WSF BAINBRIDGE ISLAND FERRY TERMINAL PRESERVATION PROJECT

UNDERWATER SOUND LEVELS ASSOCIATED WITH PILE DRIVING AT THE BAINBRIDGE ISLAND FERRY TERMINAL PRESERVATION PROJECT

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EXECUTIVE SUMMARY

This technical report describes the data collected during pile driving efforts at the Bainbridge Island Ferry Terminal Preservation Project on Bainbridge Island during the month of October 2005. Five 24-inch diameter steel piles were monitored at different water depths at the Bainbridge Island facility. Piles were driven with a diesel hammer. Table 1 summarizes the results for each pile monitored. The bubble curtain was tested with the bubbles on and off during the pile driving events.

Ambient sound levels averaged approximately 151 dB_{peak} without construction equipment and 150 dB_{peak} to 160 dB_{peak} with construction equipment. The maximum sound reduction achieved with the bubble curtain was 14 dB. Due to the remnants of an old wood pile near pile 4 and possibly pile 5 the bottom ring of the bubble curtain could not be deployed around the bottom of the pile correctly and little or no sound level reductions were observed.

Table 1: Summary Table of Monitoring Results.

Pile #	Hydrophone Depth	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Decibel Reduction	SEL (dB)	Rise Time (msec)	SEL Per Strike
1	5 feet (midwater)	OFF	211	198	-	183	4	206
		ON	206[1]	195	14	179	13.3	197
		OFF	211[1]	197	-	181	10.7	201
		ON	205[1]	191	6	178	1.4	197
	8 feet (bottom)	OFF	215[1]	198	-	186	13.9	206
		ON	207	193	11	181	10.1	197
		OFF	214	198	-	185	6.0	201
		ON	210[1]	195	8	183	10.9	197
2	5 feet (midwater)	ON	204[1]	194	11	179	15.3	197
		OFF	209[1]	197	-	181	4.8	200
		ON	205	189	8	176	3.0	197
	9 feet (bottom)	ON	201[1]	189	14	179	5.0	197
		OFF	212	197	-	181	4.1	200
		ON	211	195	9	176	10.9	197
3	4 feet (midwater)	OFF	207	193	-	178	15.6	204
		ON	198[1]	179	8	169	11.6	198
		OFF	209	198	-	181	11.7	203
		ON	202[1]	189	7	174	11.8	196
		OFF	207	192	-	175	2.6	203
		ON	198[1]	182	6	170	3.3	204
	7 feet (bottom)	OFF	205	187	-	177	16.0	204
		ON	198[1]	184	6	174	12.0	198
		OFF	206[1]	187	-	177	11.8	203
		ON	203[1]	186	7	176	11.7	196
		OFF	202[1]	184	-	174	10.6	203
		ON	197[1]	182	3	172	10.7	204

Pile #	Hydrophone Depth	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Decibel Reduction	SEL (dB)	Rise Time (msec)	SEL Per Strike
4	5 feet (midwater)	OFF	208	192	-	178	14.5	205
		ON	204[1]	195	4	177	12.4	199
		OFF	205	194	-	176	4.6	204
		ON	204	196	1	178	5.1	196
	9 feet (bottom)	OFF	206	191	-	178	18.2	205
		ON	205	195	2	179	14.2	199
		OFF	204	193	-	177	5.2	204
		ON	206	198	0	180	5.8	196
5	5 feet (midwater)	OFF	208	195	-	179	14.8	203
		ON	207	194	5	179	4.5	197
		OFF	204	190	-	174	11.4	204
		ON	202[1]	190	0	173	2.9	197
	9 feet (bottom)	OFF	206	194	-	179	4.3	203
		ON	206	194	4	179	4.0	197
		OFF	203	191	-	176	5.0	204
		ON	203	192	0	177	5.2	197

INTRODUCTION

This technical report presents results of underwater sound levels measured during the driving of five 24-inch steel piles at the Bainbridge Island Ferry Terminal Preservation Project in October 2005 (Contract Number: 006995). The piles were driven to support the terminal trestle. Five 24-inch piles were monitored at different water depths in the harbor. The bubble curtain was tested with on/off cycles during each pile driving event. Figure 1 shows the locations of monitored piles.

PROJECT DESCRIPTION

This project will remove old rotting sections of the ferry dock and replace it with steel piles and a concrete deck. In addition, the cable transfer span at Slip 2 will be replaced with a newly designed hydraulically actuated transfer span.

The project location is on Bainbridge Island on the north side of Eagle Harbor (Figure 1). Figure 2 shows the approximate pile locations and approximate bottom topography of the harbor. Water depths at the monitoring locations varied from eight feet to ten feet deep. There was no substantial tidal flux or currents in the area monitored.

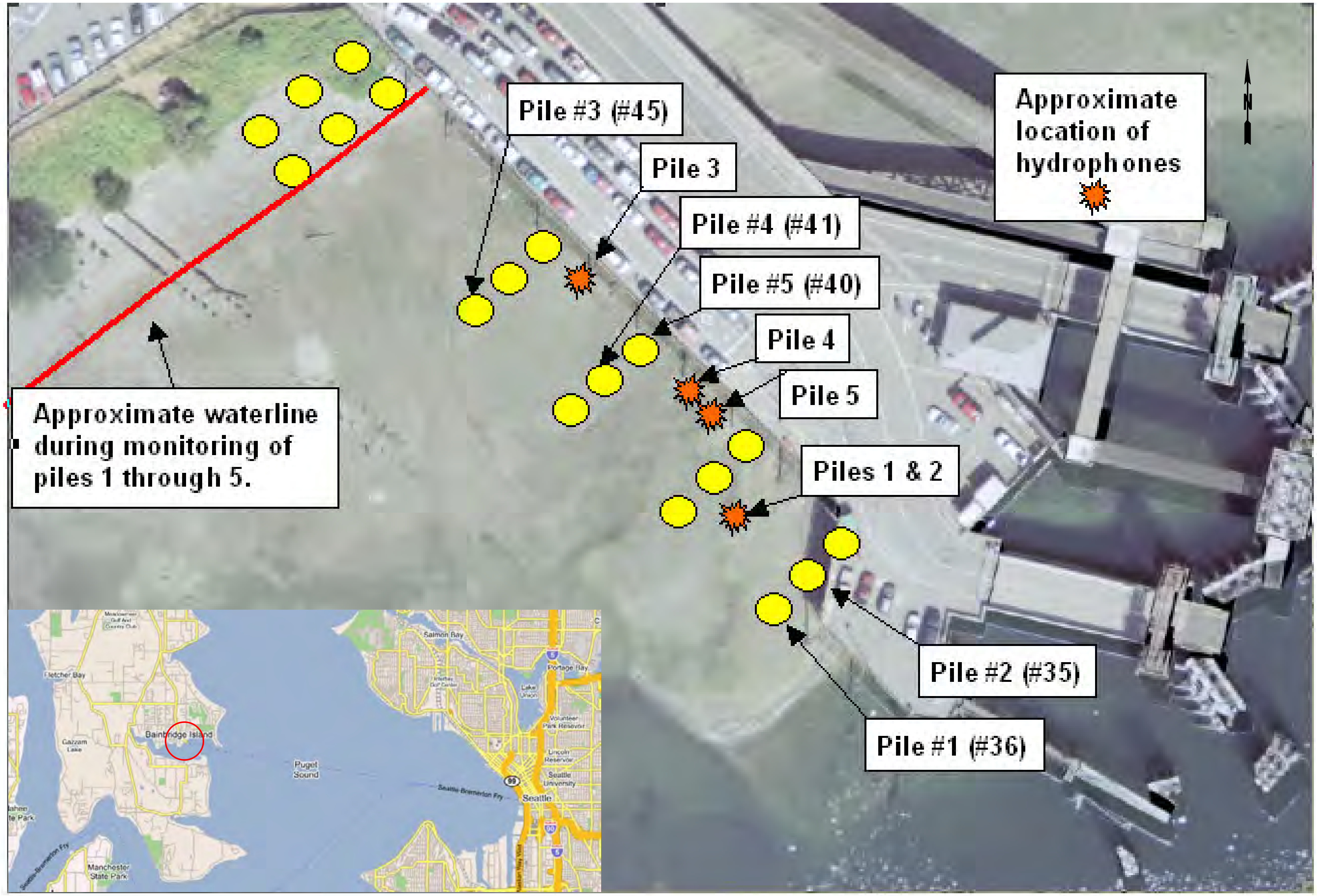


Figure 1: Location of underwater noise monitoring sites at the Bainbridge Island Ferry Terminal project. Note: The current configuration of the loading dock is different from that shown in the aerial, however, orientation of the piles is still valid. Piles are not to scale.

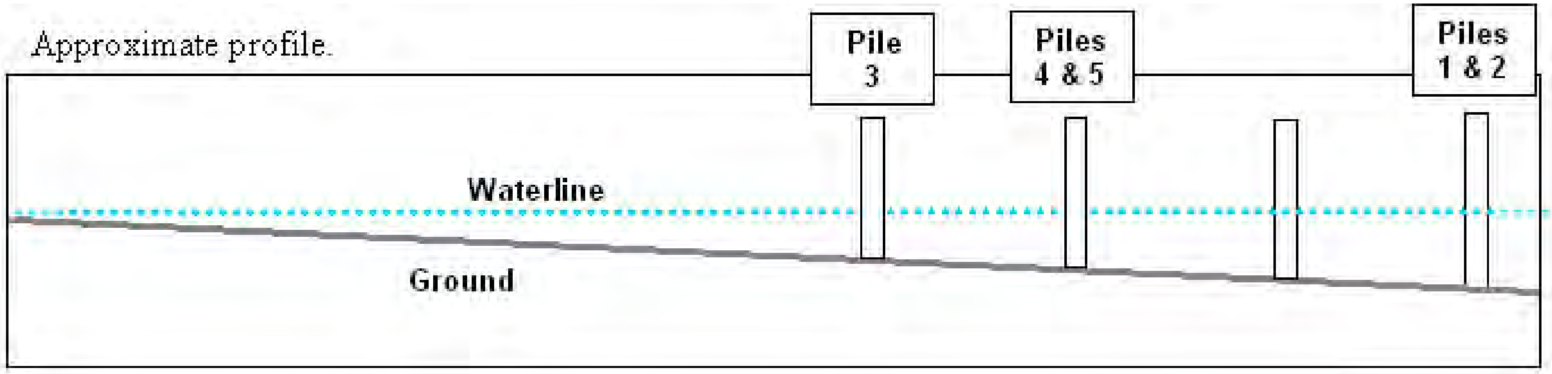


Figure 2: Location of piles relative to the bottom topography in the monitoring area. The sediment is a mixture of sand and fist-sized rocks with an occasional 1-foot diameter rock.

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.

Hastings and Popper (2005) recommend 194 dB_{SEL} as interim guidance to protect fish from physical injury and mortality for a single pile driving impact. Hastings and Popper (2005) recommendations are related to effects data from other studies through total energy exposure given in Joules per square meter ($J/m^2 = W\text{-}s/m^2$). Because SEL is a metric based on energy, sound exposure for a single strike can be summed to estimate the total energy exposure from multiple strikes, which can then be compared to the recommended interim guidance. Some recovery of the tissue will take place during the interval between strikes that is not taken into account, so this approach should be conservative.

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

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

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

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

METHODOLOGY

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

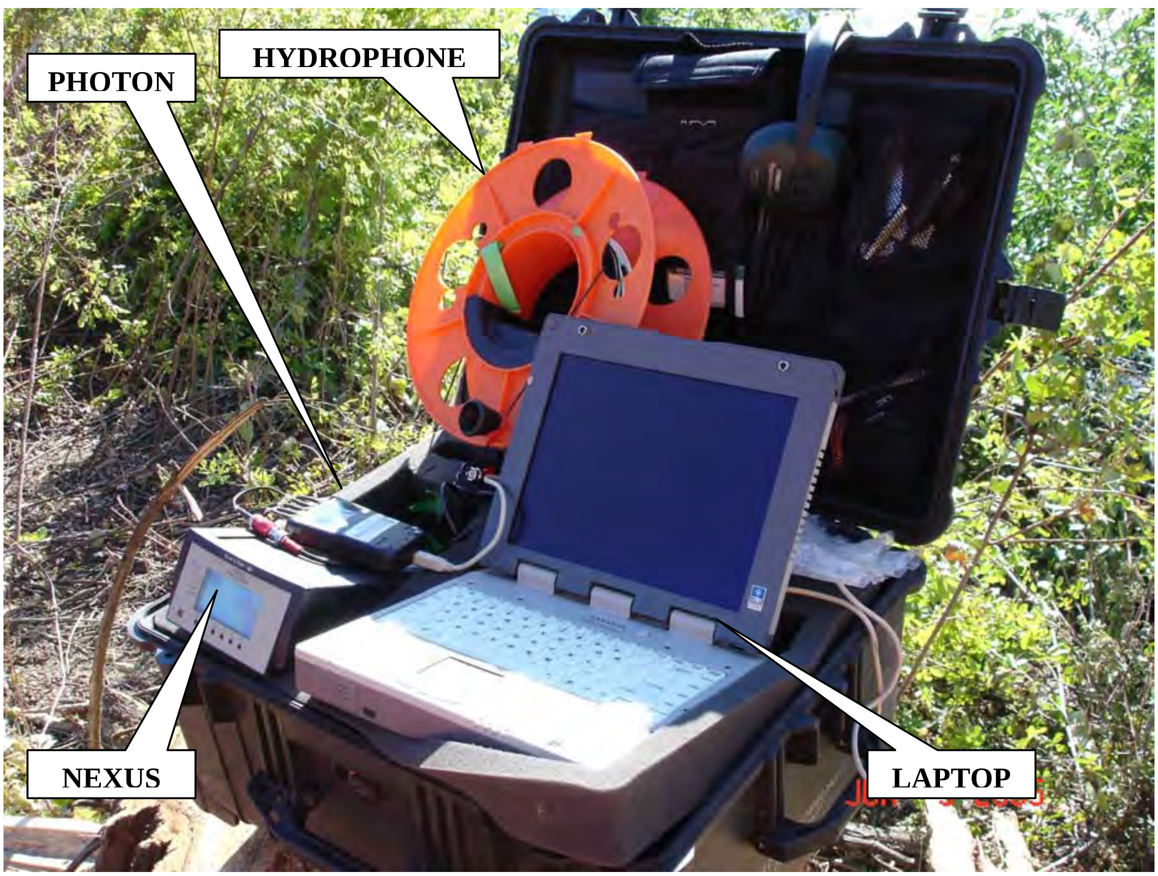


Figure 3: Underwater Sound Level Measurement Equipment

Signal analysis software provided with the Photon was set at a sampling rate of one sample every 41.7 μs (9,500 Hz). This sampling rate is more than sufficient for the bandwidth of interest for underwater pile driving impact sound and gives sufficient resolution to catch the peaks and other relevant data. The anti-aliasing filter included in the Photon also allows the capture of the true peak.

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

A vibratory hammer was used to drive the piles initially. Then all piles were driven to bearing depth with a diesel hammer. The diesel impact driver was an Delmag D46-32 with an energy rating of 85,000 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 a mix of sand and fist-sized rocks with occasional rocks of one-foot in diameter. Piles driven were open-ended hollow steel piles, 24-inches in diameter with a one-inch wall thickness. 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 –

Also known as pile # 36 according to the contractors numbering system is located approximately 30 feet southwest of the southeastern end of the dock (see Figure 1). The pile is located in 11 feet of water.

Pile 2 –

Pile 2 is also designated as pile # 35 in the contractors numbering system. It is located approximately 20 feet southwest of the southeastern end of the dock (see Figure 1). The pile is located in 11 feet of water.

Pile 3 -

Also known as pile # 45 in the contractors numbering system. It is located approximately 80 feet offshore and 30 feet from the southwest edge of the dock (see Figure 1). This pile is located in 7 feet of water.

Pile 4 -

Pile 4 is also designated as pile # 41 in the contractors numbering system. It is located approximately 20 feet southwest of the southeastern edge of the dock and 160 feet offshore (see Figure 1). The pile is located in 9 feet of water.

Pile 5 -

Pile 5 was located approximately 160 feet offshore and 20 feet from the southwest edge of the dock. It is also referred to as pile # 40 in the contractors numbering system. The pile is located in 9 feet of water.

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 tied to a static line at the surface 33 feet (10 meters) from the pile

(Figure 4) for monitoring piles 1 and 2 but simply lowered from the edge of the dock for the remainder of the piles.

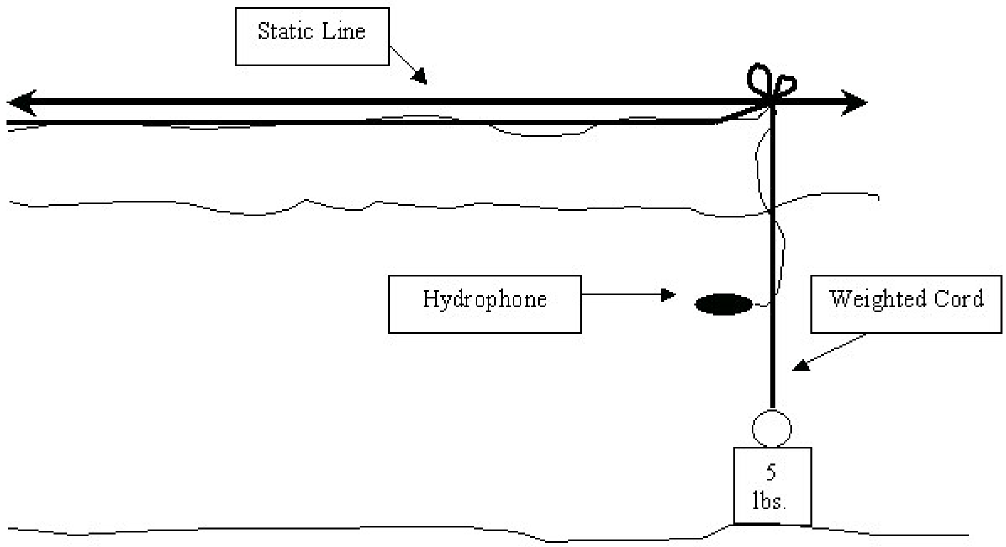


Figure 4: Diagram of hydrophone deployment at the monitoring location for piles 1 and 2.

RESULTS

UNDERWATER SOUND LEVELS

Pile 1

Pile 1 was driven with a diesel hammer in a water depth of 11 feet. The bubble curtain was off at the start of the drive and then 44 seconds into the drive the bubble curtain was turned on. The bubbles were turned off again 13 minutes later and then turned back on after three minutes.

Tables 2 and 3 indicate the results of monitoring for Pile 1. The highest absolute peak from the midwater hydrophone is 211 dB_{peak} and the absolute highest peak from the bottom hydrophone is 215 dB_{peak} for the entire driving event. The highest midwater and bottom RMS were both 198 dB_{RMS} for the entire driving event. The highest midwater SEL for the peak strike was 183 dB_{SEL} and the highest bottom SEL was 186 dB_{SEL}. As can be seen in Appendix A Figure 6 the waveform analysis for Pile 1 indicates that there was a relatively long delay between the initial onset of the impulse and the absolute peak (rise time of 13.9 milliseconds). This typically indicates a ‘ringing’ of the pile when the pile encounters a hard substrate such as rock or glacial till. In addition this was seen for all the remaining piles monitored. 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 25 dB lower than the absolute peak. The SEL for Pile 1 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 3 and 4 indicate that none of the calculated SEL values for a single strike (peak strike) exceeded the estimated summed SEL per strike thresholds. This is a very conservative estimate of potential mortality or injury impacts for multiple pile strikes.

The average peak sound reductions achieved with the bubble curtain ranged between 6 and 14 dB midwater and 8 to 11 dB on the bottom. This indicates that the bubble curtain was functioning slightly better than anticipated.

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

Pile #	Date	Hydrophone Depth	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (dB ± s.d.)	n[2]	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
1	10/18/05	5 feet (midwater)	OFF	211	198	209 ± 189	30	-	192 ± 172	183	4	206
			ON	206[1]	195	195 ± 181	207	14	182 ± 166	179	13.3	197
			OFF	211[1]	197	207 ± 196	91	-	191 ± 178	181	10.7	201
			ON	205[1]	191	201 ± 182	206	6	183 ± 165	178	1.4	197
						Total:	**534**				**Total:**	**193**

[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	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (dB ± s.d.)	n[2]	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
1	10/18/05	8 feet (bottom)	OFF	215[1]	198	211 ± 196	30	-	196 ± 175	186	13.9	206
			ON	207	193	200 ± 201	207	11	187 ± 167	181	10.1	197
			OFF	214	198	209 ± 199	91	-	193 ± 181	185	6.0	201
			ON	210[1]	195	201 ± 182	206	8	186 ± 169	183	10.9	197
						Total:	**534**				**Total:**	**193**

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

Pile 2

Pile 2 was driven in water depth of 11 feet. The contractor started the pile driving with the bubbles turned on then after two minutes, the air was turned off. The air remained off for 1.5 minutes and then turned back on for 1.75 minutes. Figure 5 indicates the visible changes in signal amplitude with bubbles off versus bubbles on.

Tables 4 and 5 indicate the results of monitoring for Pile 2. The highest absolute peak from the midwater hydrophone is 209 dB_{peak} and the absolute highest peak from the bottom hydrophone is 212 dB_{peak} for the entire driving event. The highest midwater and bottom RMS were both 197 dB_{RMS} for the entire driving event. The highest midwater and bottom SEL for the peak strike were both 181 dB_{SEL}. 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.

The SEL for Pile 2 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 5 and 6 indicate that none of the calculated SEL values for a single strike (peak strike) exceeded the estimated summed SEL per strike thresholds. This is a very conservative estimate of potential mortality or injury impacts for multiple pile strikes.

The average peak sound reductions achieved with the bubble curtain ranged between 6 and 11 dB midwater and 9 to 14 dB on the bottom. This indicates that the bubble curtain was functioning slightly better than anticipated.

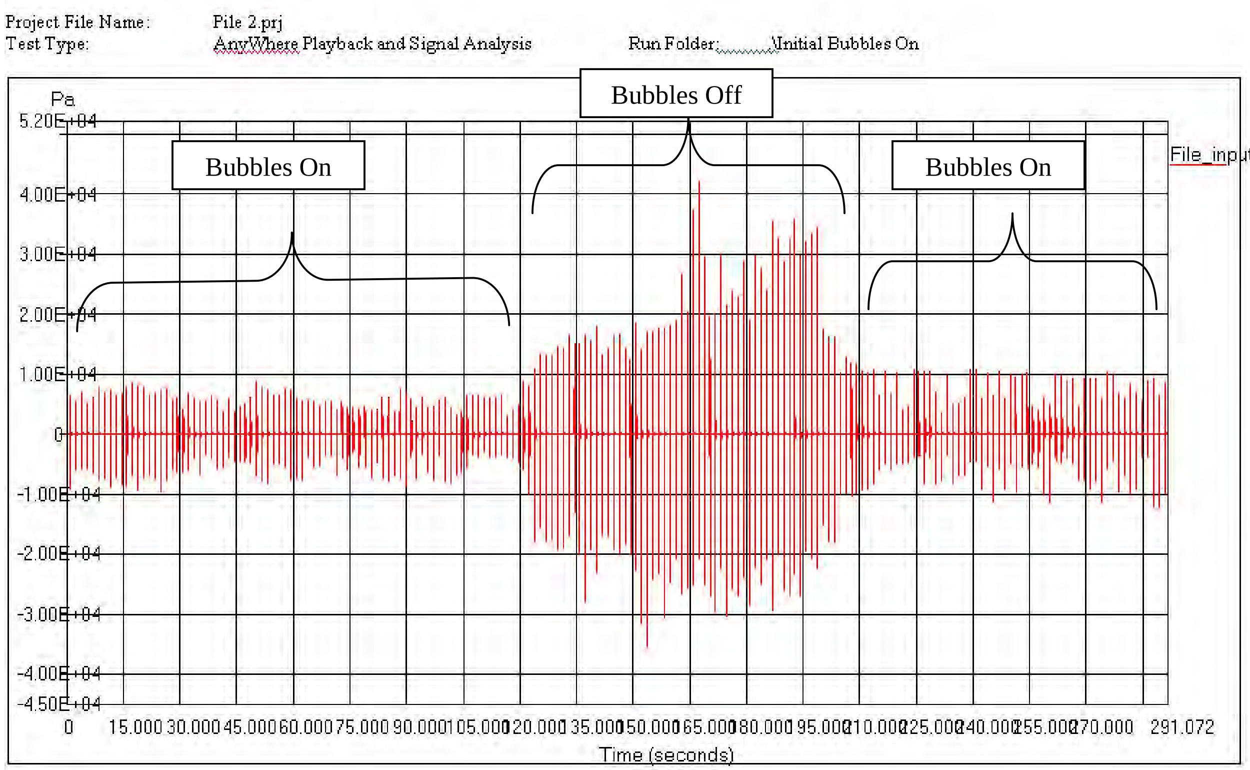


Figure 5: Waveform recording indicating the effects on amplitude with bubble curtain on versus bubble curtain off for pile 2.

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

Pile #	Date	Hydrophone Depth	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (dB ± s.d.)	n[2]	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
2	10/18/05	5 feet (midwater)	ON	204[1]	194	196 ± 182	226	11	186 ± 171	179	15.3	197
			OFF	209[1]	197	207 ± 196	103	-	190 ± 180	181	4.8	200
			ON	205	189	201 ± 185	223	6	184 ± 168	176	3.0	197
						Total:	**552**				**Total:**	**193**

[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	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (dB ± s.d.)	n[2]	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
2	10/18/05	9 feet (bottom)	ON	201[1]	189	196 ± 185	226	14	182 ± 169	179	5.0	197
			OFF	212	197	210 ± 198	103	-	193 ± 182	181	4.1	200
			ON	211	195	201 ± 187	223	9	186 ± 171	176	10.9	197
						Total:	**552**				**Total:**	**193**

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

Pile 3

Pile 3 was driven in water depth of 7 feet. The contractor started the pile driving with the bubbles turned off then after one munute, the air was turned on. The air remained on for just over four minutes and then turned back off for approximately 1.5 minutes. Finally the air was turned on for the remainder of the drive after just over one minute.

Tables 6 and 7 indicate the results of monitoring for Pile 3. The highest absolute peak from the midwater hydrophone is 209 dB_{peak} and the absolute highest peak from the bottom hydrophone is 206 dB_{peak} for the entire driving event. The highest midwater RMS was 198 dB_{RMS} and 187 dB_{RMS} for the bottom. The highest midwater SEL for the peak strike was 181 dB_{SEL} and 177 dB_{SEL} for the bottom. 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.

The SEL for Pile 3 averaged around 29 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 7 and 8 indicate that none of the calculated SEL values for a single strike (peak strike) exceeded the estimated summed SEL per strike thresholds. This is a very conservative estimate of potential mortality or injury impacts for multiple pile strikes.

The average peak sound reductions achieved with the bubble curtain ranged between 6 and 8 dB midwater and 3 to 7 dB on the bottom. This indicates that the bubble curtain was functioning as expected.

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

Pile #	Date	Hydrophone Depth	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (dB ± s.d.)	n[2]	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
3	10/20/05	4 feet (midwater)	OFF	207	193	204 ± 189	45	-	187 ± 172	178	15.6	204
			ON	198[1]	179	196 ± 176	173	8	178 ± 156	169	11.6	198
			OFF	209	198	204 ± 193	52	-	186 ± 174	181	11.7	203
			ON	202[1]	189	197 ± 181	274	7	178 ± 158	174	11.8	196
			OFF	207	192	203 ± 191	50	-	182 ± 168	175	2.6	203
			ON	198[1]	182	197 ± 175	45	6	179 ± 157	170	3.3	204
						Total:	**639**				**Total:**	**192**

[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	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (dB ± s.d.)	n[2]	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
3	10/20/05	7 feet (bottom)	OFF	205	187	202 ± 185	45	-	186 ± 170	177	16.0	204
			ON	198[1]	184	196 ± 177	173	6	182 ± 161	174	12.0	198
			OFF	206[1]	187	203 ± 189	52	-	185 ± 167	177	11.8	203
			ON	203[1]	186	196 ± 178	274	7	180 ± 162	176	11.7	196
			OFF	202[1]	184	199 ± 185	50	-	182 ± 165	174	10.6	203
			ON	197[1]	182	196 ± 173	45	3	181 ± 176	172	10.7	204
						Total:	**639**				**Total:**	**192**

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

Pile 4

Pile 4 was driven in water depth of 9 feet. The contractor started the pile driving with the bubbles turned off then after approximately 45 seconds, the air was turned on. The air remained on for just over three minutes and then turned back off for 1 minute. Finally, the air was turned on for the remainder of the drive.

Tables 8 and 9 indicate the results of monitoring for Pile 4. The highest absolute peak from the midwater hydrophone is 208 dB_{peak} and the absolute highest peak from the bottom hydrophone is 206 dB_{peak} for the entire driving event. The highest midwater RMS was 196 dB_{RMS} and 198 dB_{RMS} for the bottom. The highest midwater SEL for the peak strike was 178 dB_{SEL} and 180 dB_{SEL} for the bottom. 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.

The SEL for Pile 4 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 9 and 10 indicate that none of the calculated SEL values for a single strike (peak strike) exceeded the estimated summed SEL per strike thresholds. This is a very conservative estimate of potential mortality or injury impacts for multiple pile strikes.

The average peak sound reductions achieved with the bubble curtain ranged between 1 and 4 dB midwater and 0 to 2 dB on the bottom. An old broken wooden pile was observed near the base of the new pile after the pile had been driven. The broken pile interfered with the bottom ring of the bubble curtain seating itself properly on the bottom. This allowed some of the sound to leak through the bubble curtain and is indicated by the lower sound reductions.

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

Pile #	Date	Hydrophone Depth	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (dB ± s.d.)	n[2]	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
4	10/20/05	5 feet (midwater)	OFF	208	192	204 ± 192	33	-	186 ± 171	178	14.5	205
			ON	204[1]	195	200 ± 193	134	4	184 ± 174	177	12.4	199
			OFF	205	194	203 ± 182	41	-	186 ± 166	176	4.6	204
			ON	204	196	202 ± 185	224	1	186 ± 170	178	5.1	196
						Total:	**432**				**Total:**	**194**

[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	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (dB ± s.d.)	n[2]	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
4	10/20/05	9 feet (bottom)	OFF	206	191	203 ± 189	33	-	186 ± 169	178	18.2	205
			ON	205	195	201 ± 191	134	2	186 ± 174	179	14.2	199
			OFF	204	193	203 ±179	41	-	187 ± 166	177	5.2	204
			ON	206	198	203 ± 184	224	0	188 ± 170	180	5.8	196
						Total:	**432**				**Total:**	**194**

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

Pile 5

Pile 5 was driven in water depth of 9 feet. The contractor started the pile driving with the bubbles turned off then after approximately one minute, the air was turned on. The air remained on for just over five minutes and then turned back off for one minute. Finally, the air was turned on for the remainder of the drive.

Tables 10 and 11 indicate the results of monitoring for Pile 5. The highest absolute peak from the midwater hydrophone is 208 dB_{peak} and the absolute highest peak from the bottom hydrophone is 206 dB_{peak} for the entire driving event. The highest midwater RMS was 195 dB_{RMS} and 194 dB_{RMS} for the bottom. The highest midwater SEL for the peak strike were both 179 dB_{SEL} for the midwater and bottom. 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.

The SEL for Pile 5 averaged around 29 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 11 and 12 indicate that none of the calculated SEL values for a single strike (peak strike) exceeded the estimated summed SEL per strike thresholds. This is a very conservative estimate of potential mortality or injury impacts for multiple pile strikes.

The average peak sound reductions achieved with the bubble curtain ranged between 0 and 5 dB midwater and 0 to 4 dB on the bottom. It was not observed but suspected that a rock or other obstacle was interfering with the seating of the bottom ring of the bubble curtain on the bottom. Since this pile was adjacent to pile 4 it may have been the same broken pile that prevented the bubble curtain from functioning properly at this pile as well. This is indicated by the lower than expected noise reductions for this pile.

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

Pile #	Date	Hydrophone Depth	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (dB ± s.d.)	n[2]	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
5	10/20/05	5 feet (midwater)	OFF	208	195	204 – 193	55	-	186 - 174	179	14.8	203
			ON	207	194	199 - 188	202	5	181 - 166	179	4.5	197
			OFF	204	190	200 - 185	47	-	183 - 166	174	11.4	204
			ON	202[1]	190	200 - 182	203	0	183 - 160	173	2.9	197
						Total:	**507**				**Total:**	**193**

[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	Bubble Curtain Air ON/OFF	Absolute Peak (dB)	RMS (peak) (dB)	Average Peak (dB ± s.d.)	n[2]	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	Estimated SEL Per Strike
5	10/20/05	9 feet (bottom)	OFF	206	194	203 – 192	55	-	187 - 176	179	4.3	203
			ON	206	194	199 – 185	202	4	186 - 166	179	4.0	197
			OFF	203	191	201 - 186	47	-	185 - 166	176	5.0	204
			ON	203	192	202 - 180	203	0	186 - 166	177	5.2	197
						Total:	**507**				**Total:**	**193**

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

SEL

SEL was calculated for each of the absolute peak strikes for each pile. 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.

Rise Time

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

In all piles, except for the end of the drive of Pile 1, the rise times were relatively long. This could be an indication that the pile was ringing due to the relatively 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.

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. None of the birds observed indicated signs of distress or abnormal behavior.

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

CONCLUSIONS

Except for one or two strikes when the pile driver was operating at minimal energy, all pile strikes exceeded the 180 dB_{peak} and 150 dB_{RMS} thresholds set by NMFS. The bubble curtain performed better for piles 1, 2, and 3. For piles 4 and 5 the bubble curtain performed as anticipated but not as well as the previous three piles. For pile 4 there was an old broken pile at the base of the pile that prevented the bubble ring on the bottom from seating properly. It is unclear why the bubble curtain on pile 5 did not function as well as for the first three piles, but it is believed that an obstruction, such as a large rock or broken wooden pile, prevented the bottom ring from seating properly on the bottom.

All piles, with the exception of the end of the drive of pile 1, 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.

REFERENCES

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

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

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

APPENDIX A– WAVEFORM ANALYSIS FIGURES

PILE 1 – BUBBLE CURTAIN INITIAL OFF

Figure 6a

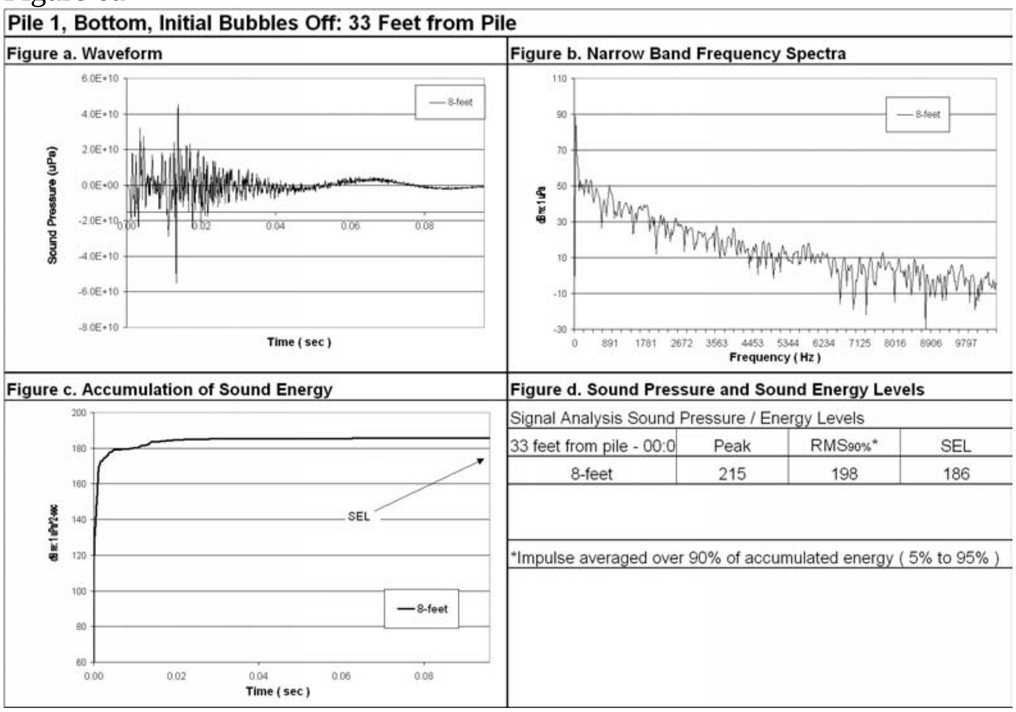


Figure 6b

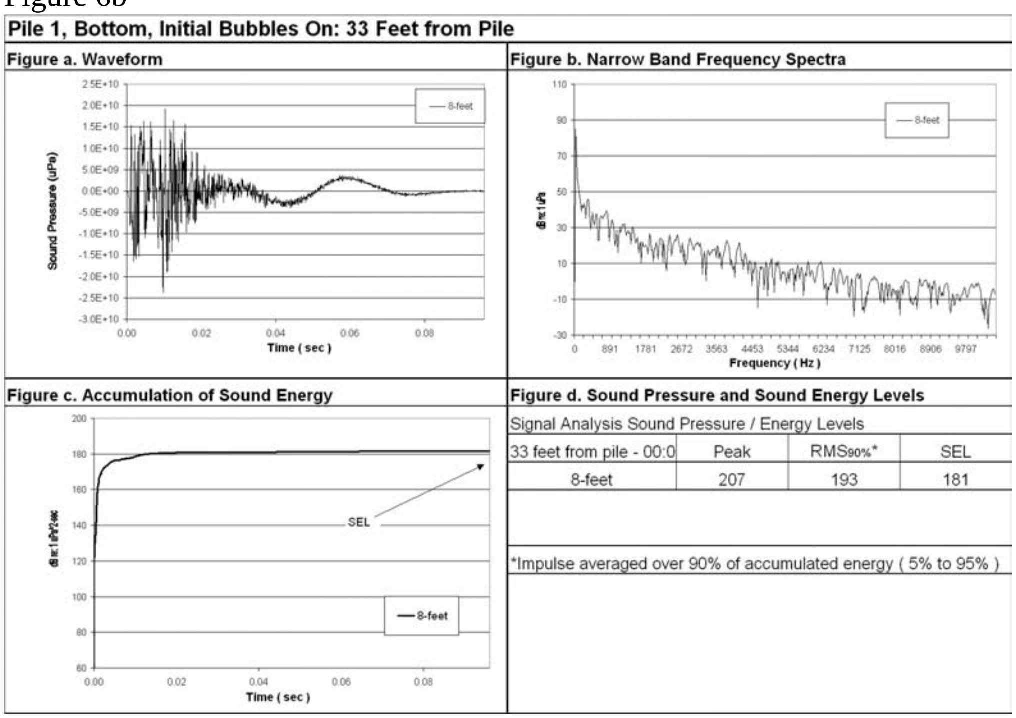


Figure 6: Waveform Analysis of Pile 1 Sound Pressure Levels with Bubble Curtain Initial Off, Midwater and Bottom.

PILE 1 – BUBBLE CURTAIN INITIAL ON

Figure 7a

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

Figure a. Waveform

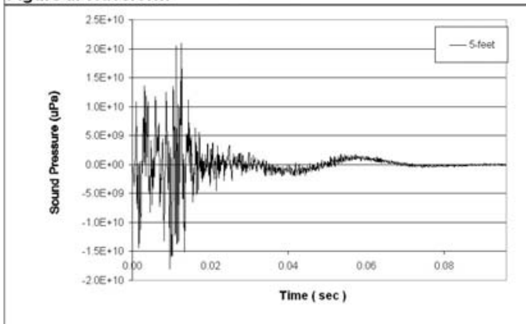


Figure b. Narrow Band Frequency Spectra

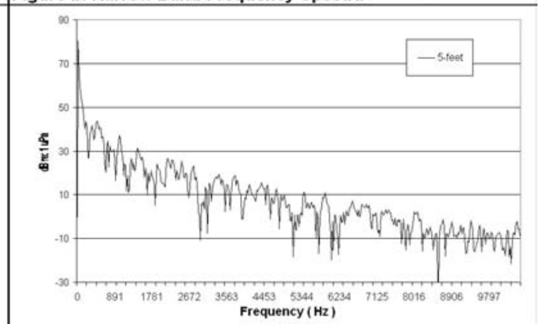


Figure c. Accumulation of Sound Energy

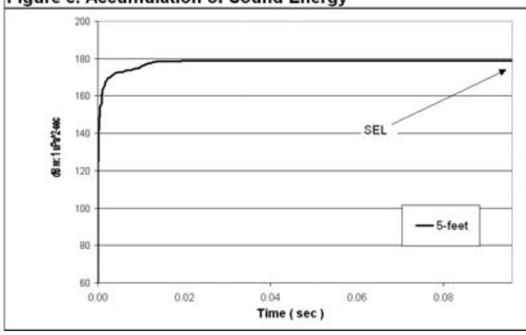


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
5-feet	206	195	179

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

Figure 7b

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

Figure a. Waveform

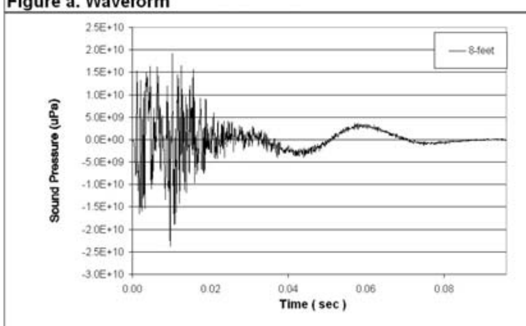


Figure b. Narrow Band Frequency Spectra

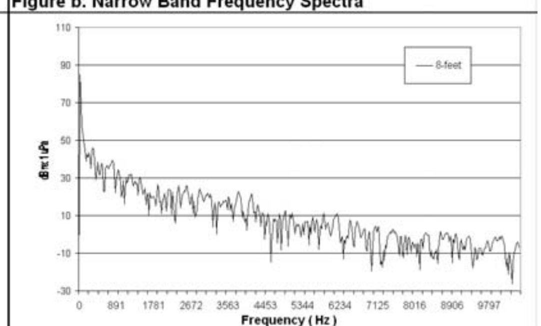


Figure c. Accumulation of Sound Energy

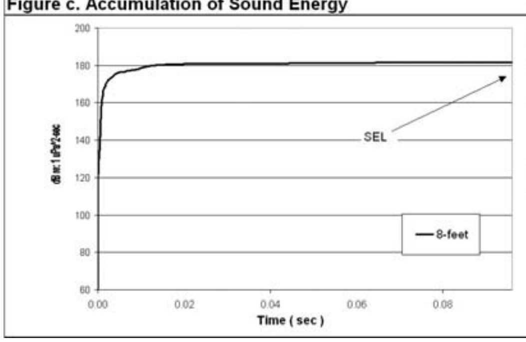


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

feet from pile - 00:00:(	Peak	RMS90%*	SEL
8-feet	207	193	181

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

Figure 7: Waveform Analysis of Pile 1 Sound Pressure Levels with Bubble Curtain Initial On, Midwater and Bottom.

PILE 1 – BUBBLE CURTAIN FINAL OFF

Figure 8a

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

Figure a. Waveform

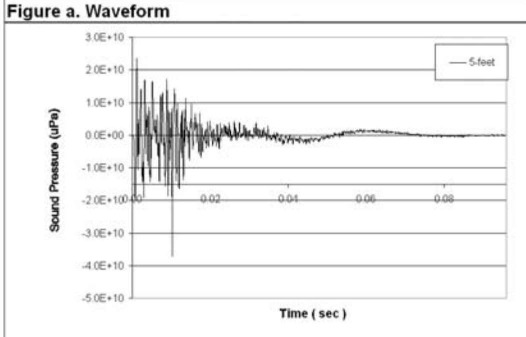


Figure b. Narrow Band Frequency Spectra

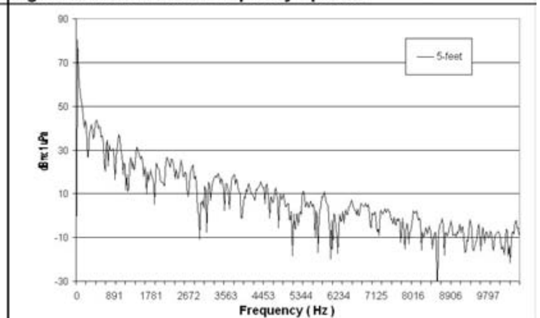


Figure c. Accumulation of Sound Energy

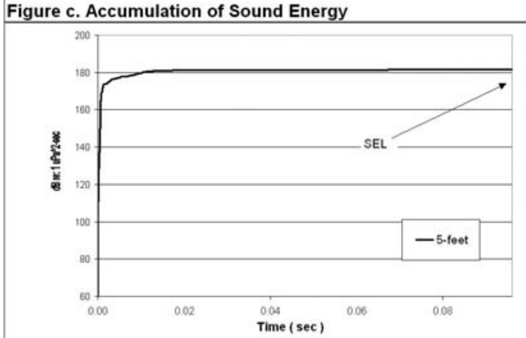


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
5-feet	211	197	181

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

Figure 8b

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

Figure a. Waveform

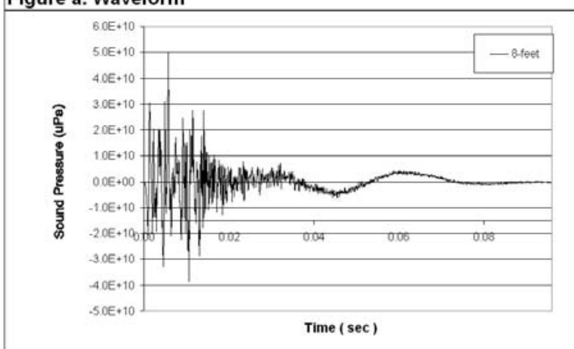


Figure b. Narrow Band Frequency Spectra

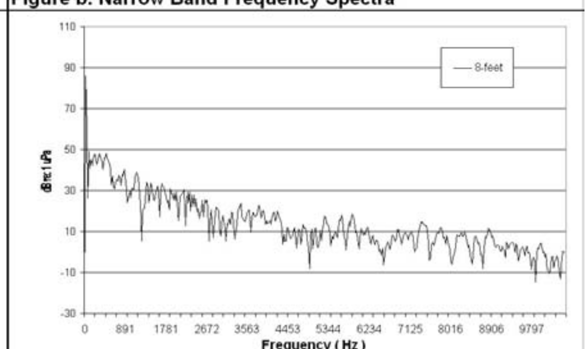


Figure c. Accumulation of Sound Energy

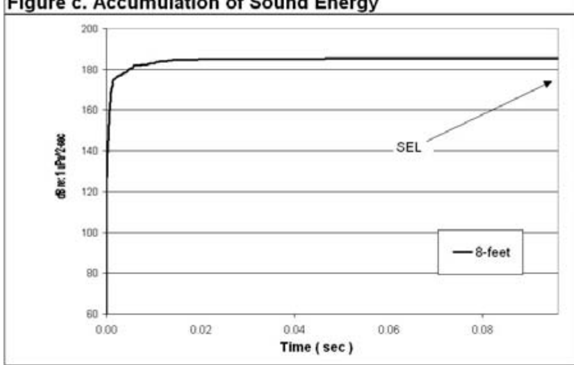


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
8-feet	214	198	185

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

Figure 8: Waveform Analysis of Pile 1 Sound Pressure Levels with Bubble Curtain Final Off, Midwater and Bottom.

PILE 1 – BUBBLE CURTAIN FINAL ON

Figure 9a

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

Figure a. Waveform

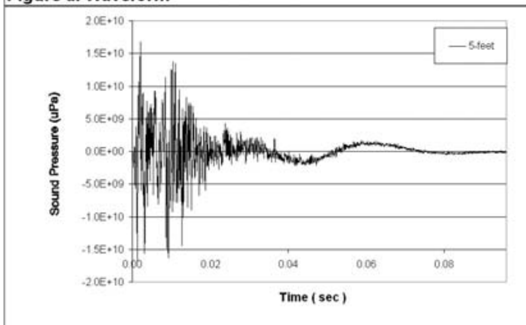


Figure b. Narrow Band Frequency Spectra

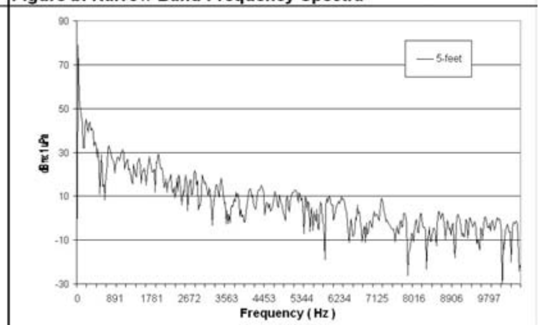


Figure c. Accumulation of Sound Energy

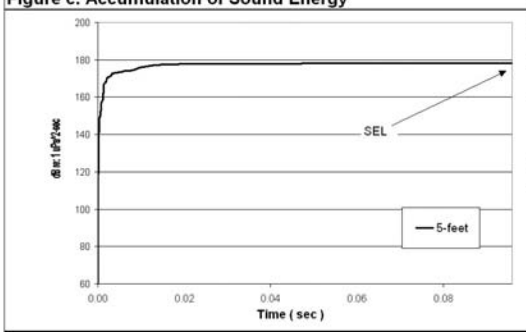


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
5-feet	205	191	178

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

Figure 9b

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

Figure a. Waveform

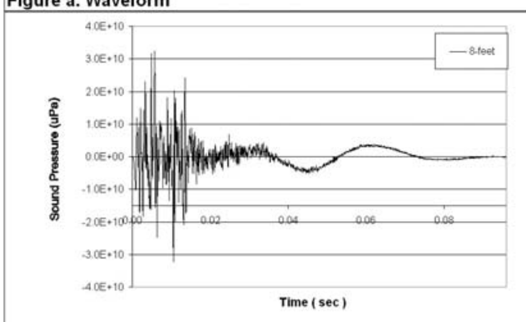


Figure b. Narrow Band Frequency Spectra

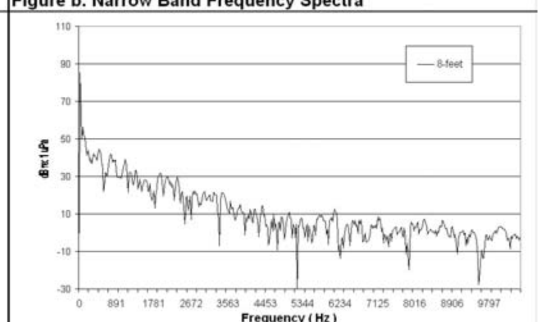


Figure c. Accumulation of Sound Energy

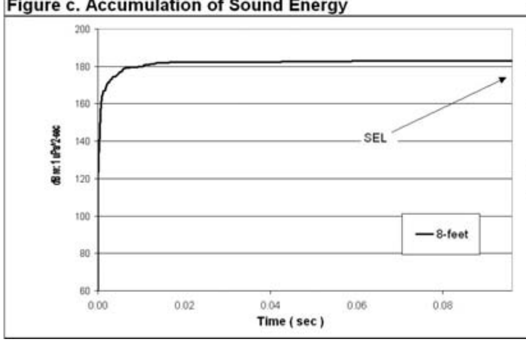


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
8-feet	210	195	183

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

Figure 9: Waveform Analysis of Pile 1 Sound Pressure Levels with Bubble Curtain Final On, Midwater and Bottom.

PILE 2 – INITIAL BUBBLE CURTAIN ON

Figure 10a

Pile 2, Midwater, Initial Bubbles On: 33 Feet from Pile

Figure a. Waveform

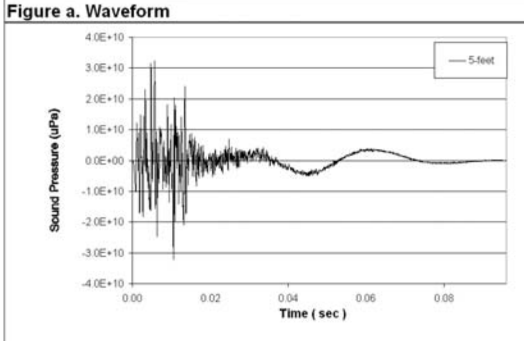


Figure b. Narrow Band Frequency Spectra

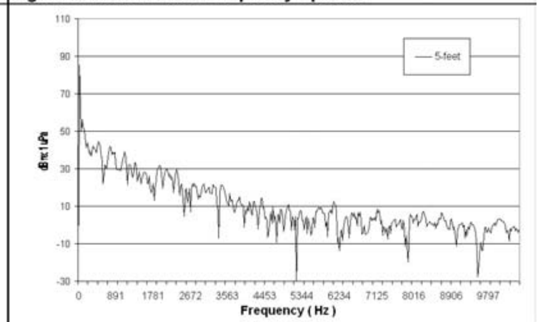


Figure c. Accumulation of Sound Energy

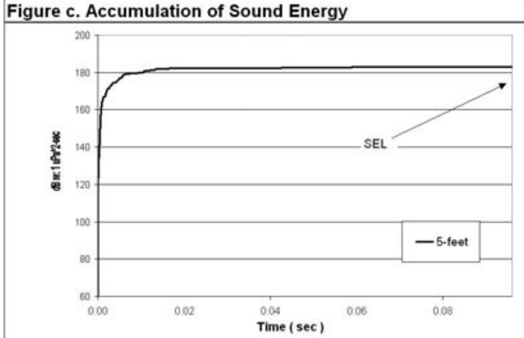


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
5-feet	210	195	183

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

Figure 10b

Pile 2, Bottom, Initial Bubbles On: 33 Feet from Pile

Figure a. Waveform

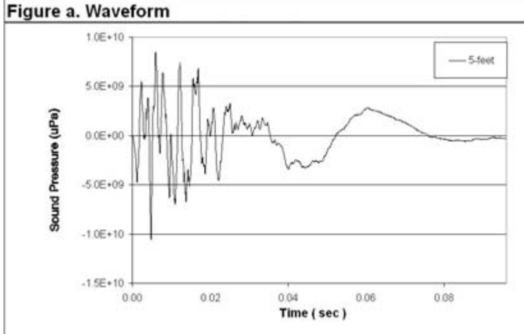


Figure b. Narrow Band Frequency Spectra

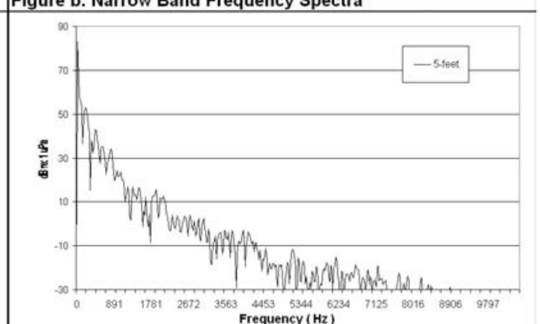


Figure c. Accumulation of Sound Energy

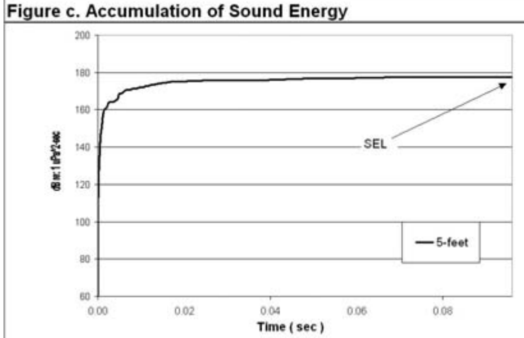


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

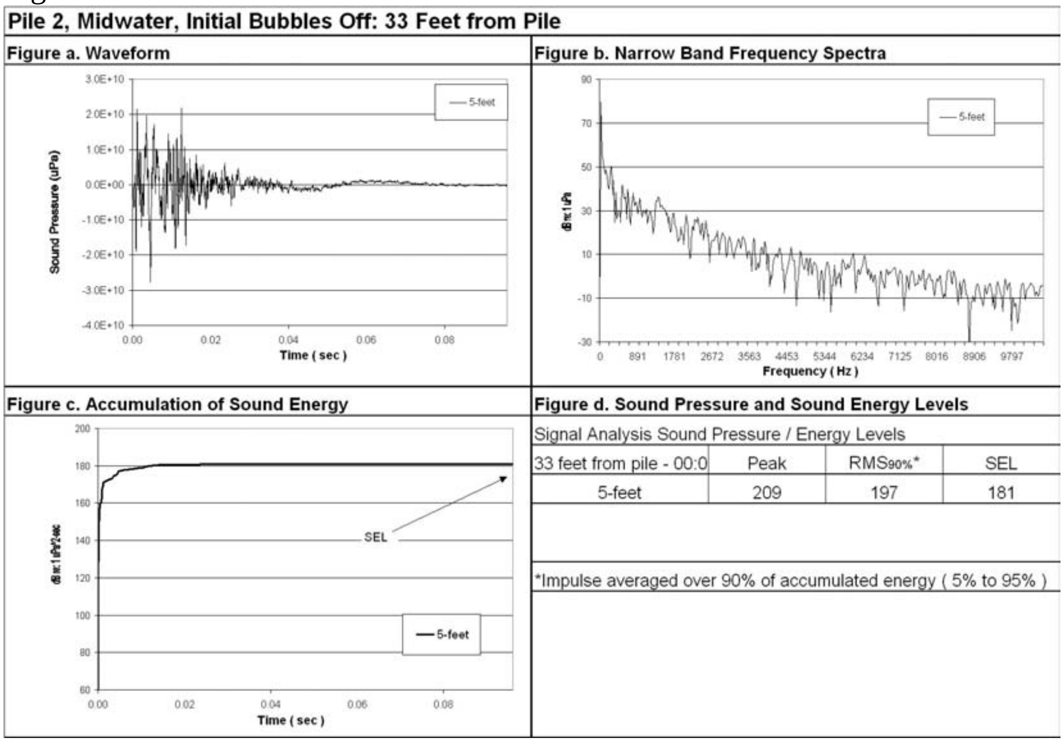
33 feet from pile - 00:0	Peak	RMS90%*	SEL
5-feet	201	189	177

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

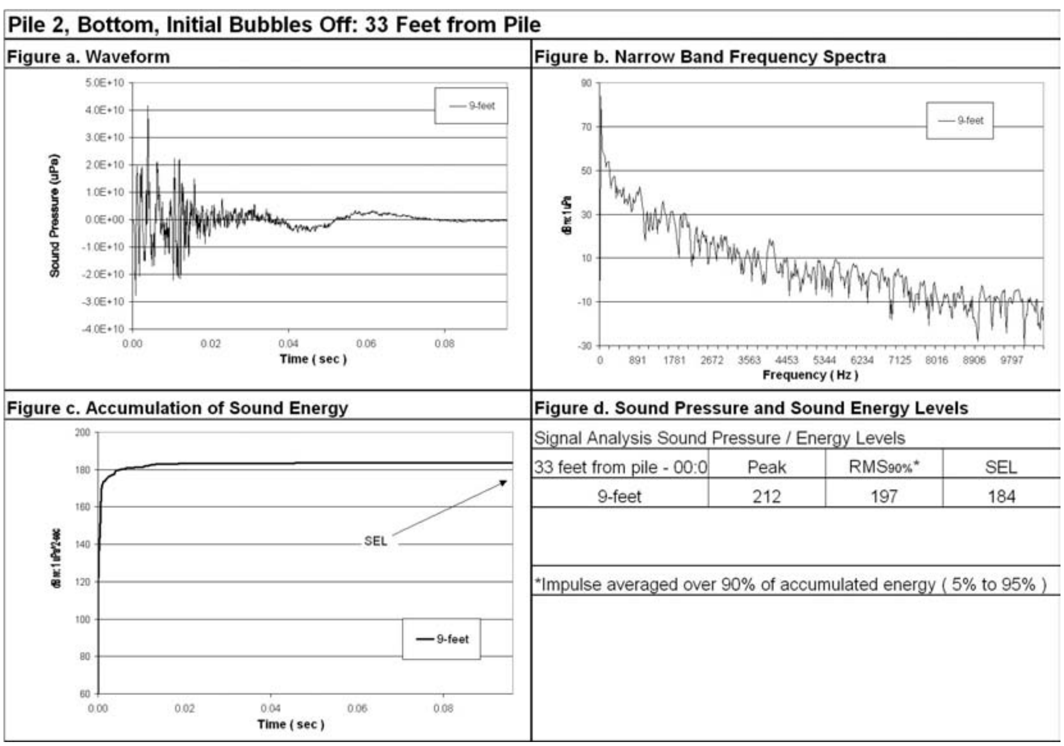
Figure 10: Waveform Analysis of Pile 2 Sound Pressure Levels with Bubble Curtain Initial On, Midwater and Bottom.

PILE 2 – INITIAL BUBBLE CURTAIN OFF

Figure 11a



33 feet from pile - 00:0	Peak	RMS90%*	SEL
5-feet	209	197	181



33 feet from pile - 00:0	Peak	RMS90%*	SEL
9-feet	212	197	184

Figure 11b

Figure 11: Waveform Analysis of Pile 2 Sound Pressure Levels with Bubble Curtain Initial Off, Midwater and Bottom.

PILE 2 – FINAL BUBBLE CURTAIN ON

Figure 12a

Pile 2, Midwater, Final Bubbles On: 33 Feet from Pile

Figure a. Waveform

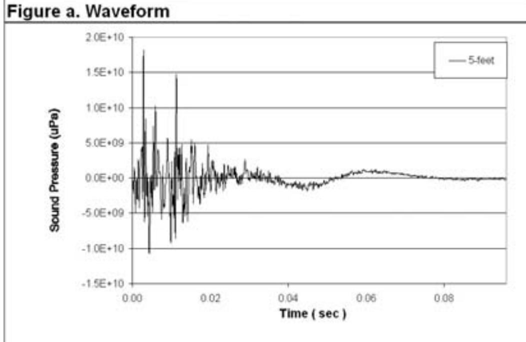


Figure b. Narrow Band Frequency Spectra

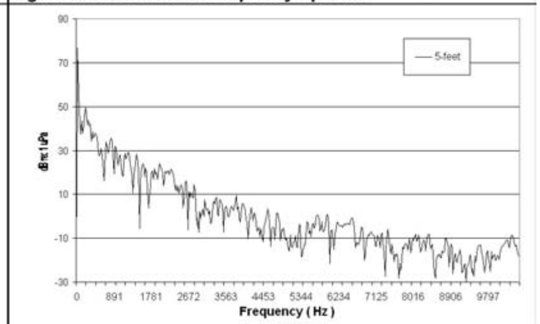


Figure c. Accumulation of Sound Energy

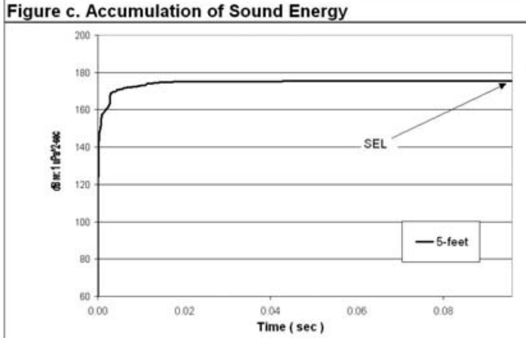


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
5-feet	205	189	176

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

Pile 2, Bottom, Final Bubbles On: 33 Feet from Pile

Figure a. Waveform

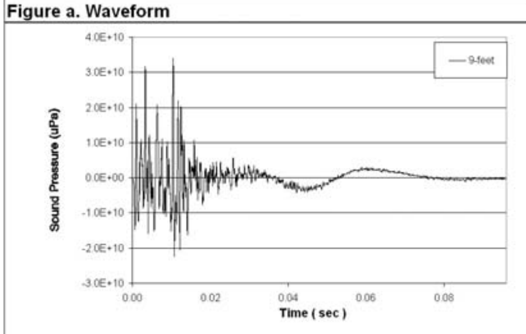


Figure b. Narrow Band Frequency Spectra

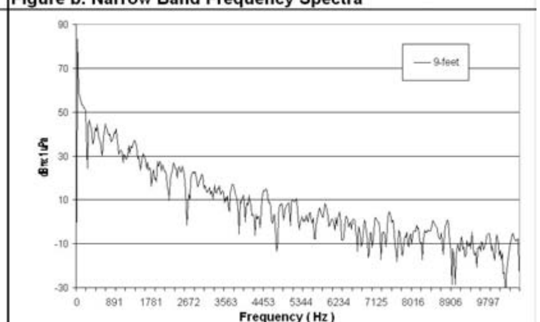


Figure c. Accumulation of Sound Energy

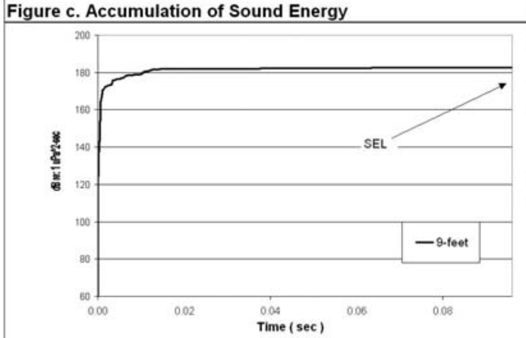


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
9-feet	211	195	183

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

Figure 12b

Figure 12: Waveform Analysis of Pile 2 Sound Pressure Levels with Bubble Curtain Final On, Midwater and Bottom.

PILE 3 – INITIAL BUBBLES OFF

Figure 13a

Pile 3, Midwater, Initial Bubbles Off: 33 Feet from Pile

Figure a. Waveform

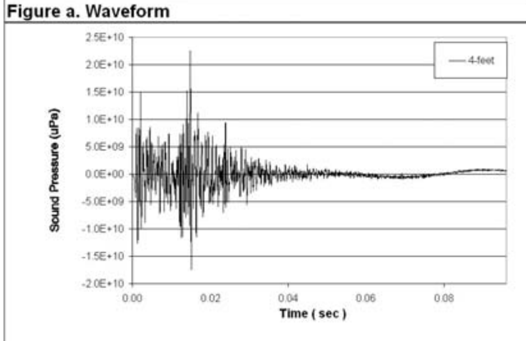


Figure b. Narrow Band Frequency Spectra

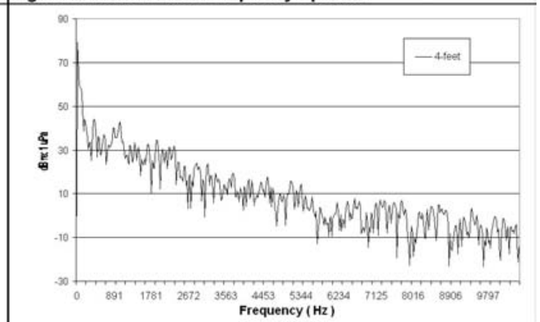


Figure c. Accumulation of Sound Energy

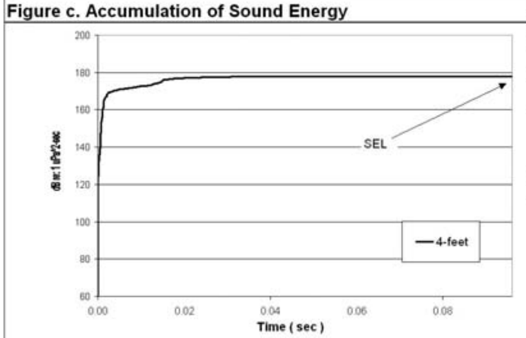


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
4-feet	207	193	178

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

Pile 3, Bottom, Initial Bubbles Off: 33 Feet from Pile

Figure a. Waveform

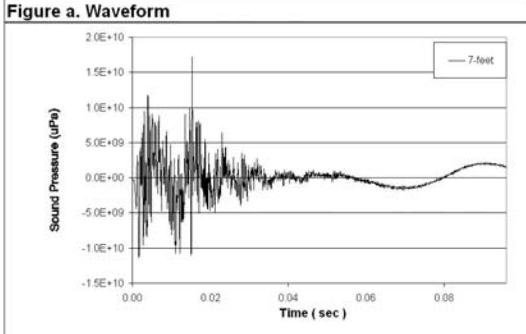


Figure b. Narrow Band Frequency Spectra

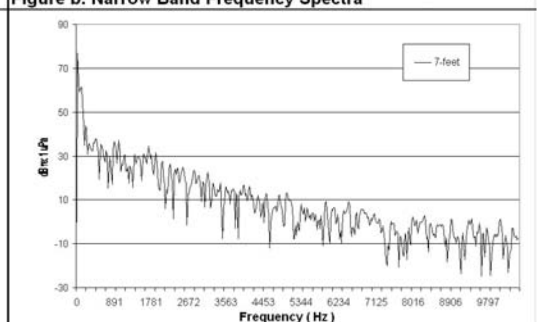


Figure c. Accumulation of Sound Energy

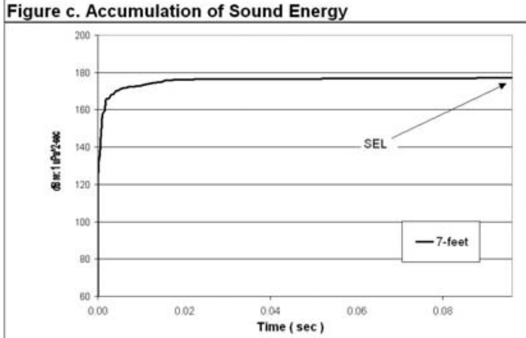


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
7-feet	205	187	177

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

Figure 13b

Figure 13: Waveform Analysis of Pile Number 3 Sound Pressure Levels with Bubble Curtain Initial Off, Midwater and Bottom.

PILE 3 – INITIAL BUBBLES ON

Figure 14a

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

Figure a. Waveform

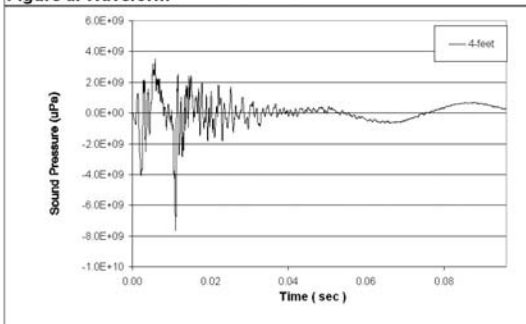


Figure b. Narrow Band Frequency Spectra

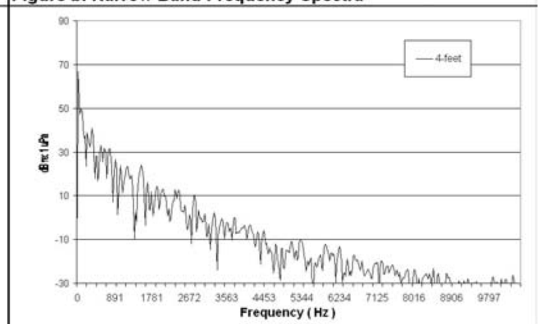


Figure c. Accumulation of Sound Energy

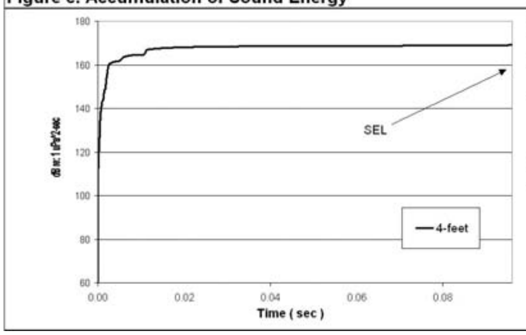


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
4-feet	198	179	169

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

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

Figure a. Waveform

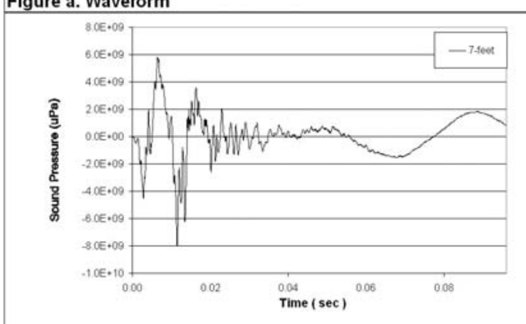


Figure b. Narrow Band Frequency Spectra

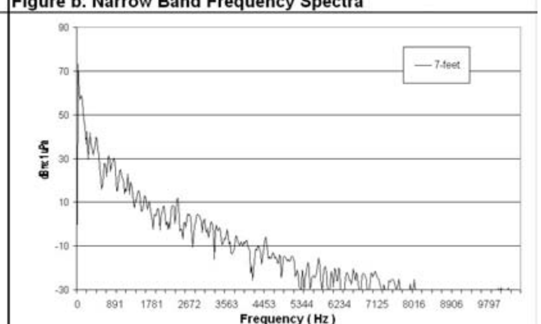


Figure c. Accumulation of Sound Energy

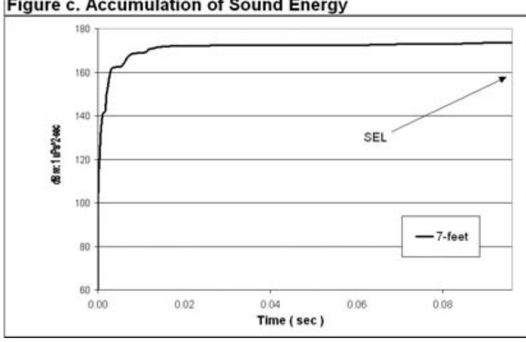


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
7-feet	198	184	174

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

Figure 14b

Figure 14: Waveform Analysis of Pile Number 3 Sound Pressure Levels with Bubble Curtain Initial On, Midwater and Bottom.

PILE 3 – SECOND BUBBLES OFF

Figure 15a

Pile 3, Midwater, Second Bubbles Off: 33 Feet from Pile

Figure a. Waveform

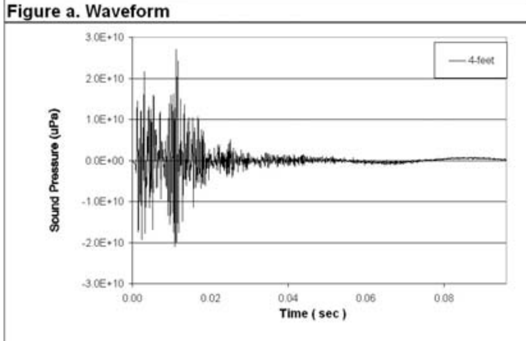


Figure b. Narrow Band Frequency Spectra

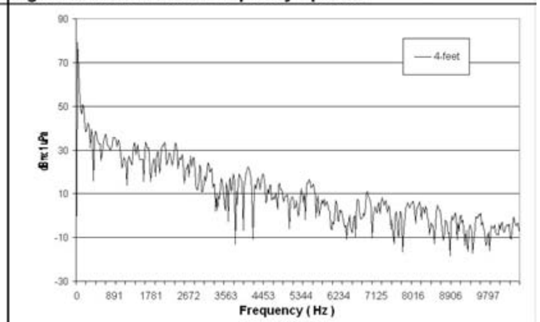


Figure c. Accumulation of Sound Energy

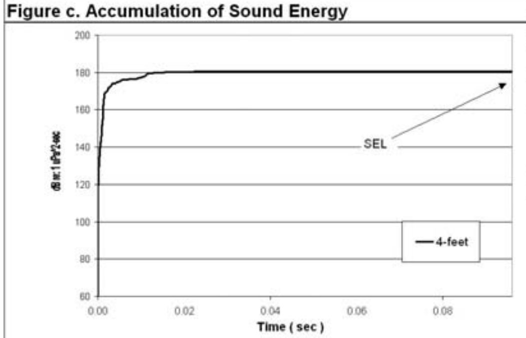


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
4-feet	209	198	181

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

Pile 3, Bottom, Second Bubbles Off: 33 Feet from Pile

Figure a. Waveform

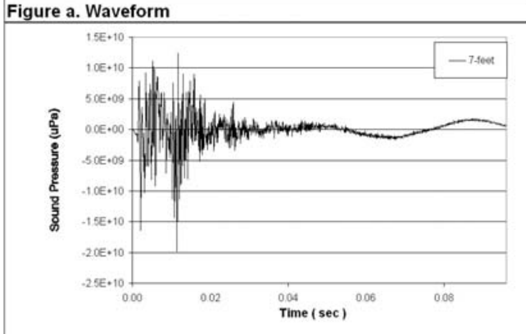


Figure b. Narrow Band Frequency Spectra

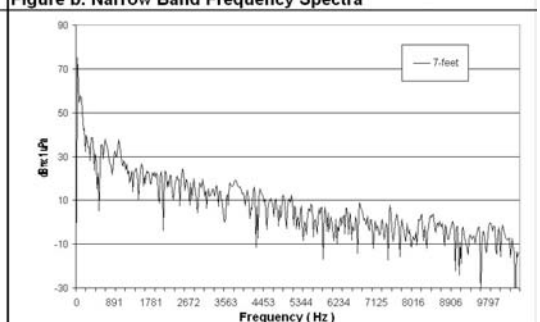


Figure c. Accumulation of Sound Energy

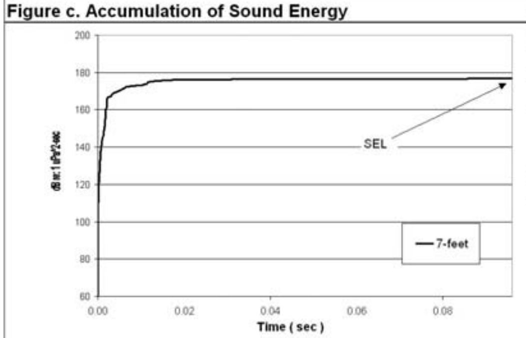


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
7-feet	206	187	177

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

Figure 15b

Figure 15: Waveform Analysis of Pile Number 3 Sound Pressure Levels with Bubble Curtain Second Off, Midwater and Bottom.

PILE 3 – SECOND BUBBLES ON

Figure 16a

Pile 3, Midwater, Final Bubbles Off: 33 Feet from Pile

Figure a. Waveform

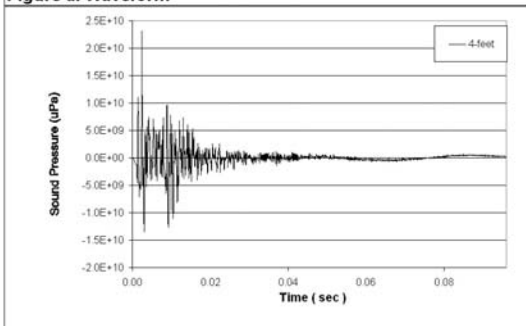


Figure b. Narrow Band Frequency Spectra

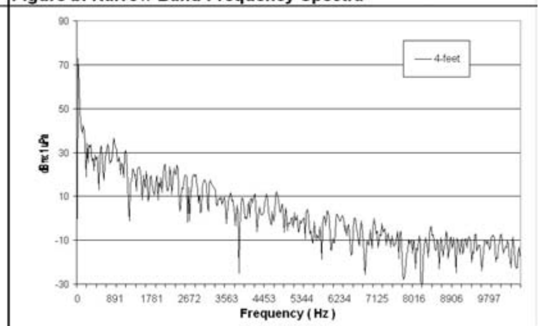


Figure c. Accumulation of Sound Energy

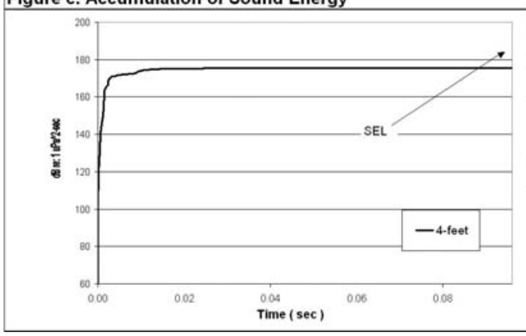


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
4-feet	207	192	175

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

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

Figure a. Waveform

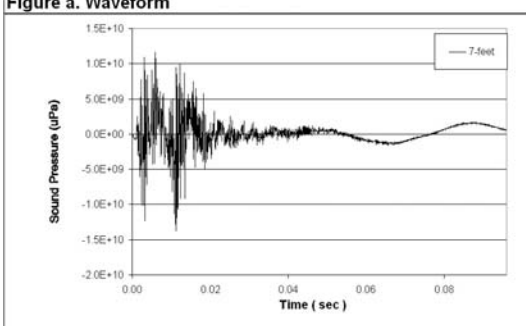


Figure b. Narrow Band Frequency Spectra

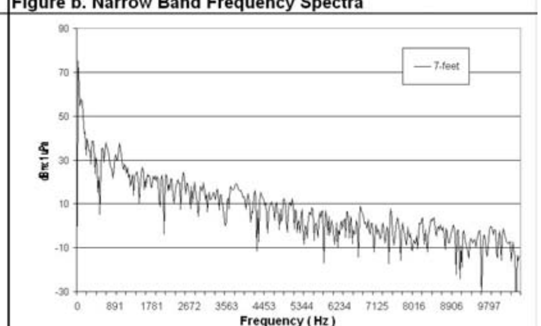


Figure c. Accumulation of Sound Energy

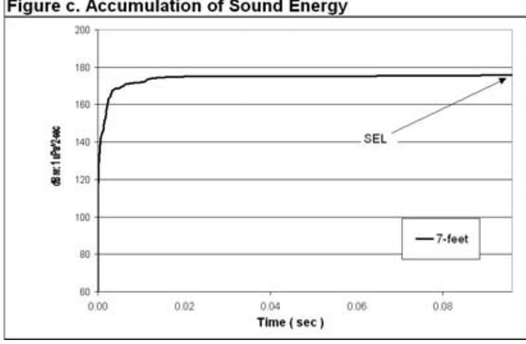


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
7-feet	203	186	176

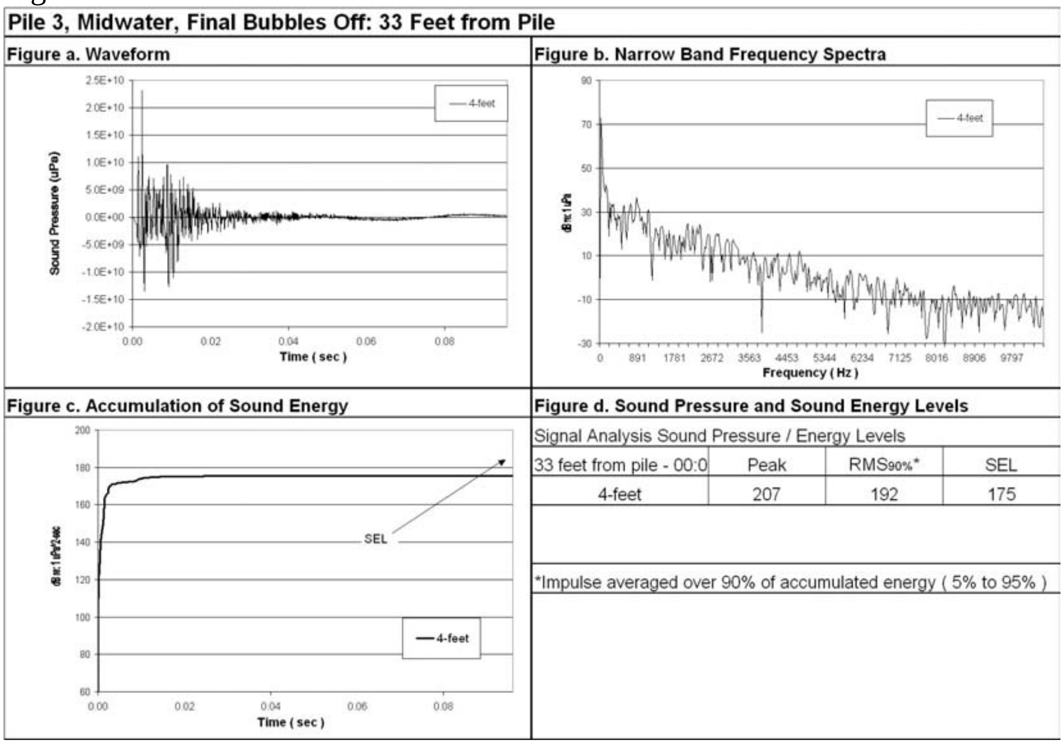
*Impulse averaged over 90% of accumulated energy (5% to 95%)

Figure 16b

Figure 16: Waveform Analysis of Pile Number 3 Sound Pressure Levels with Bubble Curtain Second On, Midwater and Bottom.

PILE 3 – FINAL BUBBLES OFF

Figure 17a



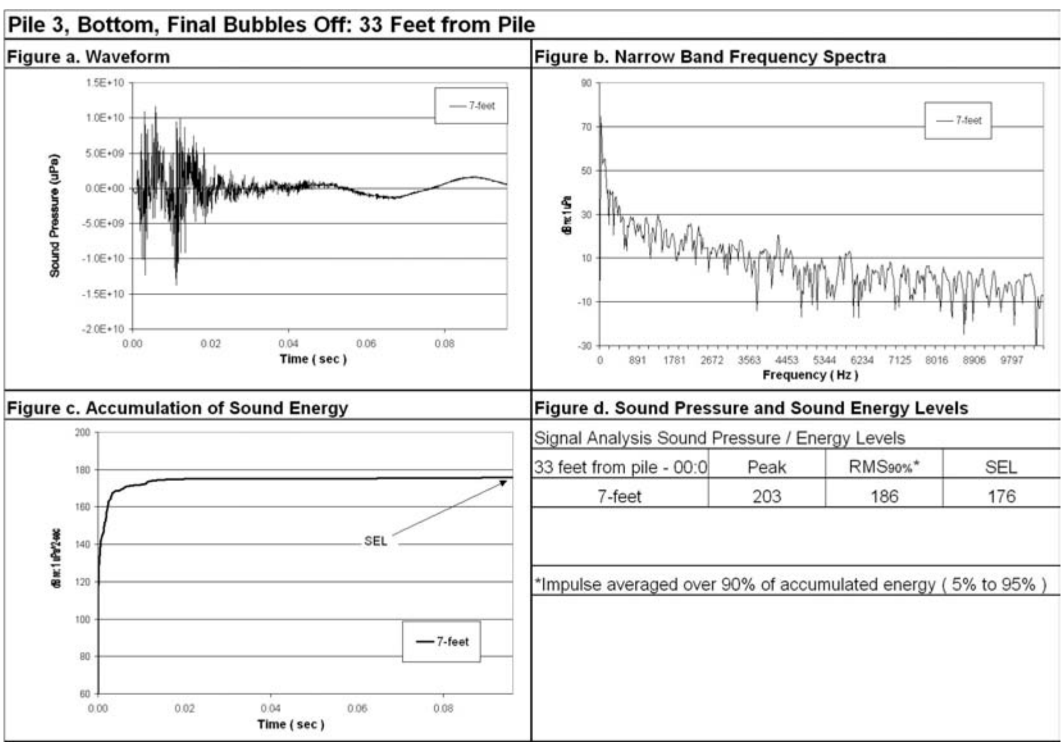


Figure 17b

Figure 17: Waveform Analysis of Pile Number 3 Sound Pressure Levels with Bubble Curtain Final Off, Midwater and Bottom.

PILE 3 – FINAL BUBBLES ON

Figure 18a

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

Figure a. Waveform

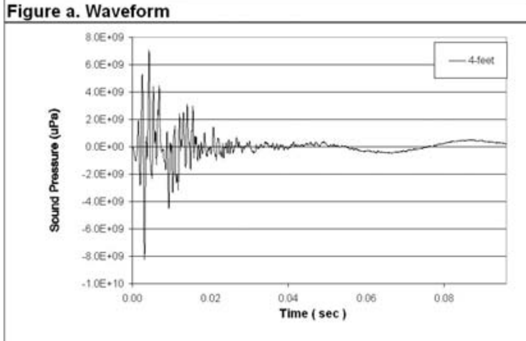


Figure b. Narrow Band Frequency Spectra

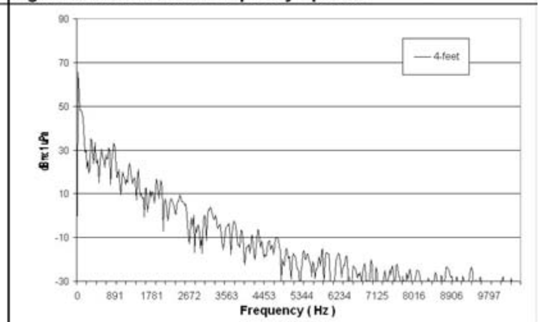


Figure c. Accumulation of Sound Energy

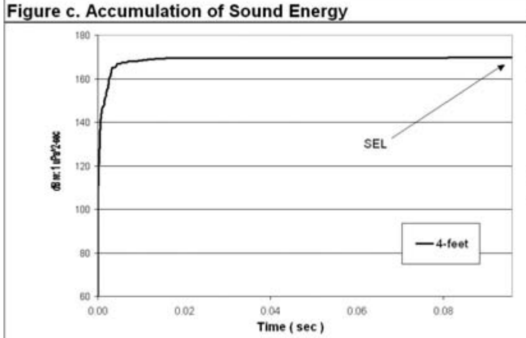


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
4-feet	198	182	170

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

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

Figure a. Waveform

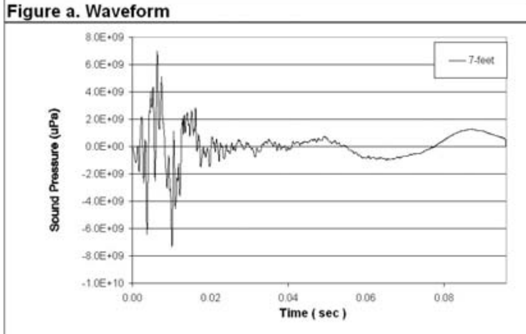


Figure b. Narrow Band Frequency Spectra

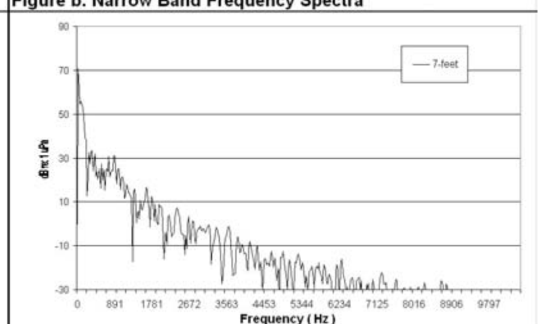


Figure c. Accumulation of Sound Energy

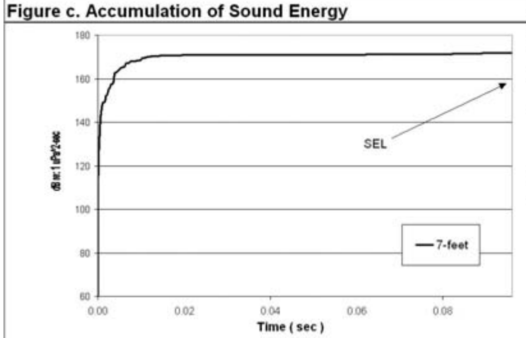


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
7-feet	197	182	172

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

Figure 18b

Figure 18: Waveform Analysis of Pile Number 3 Sound Pressure Levels with Bubbles Curtain Final On, Midwater and Bottom.

PILE 4 – INITIAL BUBBLES OFF

Figure 19a

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

Figure a. Waveform

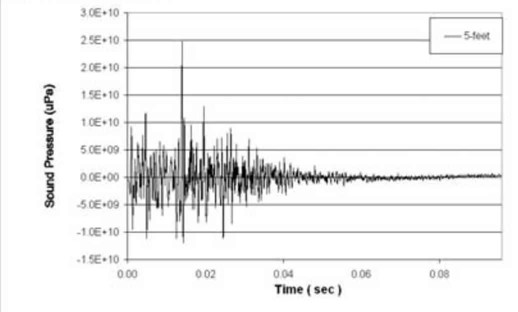


Figure b. Narrow Band Frequency Spectra

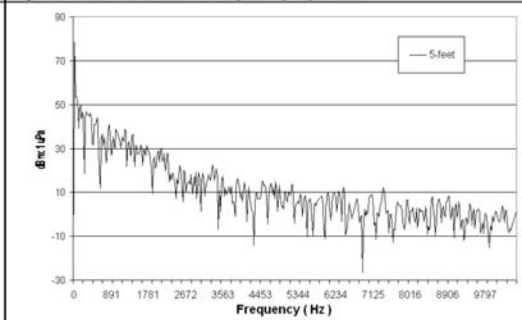


Figure c. Accumulation of Sound Energy

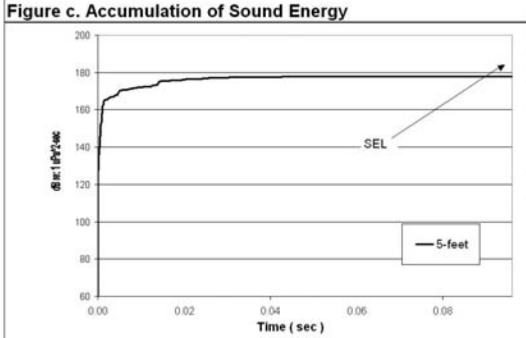


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
5-feet	208	192	178

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

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

Figure a. Waveform

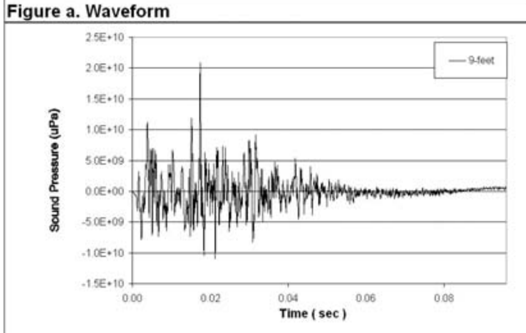


Figure b. Narrow Band Frequency Spectra

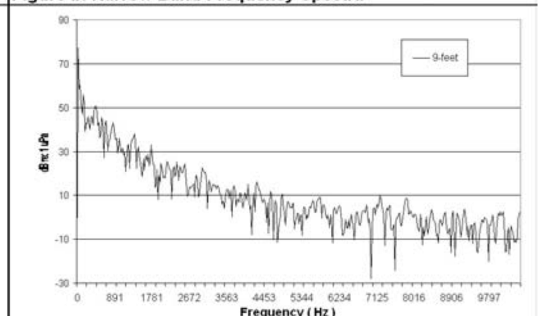


Figure c. Accumulation of Sound Energy

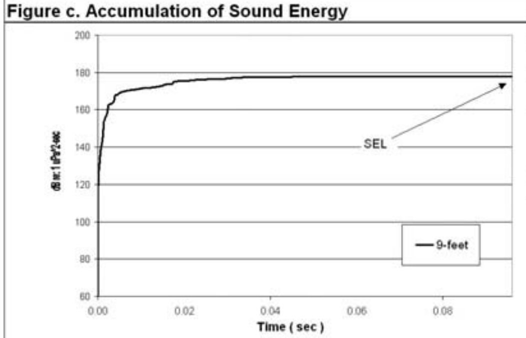


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
9-feet	206	191	178

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

Figure 19b

Figure 19: Waveform Analysis of Pile Number 4 Sound Pressure Levels with Bubbles Curtain Initial Off, Midwater and Bottom.

PILE 4 – INITIAL BUBBLES ON

Figure 20a

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

Figure a. Waveform

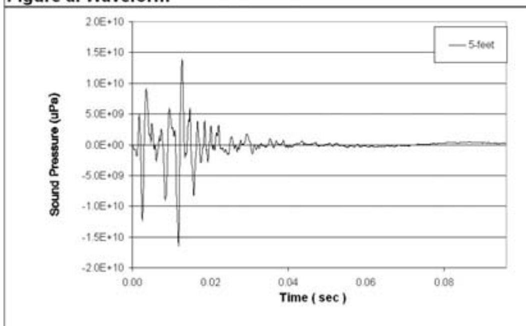


Figure b. Narrow Band Frequency Spectra

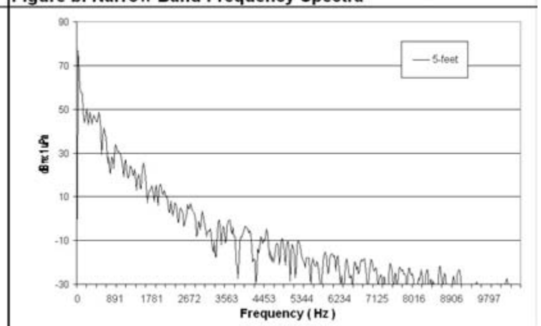


Figure c. Accumulation of Sound Energy

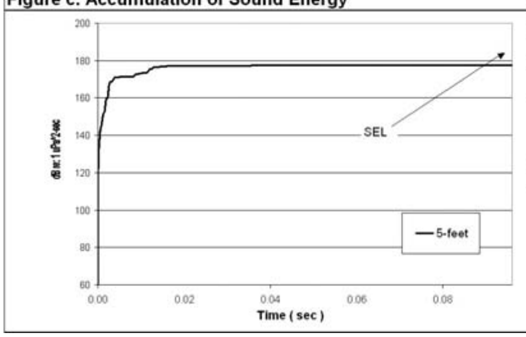


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
5-feet	204	195	177

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

Figure 20b

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

Figure a. Waveform

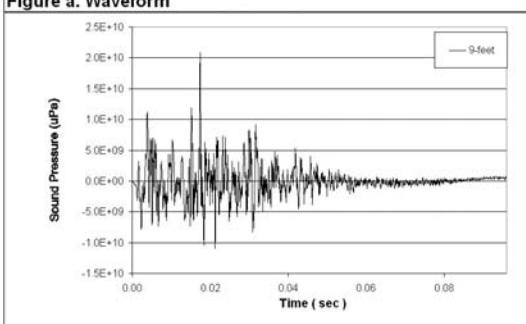


Figure b. Narrow Band Frequency Spectra

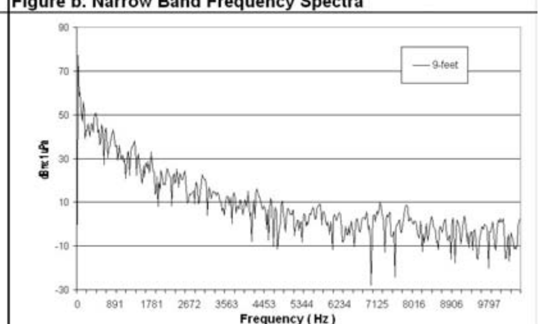


Figure c. Accumulation of Sound Energy

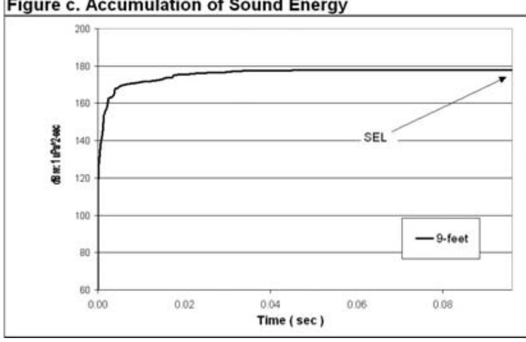


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

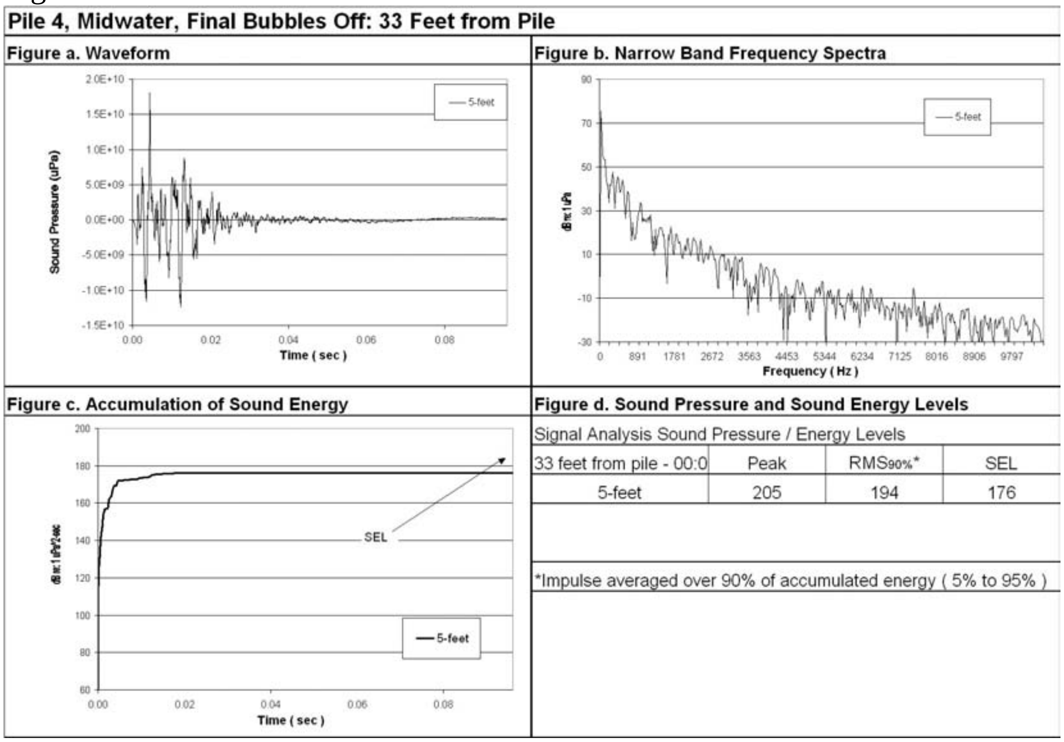
33 feet from pile - 00:0	Peak	RMS90%*	SEL
9-feet	206	191	178

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

Figure 20: Waveform Analysis of Pile Number 4 Sound Pressure Levels with Bubbles Curtain Initial On, Midwater and Bottom.

PILE 4 – FINAL BUBBLES OFF

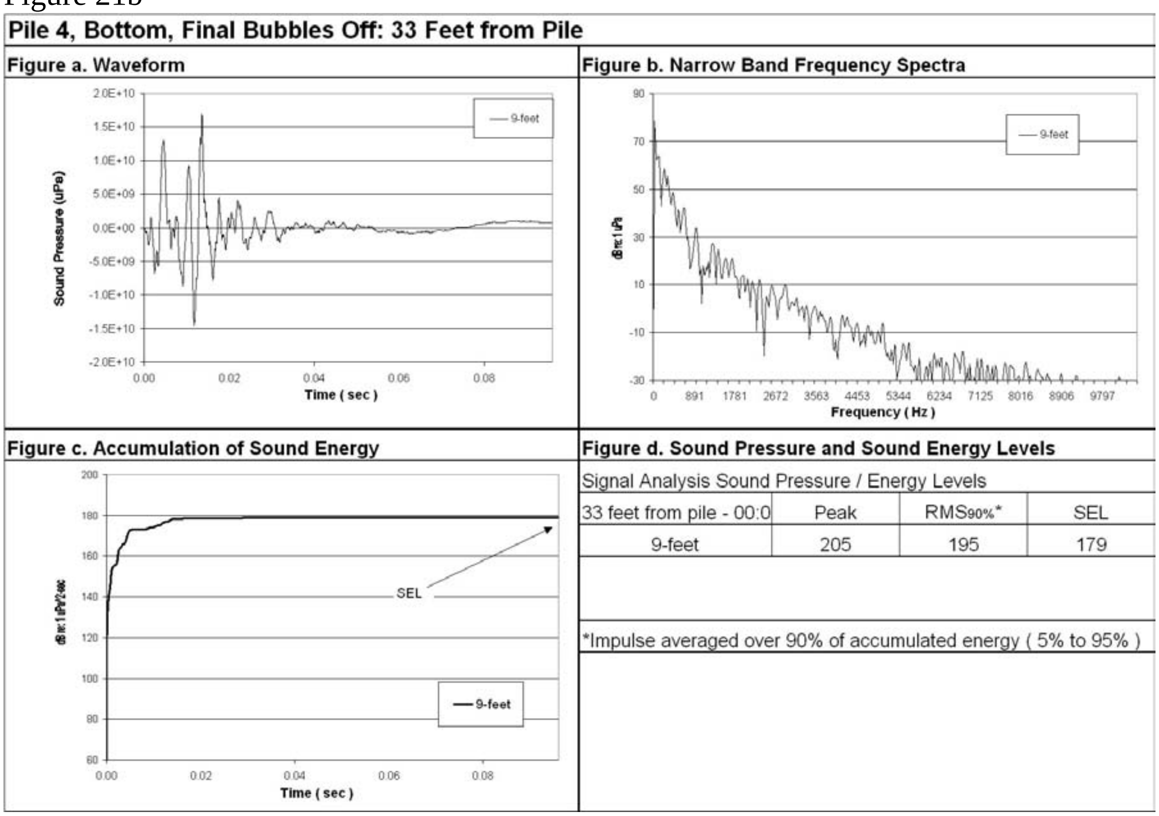
Figure 21a



Signal Analysis Sound Pressure / Energy Levels			
33 feet from pile - 00:0	Peak	RMS90%*	SEL
5-feet	205	194	176

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

Figure 21b



Signal Analysis Sound Pressure / Energy Levels			
33 feet from pile - 00:0	Peak	RMS90%*	SEL
9-feet	205	195	179

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

Figure 21: Waveform Analysis of Pile Number 4 Sound Pressure Levels with Bubbles Curtain Final Off, Midwater and Bottom.

PILE 4 – FINAL BUBBLES ON

Figure 22a

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

Figure a. Waveform

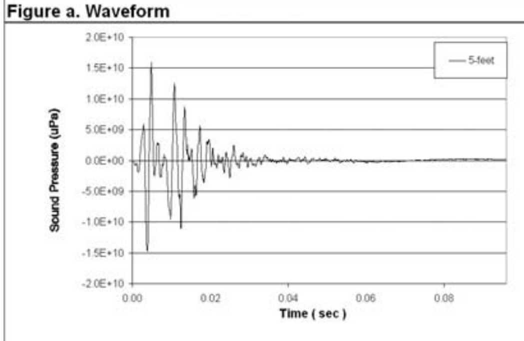


Figure b. Narrow Band Frequency Spectra

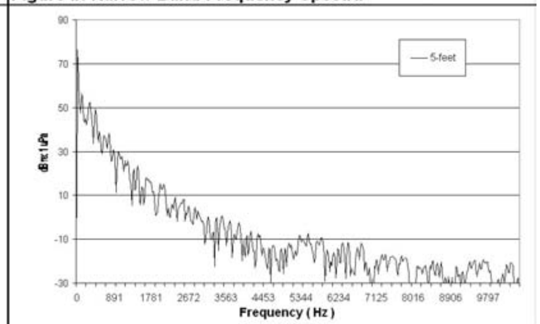


Figure c. Accumulation of Sound Energy

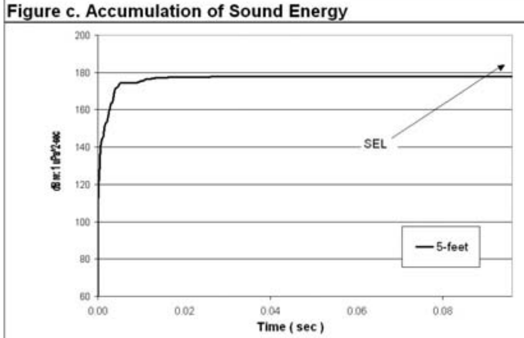


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
5-feet	204	196	178

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

Figure 22b

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

Figure a. Waveform

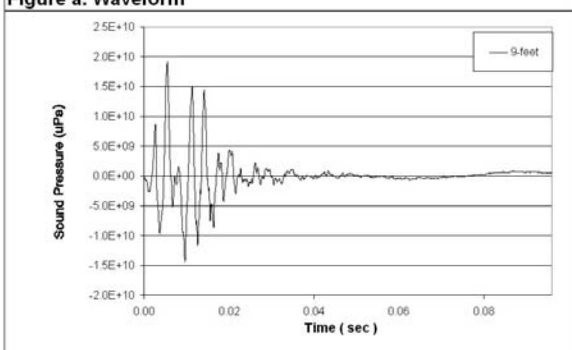


Figure b. Narrow Band Frequency Spectra

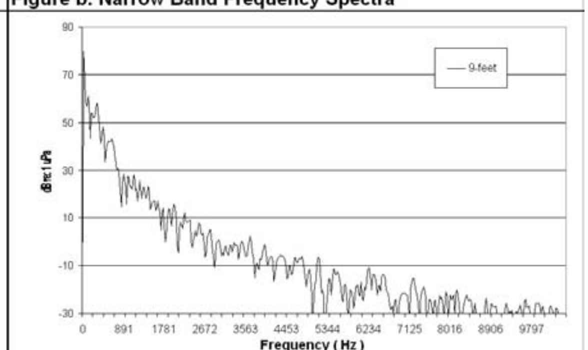


Figure c. Accumulation of Sound Energy

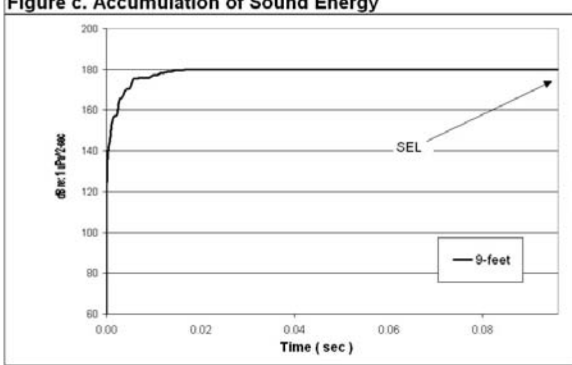


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
9-feet	206	198	180

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

Figure 22: Waveform Analysis of Pile Number 4 Sound Pressure Levels with Bubbles Curtain Final On, Midwater and Bottom.

PILE 5 – INITIAL BUBBLES OFF

Figure 23a

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

Figure a. Waveform

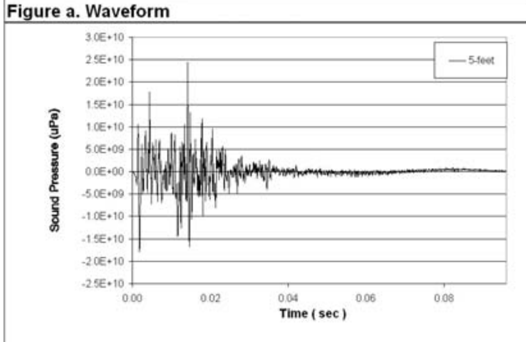


Figure b. Narrow Band Frequency Spectra

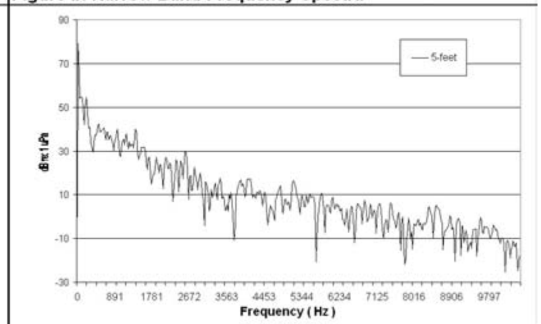


Figure c. Accumulation of Sound Energy

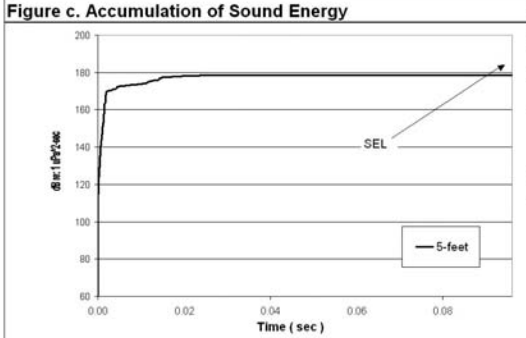


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
5-feet	208	195	179

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

Figure 23b

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

Figure a. Waveform

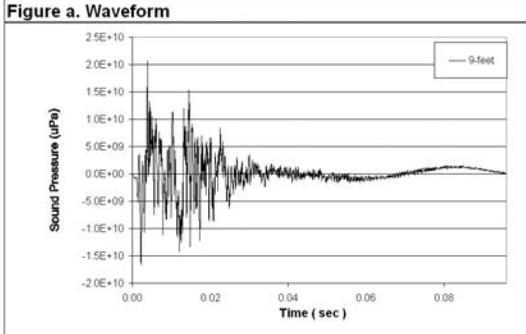


Figure b. Narrow Band Frequency Spectra

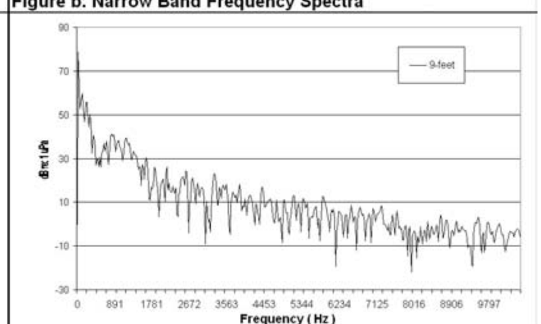


Figure c. Accumulation of Sound Energy

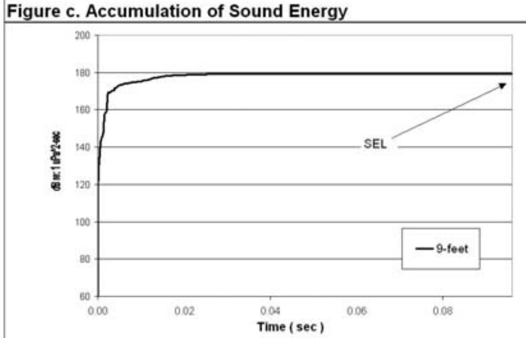


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
9-feet	206	194	179

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

Figure 23: Waveform Analysis of Pile Number 5 Sound Pressure Levels with Bubbles Curtain Initial Off, Midwater and Bottom.

PILE 5 – INITIAL BUBBLES ON

Figure 24a

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

Figure a. Waveform

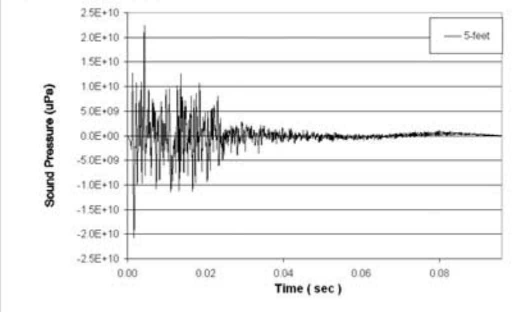


Figure b. Narrow Band Frequency Spectra

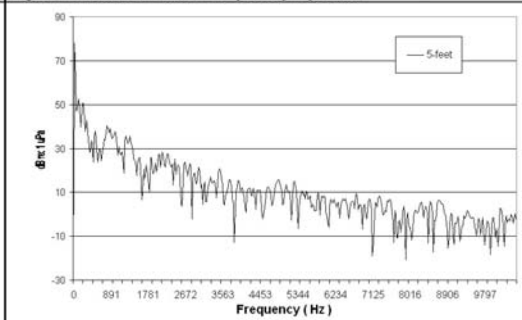


Figure c. Accumulation of Sound Energy

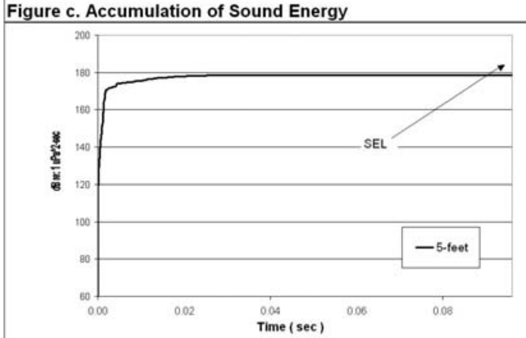


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
5-feet	207	194	179

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

Figure 24b

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

Figure a. Waveform

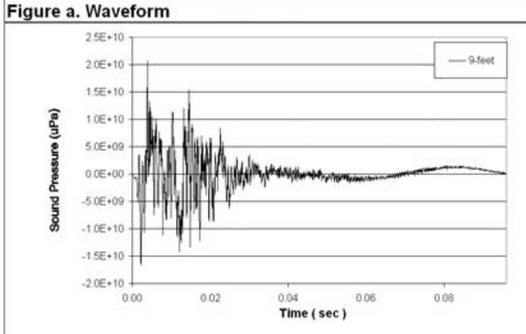


Figure b. Narrow Band Frequency Spectra

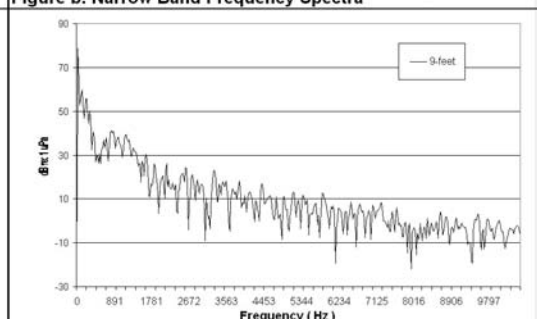


Figure c. Accumulation of Sound Energy

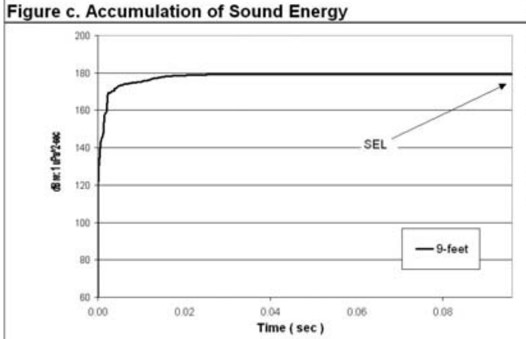


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

} feet from pile - 00:00:(	Peak	RMS90%*	SEL
9-feet	206	194	179

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

Figure 24: Waveform Analysis of Pile Number 5 Sound Pressure Levels with Bubbles Curtain Initial On, Midwater and Bottom.

PILE 5 – FINAL BUBBLES OFF

Figure 25a

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

Figure a. Waveform

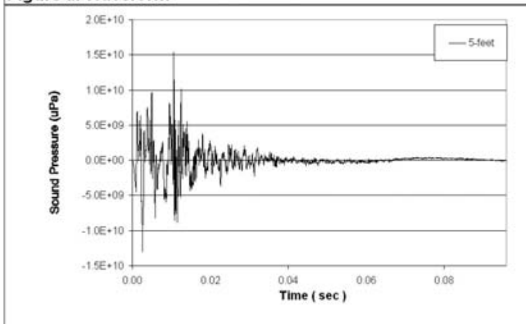


Figure b. Narrow Band Frequency Spectra

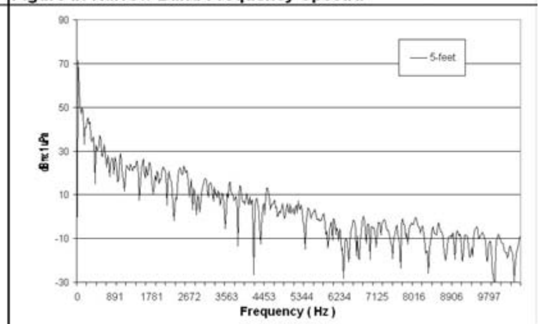


Figure c. Accumulation of Sound Energy

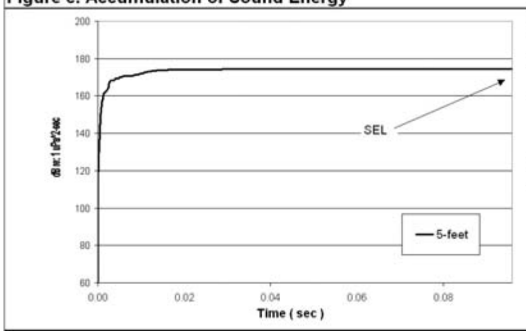


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
5-feet	204	190	174

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

Figure 25b

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

Figure a. Waveform

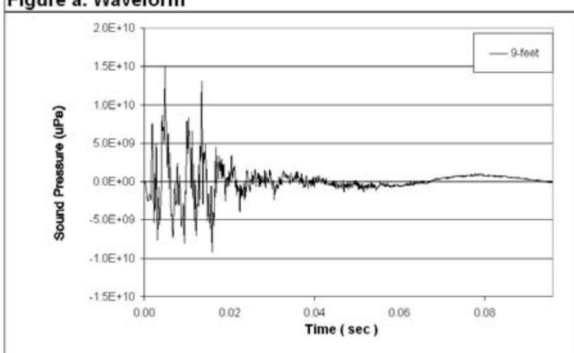


Figure b. Narrow Band Frequency Spectra

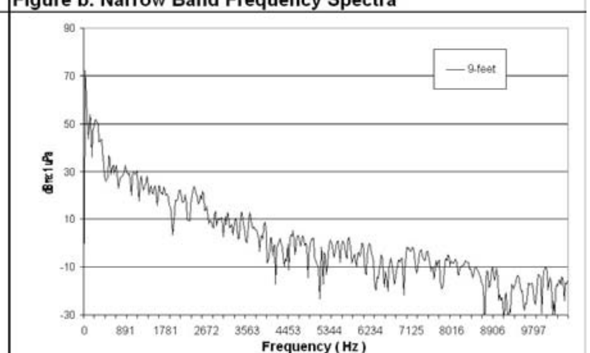


Figure c. Accumulation of Sound Energy

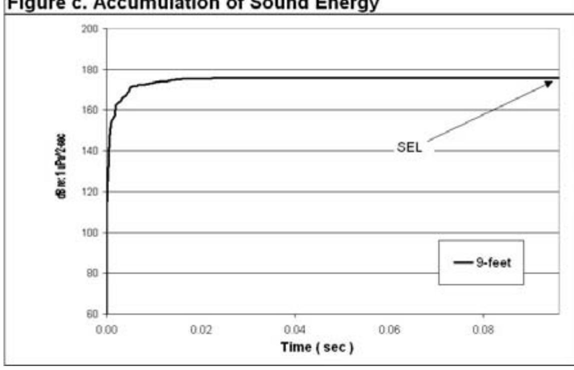


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
9-feet	203	191	176

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

Figure 25: Waveform Analysis of Pile Number 5 Sound Pressure Levels with Bubbles Curtain Final Off, Midwater and Bottom.

PILE 5 – FINAL BUBBLES ON

Figure 26a

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

Figure a. Waveform

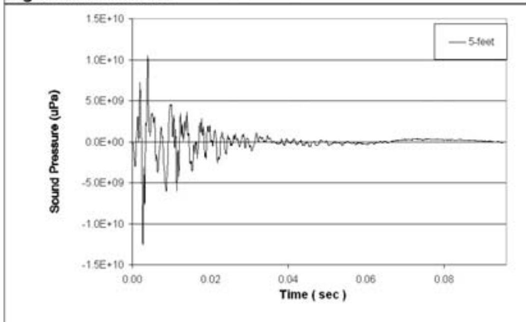


Figure b. Narrow Band Frequency Spectra

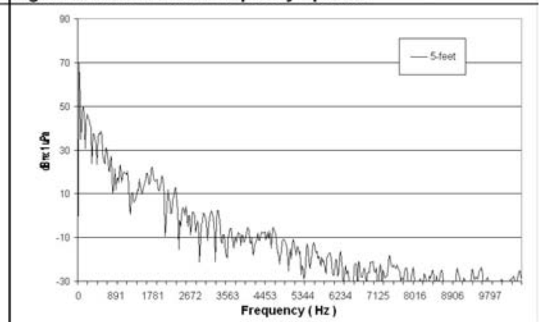


Figure c. Accumulation of Sound Energy

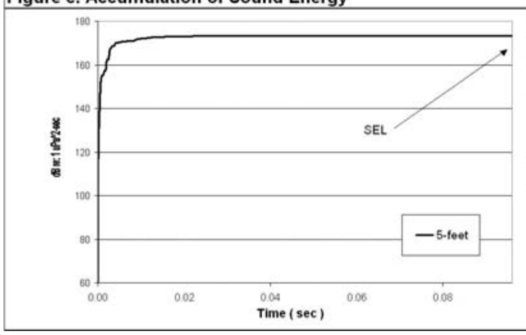


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
5-feet	202	190	173

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

Figure 26b

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

Figure a. Waveform

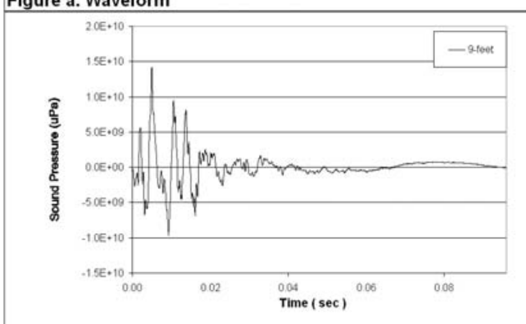


Figure b. Narrow Band Frequency Spectra

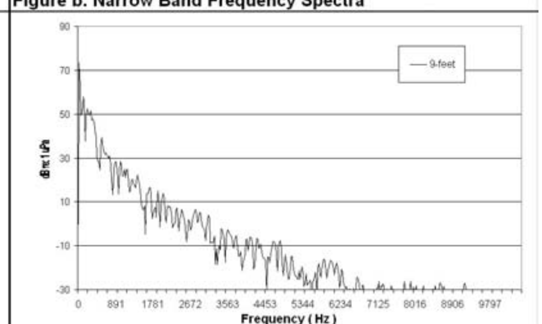


Figure c. Accumulation of Sound Energy

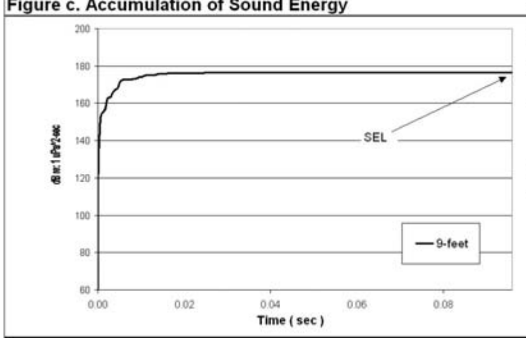


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33 feet from pile - 00:0	Peak	RMS90%*	SEL
9-feet	203	192	177

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

Figure 26: Waveform Analysis of Pile Number 5 Sound Pressure Levels with Bubbles Curtain Final On, Midwater and Bottom.