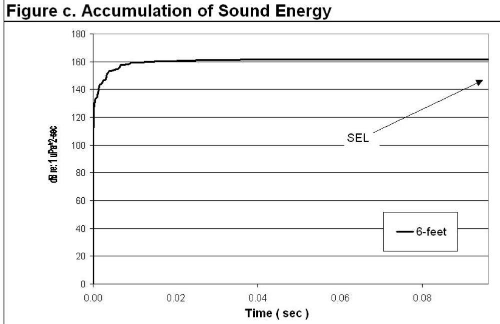


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
6-feet	188	175	162

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

Figure 18b

Pile 5, Wood, Bottom, Bubbles Off: 33 Feet from Pile

Figure a. Waveform

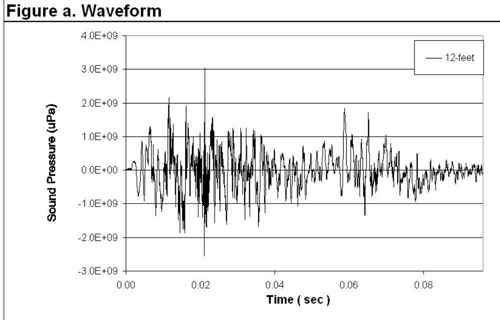


Figure b. Narrow Band Frequency Spectra

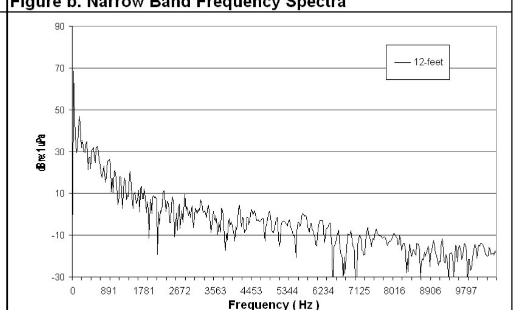


Figure c. Accumulation of Sound Energy

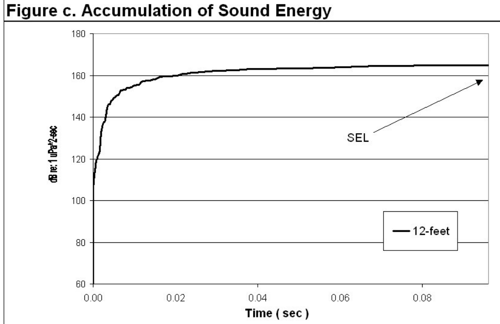


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
12-feet	190	176	165

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

Figure 24: Waveform Analysis of Pile Number 5 Sound Pressure Levels with Wood Pile Cap and Bubble Curtain Off, Midwater and Bottom.

ILE 5 – WOOD ILE CA , BUBBLE CURTAIN ON

Figure 19a

Pile 5, Wood, Midwater, Bubbles On: 33 Feet from Pile

Figure a. Waveform

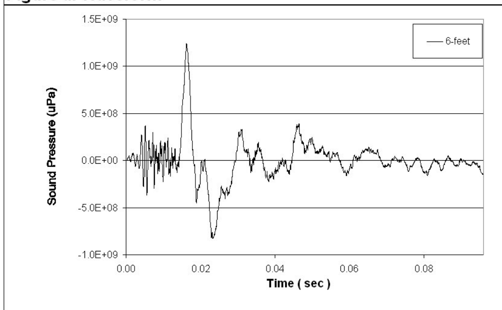


Figure b. Narrow Band Frequency Spectra

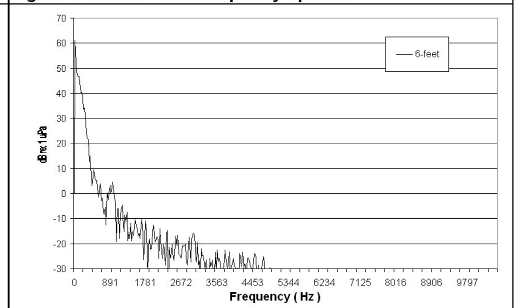


Figure c. Accumulation of Sound Energy

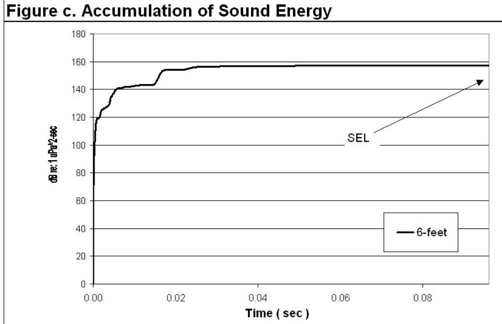


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
6-feet	182	171	157

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

Figure 19b

Pile 5, Wood, Bottom, Bubbles On: 33 Feet from Pile

Figure a. Waveform

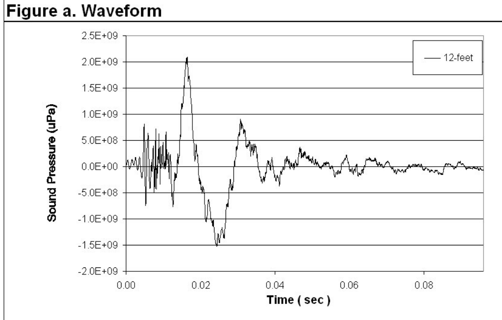


Figure b. Narrow Band Frequency Spectra

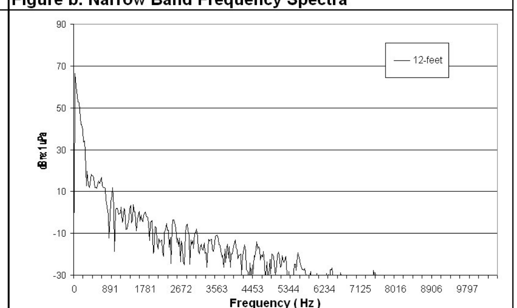


Figure c. Accumulation of Sound Energy

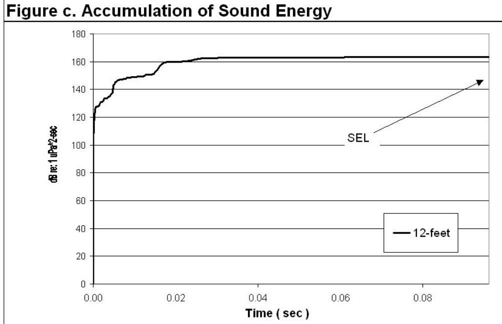


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile	Peak	RMS90%*	SEL
12-feet	186	179	163

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

Figure 25: Waveform Analysis of Pile Number 5 Sound Pressure Levels with Wood Pile Cap and Bubble Curtain On, Midwater and Bottom.