UNDERWATER SOUND LEVELS ASSOCIATED WITH RESTORATION OF THE FRIDAY HARBOR FERRY TERMINAL

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EXECUTIVE SUMMARY

This technical report describes the data collected at the Friday Harbor Ferry Terminal during the month of September 2004 when a bubble curtain was tested for the first time. Also included is data collected during the months of February and March 2005 at the Friday Harbor Ferry Terminal project. The data presented here correspond to the piles driven during September 17 through 22, 2004; between February 10^{th} through 12^{th}, 2005; February 23rd through 24th, 2005; and March 4^{th}, 2005. Three 24-inch diameter piles were monitored at dolphin #3 using three different hammer types (diesel, air, and hydraulic) (Figure 1). Five 24-inch piles were monitored to test the effectiveness of the bubble curtain at two wing walls in September 2004 using a diesel hammer only. Three 24-inch diameter piles were monitored at the slip bridge seat using a diesel hammer on two piles and a hydraulic hammer on the third. Two 30-inch diameter piles were monitored at the towers with a diesel hammer only. The bubble curtain was tested in different scenarios. First by turning the rings on in succession starting at the bottom ring and then turning all rings off. Then the bottom ring was first turned on full and then all the rings on and all rings off.

The analysis of the data indicate that using more than one bubble curtain ring at the bottom of the pile had no substantial advantage to reducing sound levels. The additional cost of deploying, providing air to, and manufacturing additional rings is not cost effective when compared to the benefit gained. The exception would be when a battered pile is being driven or there is a current present that does not allow full coverage of the pile with only one ring. Therefore, it is recommended that future bubble curtain systems of similar design only use one ring at the bottom of the pile when local flow does not disrupt coverage of the pile by injected air.

The average sound reduction for the bottom ring on full was 3 dB. The average sound reduction for all rings on full was 1 dB. However the maximum sound reduction was 16 dB for the bottom ring on full.

Table 1: Summary Table of Monitoring Results (ranges are for bottom and midwater sensors).

Pile #	Bubble Curtain Scenario	Average Peak (dB)	Average RMS (dB)	SEL (dB re: 1 μPa^2-sec)	Rise Time (msec)
1	All Off	199	193-184	179-180	4-26
	Bottom ½ Flow	189-192	170-174	167-170	2.3-5.7
	Bottom + Mid ½ Flow	197-201	181-184	172-176	2.1-7.0
	Bottom, Mid, + Top ½ Flow	194-197	177-181	170-174	3.3-7.0
	Bottom Full, Mid + Top ½ Flow	194-200	178-183	172-177	2.5-20
	Bottom + Mid Full, Top ½ Flow	195-201	179-184	174-176	2.4-21
	All Rings Full Flow	194-199	177-181	173-176	2.0-21
	All Rings Off	180-183	166-170	176-180	2.8-23
2	All Rings Off (Initial)	194-195	178-180	171-174	3.2-6.7
	Bottom Ring Full Flow	199-201	182-184	174-178	2.4-7.3
	All Rings Full Flow	198-203	181-185	174-178	3.1-8.7

Pile #	Bubble Curtain Scenario	Average Peak (dB)	Average RMS (dB)	SEL (dB re: 1 μPa^2-sec)	Rise Time (msec)
	All Rings Off (Final)	202-205	185-186	178-179	2.3-7.9
3	All Rings Off	197-199	182-184	174-176	1.2-3.0
	Bottom Ring Full Flow	200-203	182-186	173-179	1.0-7.0
	All Rings Full Flow	201-203	182-186	173-178	1.6-6.8
	All Rings Off	200-204	183-186	174-179	0.6-0.7
4	Bottom Ring On Full	208	184-190	176-184	1.2-8.4
	All Rings On Full	206-210	189-194	182-185	0.6
	All Rings Off	209-210	192-194	185	0.6
5	Bottom Ring On Full	206-214	190-196	182-188	1.0-4.4
	All Rings On Full	209-216	191-197	182-187	1.1-22
	All Rings Off	208-215	189-195	181-187	0.5-1.1
6	Bottom Ring On Full	193-196	178-181	167-174	38-28
	All Rings On Full	202-211	186-192	178-184	2.0-5.6
	All Rings Off	204-212	188-193	180-184	0.7-2.2
7	Bottom Ring On Full	203	189	180	2.2-5.9
	All Rings On Full	202-209	189-194	181-186	2.4-41.3
8	Bottom Ring On Full	207-210	190-193	181-184	6.5-23
	All Rings On Full	205-210	191-193	182-186	7.0-23
	All Rings Off	209-212	195-196	186-187	23-33

INTRODUCTION

This technical report presents results of underwater sound levels measured during the driving of 10 piles at the Friday Harbor ferry terminal during February 2005 and March 2005 at the Friday Harbor Ferry Terminal project (Contract number: C6737). The data presented here correspond to the piles driven during September 17 through 22, 2004; between February 10th through 12th, 2005; February 23rd through 24th, 2005; and March 4th, 2005. Five 24-inch piles were monitored to test the effectiveness of the bubble curtain at two wing walls in September 2004 using a diesel hammer only. Three 24-inch diameter piles were monitored at dolphin #3 using three different hammer types (diesel, air, and hydraulic) (Figure 1). Three 24-inch diameter piles were monitored at the slip bridge seat using a diesel hammer on two piles and a hydraulic hammer on the third. Two 30-inch diameter piles were monitored at the towers with a diesel hammer only. The bubble curtain was tested during the second testing phase in different scenarios. First by turning the rings on in succession starting at the bottom ring and then turning all rings off. Then the bottom ring was first turned on full and then all the rings on and all rings off.. The driving of 24- and 30-inch diameter steel piles was conducted as part of the restoration of the ferry terminal at Friday Harbor. Figure 1 shows the locations of monitored piles.

PROJECT DESCRIPTION

This contract provides for the implemention of a ferry terminal preservation project to ensure the safety and continued operation of ferry service to and from Friday Harbor. The project will repair and replace towers, the transfer span and apron, bridge seat, tie-up slip wingwalls and dolphins of the Friday Harbor Ferry Terminal on San Juan Island.

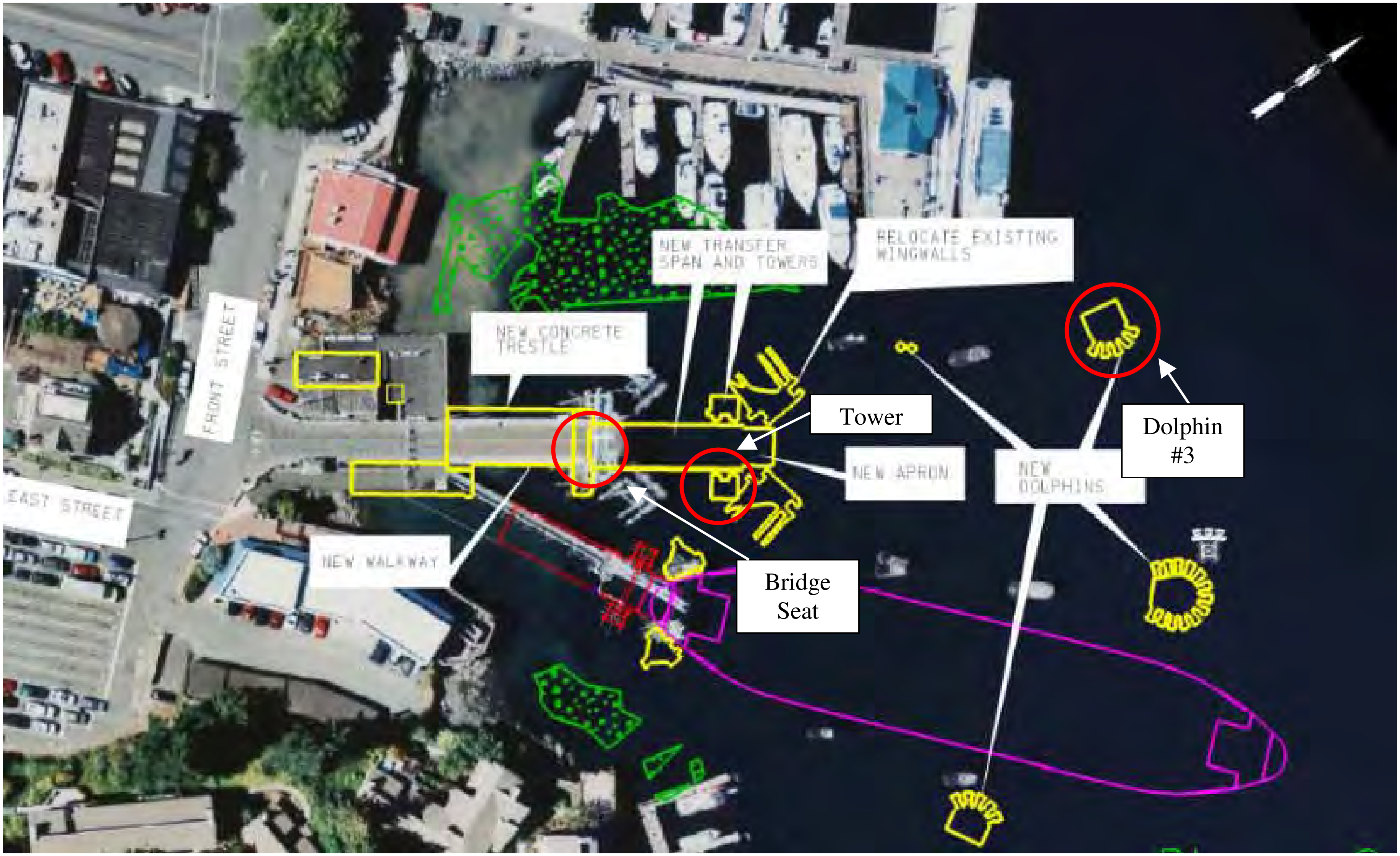


Figure 1: Location of Underwater Noise Monitoring at Friday Harbor. There were three 24-inch piles monitored at Dolphin #3, three 24-inch piles monitored at the Bridge Seat, and two 30-inch piles monitored at the Tower.

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 NOAA Fisheries 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 kPa and also converted to dB re: 1 μPa.

Rise time is another descriptor used in wave form analysis to describe the characteristics of underwater impulses. Rise time is the time in microseconds (ms) it takes the wave form 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). Hastings has abandoned her previous 180 dB_{peak} and 150 dB_{rms} thresholds (Hastings, 2002) and is now, along with Dr. Popper, proposing 194 dB SEL as the new barotrauma threshold for fish. SEL is often used as a metric for a single acoustic event and is often used as an indication of the energy dose. SEL is calculated by summing the cumulative pressure squared (p^2), integrating over time, and normalizing to one second. This metric accounts for both negative and positive pressures because p^2 is positive for both and thus both are treated equally in the cumulative sum of p^2 (Hastings and Popper, 2005). The units for SEL are dB re: 1 micropascal^2-sec.

METHODOLOGY

Underwater sound levels were measured using two Reson TC 4013 hydrophones. One hydrophone was positioned approximately one foot above the bottom and the other at a mid-water level. Both hydrophones were located at a distance of 30 feet from the pile and inshore of the pile being monitored. The measurement system includes a Brüel and Kjær Nexus type 2692 4-channel signal conditioner, which kept the high underwater sound levels within the dynamic range of the signal analyzer (Figure 2). The output of the Nexus signal conditioner was received by a Dactron Photon 4-channel signal spectrum analyzer that was attached to an Itronix GoBook II laptop computer. The waveform of the pile strikes along with the number of strikes, overpressure minimum and maximum, absolute peak values, and RMS sound levels, integrated over 90% of the duration of the pulse, were captured and stored on the laptop hard drive for subsequent signal analysis. The system and software calibration is checked annually against a NIST traceable standard. The operation of the hydrophone was checked in the field using a GRAS type 42AC high-level pistonphone with a hydrophone adaptor. The pistonphone signal was 146 dB re: 1 μPa. The pistonphone signal levels produced by the pistonphone and measured by the measurement system were within 1 dB and the operation of the system was judged to be acceptable over the study period. A photograph of the system and its components are shown in Figure 2.

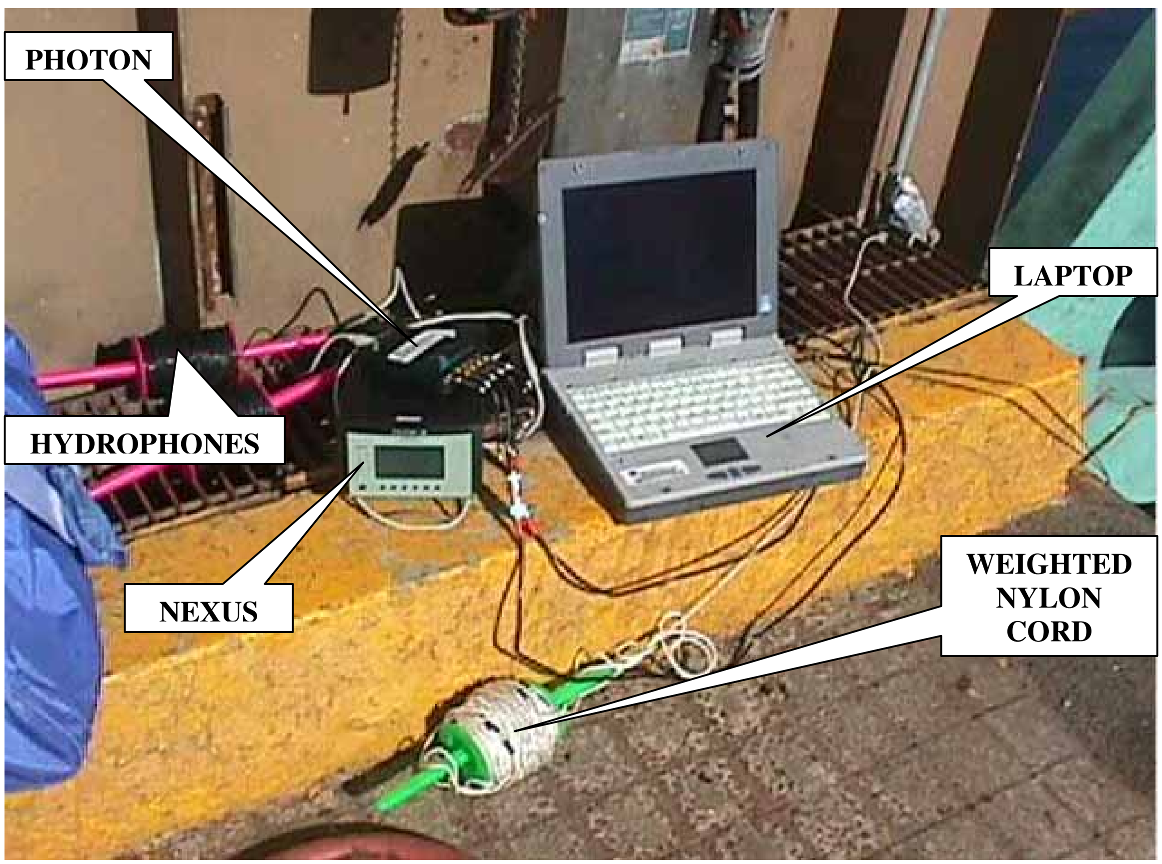


Figure 2: Underwater Sound Level Measurement Equipment

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.

All piles were first driven with a vibratory hammer then proofed with an impact hammer. The diesel pile driver was an ICE Model 120S with an energy rating of 60,000 ft-lbs. The air hammer used was a Vulcan 200C with an energy rating of 50,000 ft-lbs. The hydraulic pile driver was an ICE 220 with an energy rating of 88,000 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 silty sand down to a depth of approximately 30 feet where a hard clay lens exists. At the location where the bridge seat piles were driven a large rock ledge was found approximately 35 feet below the mud line.

Piles driven were open-ended hollow steel piles, 24- and 30-inches in diameter with a ½ inch wall thickness. Piles were proofed to achieve load bearing capacity. A schedule of sampling conditions for each pile is provided in the Table 1 below. All measurements were made 33 feet from the pile and at two depths, one foot from the bottom and mid water depth. All dB reported are referenced to one micropascal.

Table 2: Sampling Conditions Schedule for Each Pile Monitored.

Location	Pile #	Time	Water Depth (ft)	Air Temperature (°F)	Wind Speed (Kts)	Substrate	Pile Diameter (inches)
Dolphin #3	1	1520h	42	53	0.8	Sandy silt/clay	24
	2	1612h	44	52	1.5	Sandy silt/clay	24
	3	1036h	47	49	0.0	Sandy silt/clay	24
Bridge Seat	4	1525h	33	65	0.0	Sandy silt/rock	24
	5	0741h	33	34	0.8	Sandy silt/rock	24
	6	1323h	33	70	0.1	Sandy silt/rock	24
Tower	7	nr	40	nr	nr	Sandy silt/clay	30
	8	nr	34	nr	nr	Sandy silt/clay	30

nr – not recorded

Each measured pile site is described below:

Dolphin #3-

1. Located in the center of the template at Dolphin #3 approximately 150 feet from the shoreline in 42 feet of water.

2. Located on the Northeast side of the template at Dolphin #3 approximately 160 feet from the shoreline and in 44 feet of water.

3. Located on the North side of the template at Dolphin #3 approximately 150 feet from the shoreline and in 47 feet of water.

Bridge Seat-

4. Located on the Northwest side of the template at the bridge seat approximately 100 feet from the shoreline in 33 feet of water.

5. Located on the Northwest side of the template at the bridge seat approximately 100 feet from the shoreline in 33 feet of water.

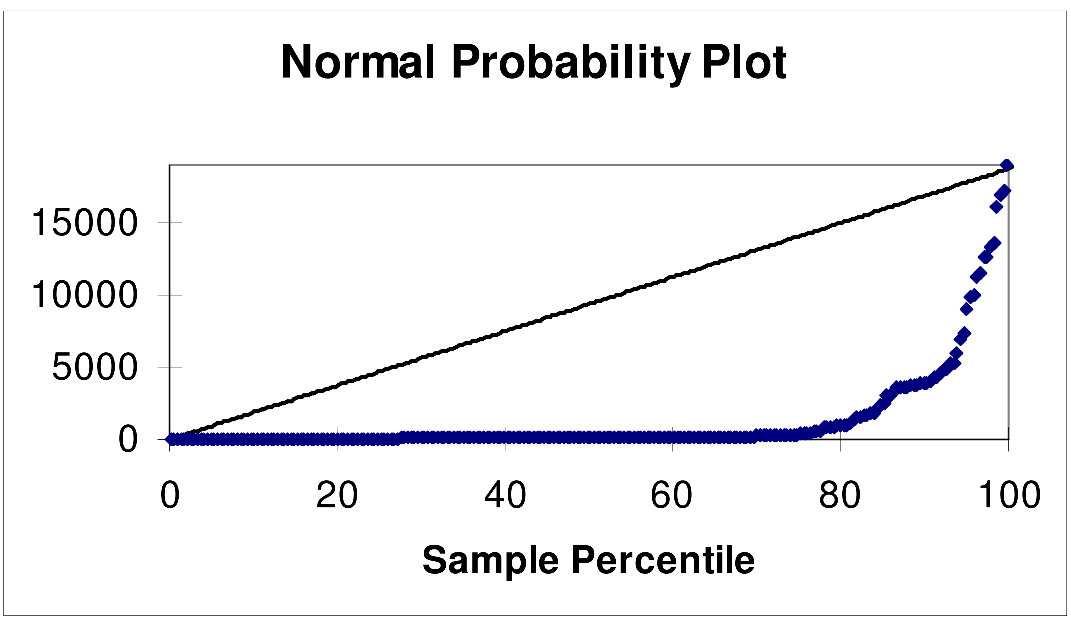
6. Located on the Northwest side of the template at the bridge seat approximately 100 feet from the shoreline in 33 feet of water.

Tower-

7. Located on the West side of the template at the tower approximately 75 feet from the shoreline in 34 feet of water.

8. Located on the East side of the template at the tower approximately 75 feet from the shoreline in 34 feet of water.

The location of the hydrophones is determined by allowing a clear line of sight between the pile and the hydrophones with no other structures nearby. The distance from the pile to the hydrophone location was measured using a Bushnell Yardage Pro rangefinder. The hydrophones were 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. The cord and cables are supported at the surface by plastic floats until they were attached to the equipment.



Statistical comparisons were performed comparing the initial bubbles off peak values with the peak values of the various bubble ring on conditions to determine whether additional rings and additional air flow make a difference in sound reduction. The data were first tested for normality and homogeneity of variances using normal probability plots such as the one above and the variance ratio test for equal variances (Zar, 1984). The example above is typical of all the normal probability plots for all data sets. The diagonal line is normal and the diamond symbols represent our data which is skewed from normality. In all cases due to the high degree of variability within each category but also between categories the data were found to be non-normal and have non-equal variances. Therefore, the Mann-Whitney U test was used for the comparisons (Zar, 1974).

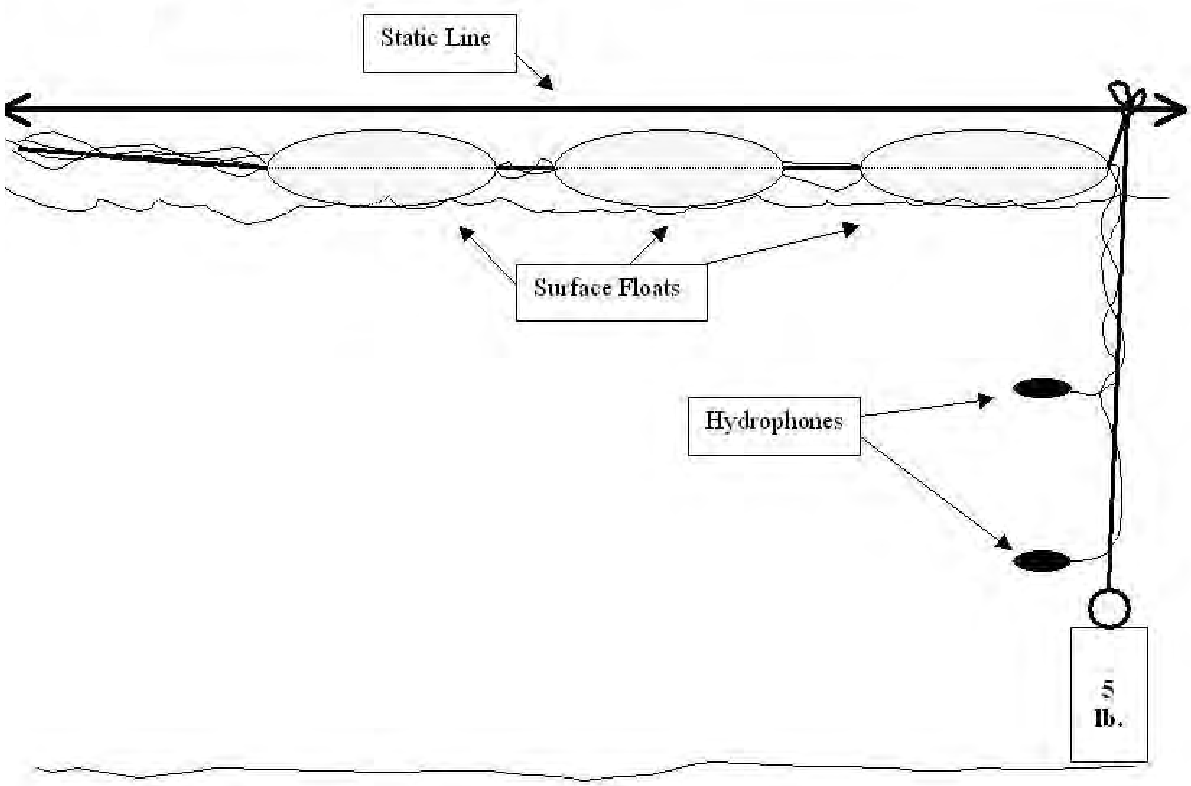


Figure 3: Hydrophone Weight and Float System

RESULTS

UNDERWATER SOUND LEVELS

Initial Bubble Curtain Testing

September 8th through 22nd, 2004 eight 24-inch steel piles were monitored for underwater sound levels to evaluate the effectiveness of a bubble curtain. The piles were driven with a diesel hammer at two wingwall structures. No dynamic pile driving measurements were made on any of these piles.

The first few piles indicated no change in sound levels between the bubble curtain turned on or turned off. It was determined that the contractor had not deployed the bubble rings all the way to the bottom of the pile and sound was leaking through the bottom of the bubble curtain into the water column. WSDOT and the contractor added 160-pounds of weights to the bubble curtain assembly to seat the curtain on the bottom and prevent unattenuated sound from escaping beneath the curtain. Seating the bottom ring on the bottom and adding weights to keep it in position dramatically improved the bubble curtain's effectiveness.

The bubble curtain was then modified by removing the bottom weights and adding a canvas "curtain" to form a kind of gasket on the bottom of the bubble curtain to conform to the bottom contours. Monitoring of these piles indicates that the bubble curtain was reducing the absolute peak overpressure by 12 dB (82% reduction), and the average of the first hundred peak readings by 9 dB (± 2 dB).

While the level of noise reduction did not meet the 180 dB_{peak} (1000 Pa) target threshold identified during consultation or the 20 dB target reduction of absolute peak pressure, WSF is encouraged that the bubble curtain is effective in reducing the absolute mean peak overpressure by 82%.

Additional Bubble Curtain Testing

February 10th through March 4th, 2005 monitoring provided opportunities to further test the effectiveness of the bubble curtain along with different hammer types. The first pile tested was driven with a diesel hammer described in the previous section and followed the following bubble curtain air flow scenarios for at least 10 strikes each.

- All Rings Off -
- Bottom Ring ½ Flow 55 psi ~ 100 cfm
- Bottom Ring and Mid Ring ½ Flow 55 psi ~ 130 cfm
- Bottom, Mid, and Top Ring ½ Flow 35 psi ~ 100 cfm
- Bottom Ring Full Flow, Mid and Top Ring ½ Flow 85 psi ~ 230 cfm
- Bottom and Mid Ring Full Flow, Top Ring ½ Flow 60 psi ~ 200 cfm
- All Rings Full Flow 70 psi ~ 225 cfm
- All Rings Off -

Pile 1 – Diesel Hammer

Figure 6 is a diagrammatic drawing of the hydrophone monitoring location in relation to the shoreline and other structures in the water for piles 1, 2 and 3. The drawing is not to scale.

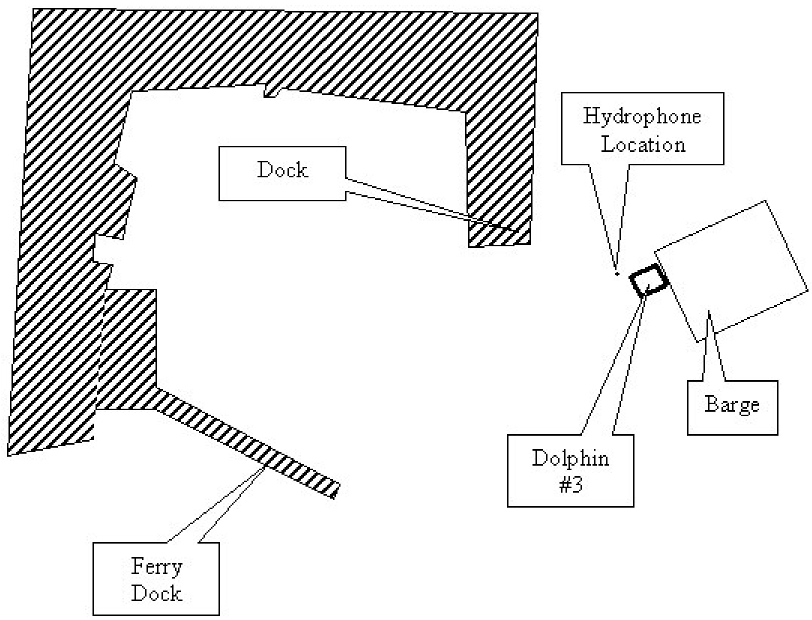


Figure 4: Diagram of Monitoring Location in Relation to the Shoreline and Other Nearby Structures.

As can be seen in Figures 4 and 5 the pile strikes without the bubble curtain on and bubble curtain on full indicates a large degree of variability between pile strikes. Variability of this nature is only presented here for Pile 1 but is representative of what was observed for all piles and hammer types. This variability could be due to adjustments of the hammer energy or differences in the angle of the hammer striking the pile. The dynamic pile driving measurements made on this pile by Miner Dynamic Engineering will be helpful in understanding this variability. However, comparisons of acoustical data with dynamic pile measurements are beyond the scope of this report.

Peak values for sound levels at the bottom with all rings off (Figure 4) ranged from 183 dB_{peak} to 206 dB_{peak} 10 meters from the pile. The midwater peaks ranged from 182 dB_{peak} to 204 dB_{peak} 10 meters from the pile. Figure 4 gives some indication of the variability between pile strikes.

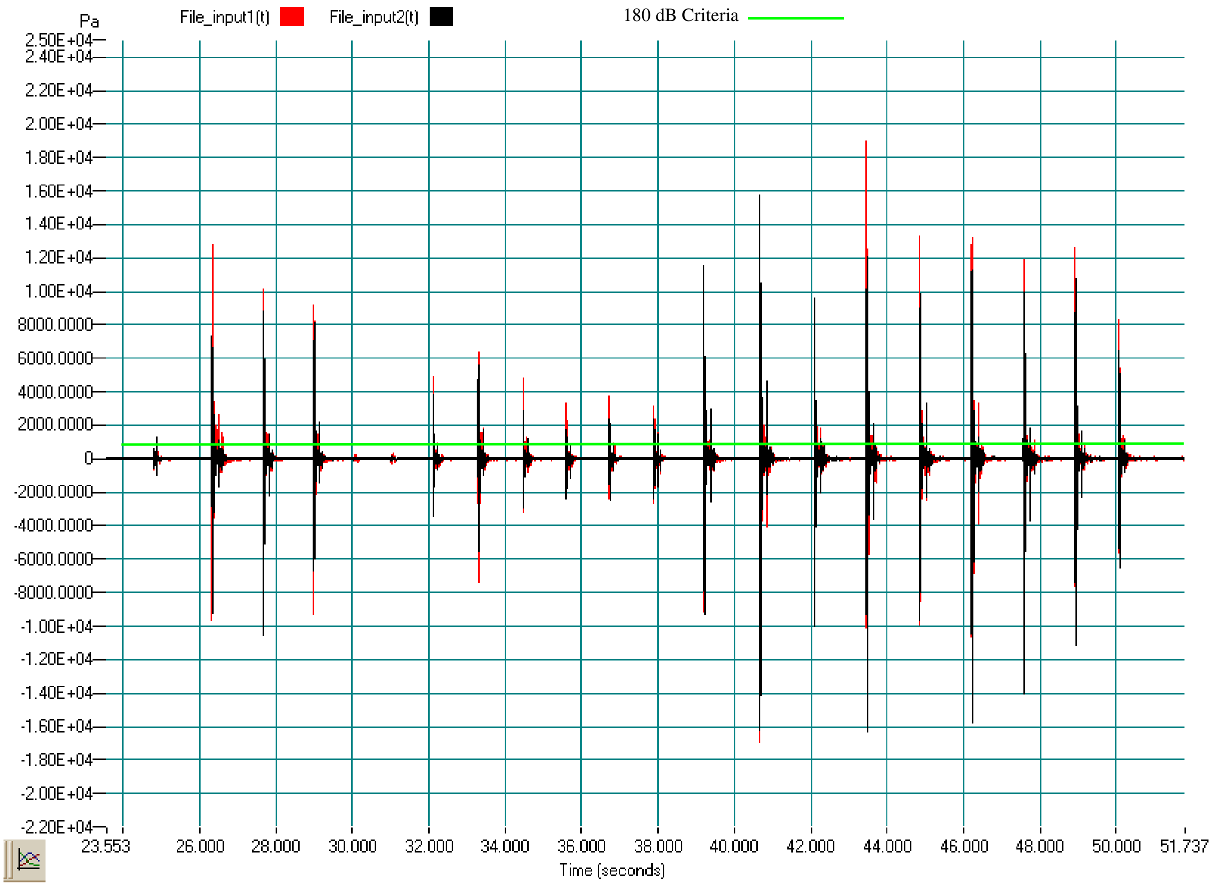


Figure 5: Pile 1 Initial Pile Strikes with Bubble Curtain Off. (File_input1(t) = bottom; File_input2(t) = midwater)

Peak values for sound levels at the bottom with all rings on (Figure 5) ranged from 180 dB_{peak} to 204 dB_{peak} ten meters from the pile. The midwater peaks ranged from 180 dB_{peak} to 206 dB_{peak} ten meters from the pile. The peak values for the bottom and midwater recordings did not occur at the same strike. Figure 5 indicates the somewhat lessened variability with the bubble curtain in operation.

Averaging the strikes for Pile 1 with bubble curtain initially off and then air flow on full for the midwater recordings gave a sound reduction of 5 dB. The average for the final bubble curtain off was actually 11 dB lower than with the bubble curtain on full. Why the average peak value with the bubble curtain on full was higher than the average peak value with the bubble curtain on is unclear. The same variability between pile strikes was seen from pile to pile and with each different hammer type that was used.

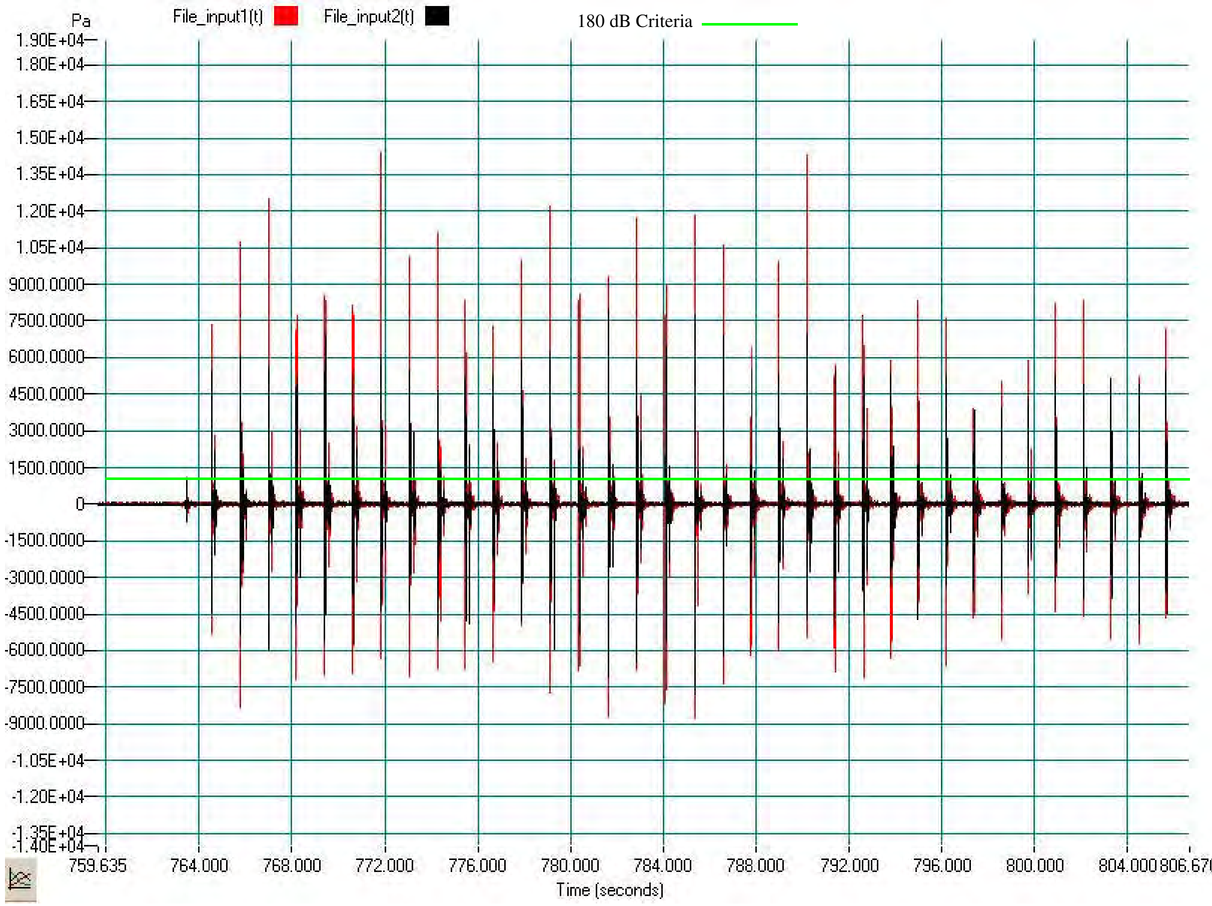


Figure 6: Pile 1 Initial Pile Strikes with Bubble Curtain On Full. (File_input1(t) = bottom; File_input2(t) = midwater)

Table 3 summarizes the acoustical data collected for Pile 1 at Dolphin #3. In general, the peak values were higher at the bottom hydrophone and indicated that the sound received by the bottom hydrophone was only slightly attenuated by use of the bubble curtain. The absolute peak (dB_{peak}), average peak (dB), average Root Mean Square (dB_{rms}), sample size, sound reduction, Sound Exposure Level (dB_{SEL}), and rise time, are reported corresponding to changes in flow rates to the bubble curtain rings.

The absolute peak values ranged from 194 dB_{peak} to 205 dB_{peak} at mid water and 196 dB_{peak} to 206 dB_{peak} at the bottom. The greatest average sound reduction was seen with the bottom ring at ½ flow (100 cfm) for both the midwater hydrophone (10 dB) and the bottom hydrophone (7 dB). The sound reductions did not improve with increasing air flow. However, because these tests were not controlled we cannot be certain that all conditions with the exception of the bubble curtain, were the same for each sequence of impacts. It will be necessary to analyze the dynamic pile driving data along with the acoustical data to provide a better context for assessment of test conditions. It is likely that other unmeasured variables are responsible for some of the observations made.

Table 3: Summary of Underwater Sound Level Impacts and Mitigation for Pile 1 at Dolphin #3.

Pile #	Date	Hammer Type	Hydrophone Depth	Bubble Curtain Rings On	Absolute Peak (dB)	Average Peak (dB ± s.d.)	n	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	% Strikes Exceeding 180 dB peak
1	2/10/05	Diesel	22 feet	All Off Initial	205[1]	199 ± 195	21	-	183 ± 180	180	26.4	100
				Bottom ½ Flow	194	189 ± 183	10	10	170 ± 166	167	5.7	100
				Bottom + Mid ½ Flow	199[1]	197 ± 178	11	2	181 ± 160	172	7.0	100
				Bottom, Mid, + Top ½ Flow	197	194 ± 183	23	5	177 ± 166	170	7.0	100
				Bottom Full, Mid + Top ½ Flow	197[1]	194 ± 183	23	5	178 ± 166	172	20.2	100
				Bottom + Mid Full, Top ½ Flow	198	195 ± 184	20	4	179 ± 170	174	20.7	100
				All Rings Full Flow	199[1]	194 ± 182	177	5	177 ± 172	173	20.5	100
				All Rings Off Final	201[1]	183 ± 188	41	-	166 ± 172	176	22.6	100
			42 feet	All Off Initial	205	199 ± 195	21	-	184 ± 180	179	4.0	100
				Bottom ½ Flow	196	192 ± 186	10	7	174 ± 166	170	2.3	100
				Bottom + Mid ½ Flow	206	201 ± 189	11	0	184 ± 166	176	2.1	100
				Bottom, Mid, + Top ½ Flow	200[1]	197 ± 187	23	2	181 ± 170	174	3.3	100
				Bottom Full, Mid + Top ½ Flow	204	200 ± 189	23	0	183 ± 172	177	2.5	100
				Bottom + Mid Full, Top ½ Flow	204[1]	201 ± 192	20	0	184 ± 174	176	2.4	95
				All Rings Full Flow	205	199 ± 189	177	0	181 ± 174	176	2.0	100
				All Rings Off Final	205	180 ± 191	41	-	170 ± 176	180	2.8	100

[1] – Absolute peak value is peak underpressure for this category.

Figure 7 shows the average peak underwater sound pressure levels (± one standard deviation). Midwater received peak level statistical comparisons made to the initial bubbles off condition indicated that only the bottom ring at ½ flow and the all rings on full conditions were significantly less (Figure 7). When compared to the final bubbles off condition all were significantly greater except the bottom and mid rings at half flow.

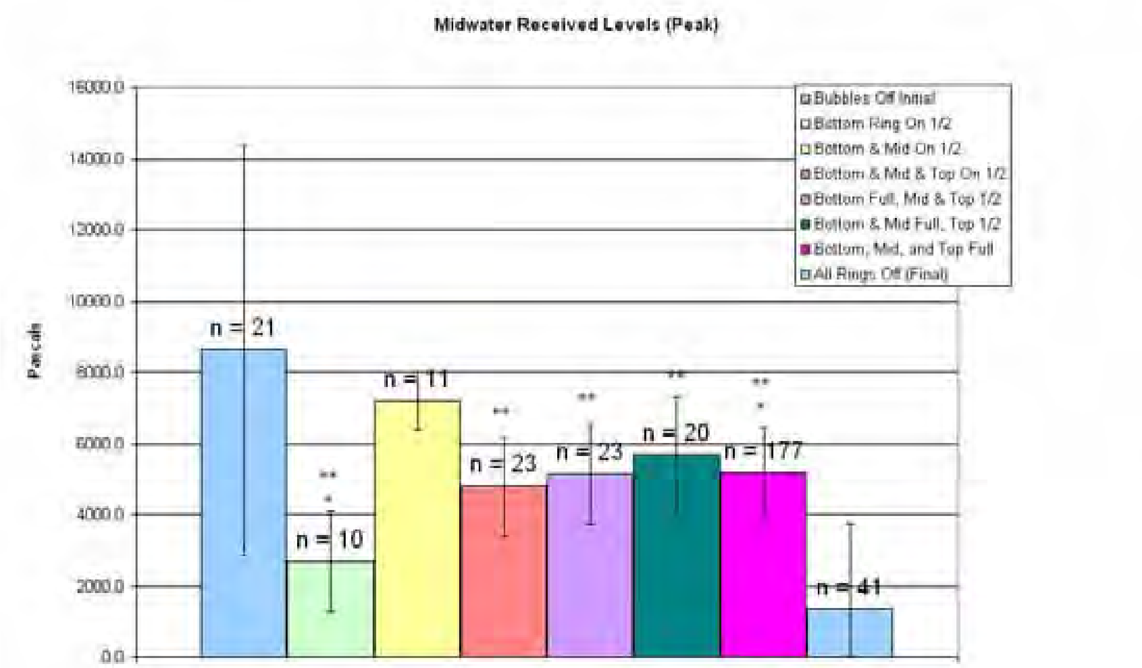


Figure 7: Pile 1, midwater average peak received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05).

Bottom received peak level comparisons (Figure 8) indicated similar associations as the midwater peak levels. However, when the comparisons were made to the initial bubbles off condition only the bottom ring at ½ flow was significantly less. When compared to the final bubbles off condition the bottom ring at ½ flow, bottom and mid rings at ½ flow, bottom and mid rings on full and top ring ½ flow, and all rings at ½ flow were significantly greater.

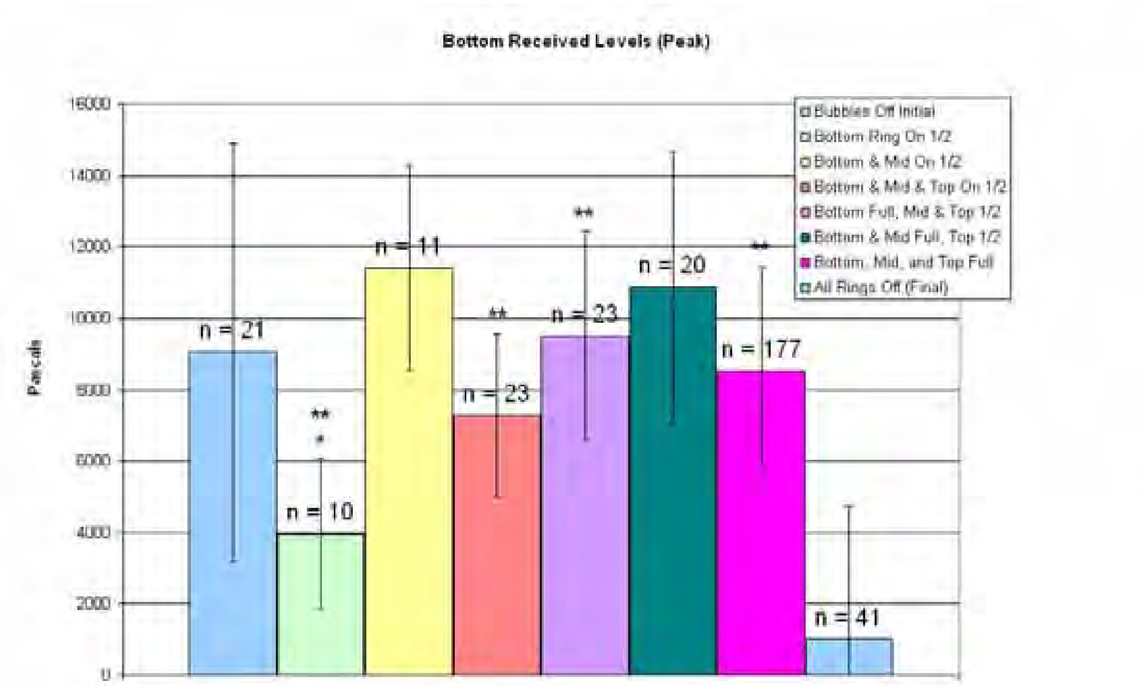


Figure 8: Pile 1, bottom average peak received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05).

RMS values are less variable than the peak values and excluding the bottom ring at ½ only indicate a slight trend towards a lower RMS value as more rings are turned on and air flow increases (Figure 9). The lowest RMS values occurred when the bottom bubble curtain ring was at half flow. The same pattern can be seen for SEL as well

Figure 9 shows the average RMS values (± one standard deviation). Midwater received RMS level statistical comparisons made to the initial bubbles off condition indicated that only the bottom ring at ½ flow was significantly less. When compared to the final bubbles off condition, none were significant.

Bottom received RMS level statistical comparisons indicated that only the bottom ring at ½ flow was significantly less than the initial bubbles of condition (Figure 10). When compared to the final bubbles off condition, all but the bottom and mid ring at ½ flow and the bottom and mid rings at full and the top at ½ flow were significantly greater.

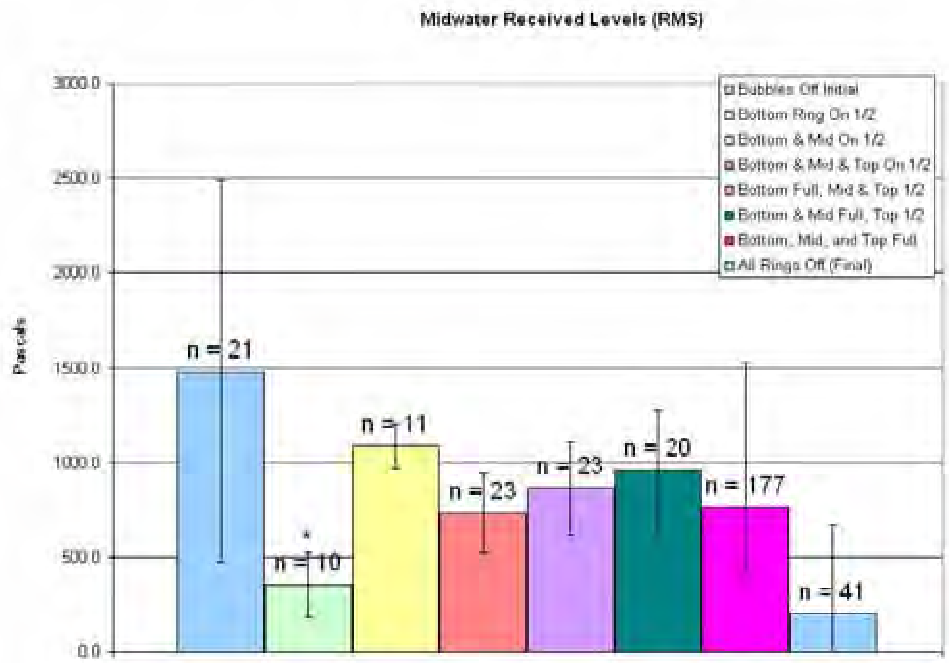


Figure 9: Pile 1, midwater average RMS received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05).

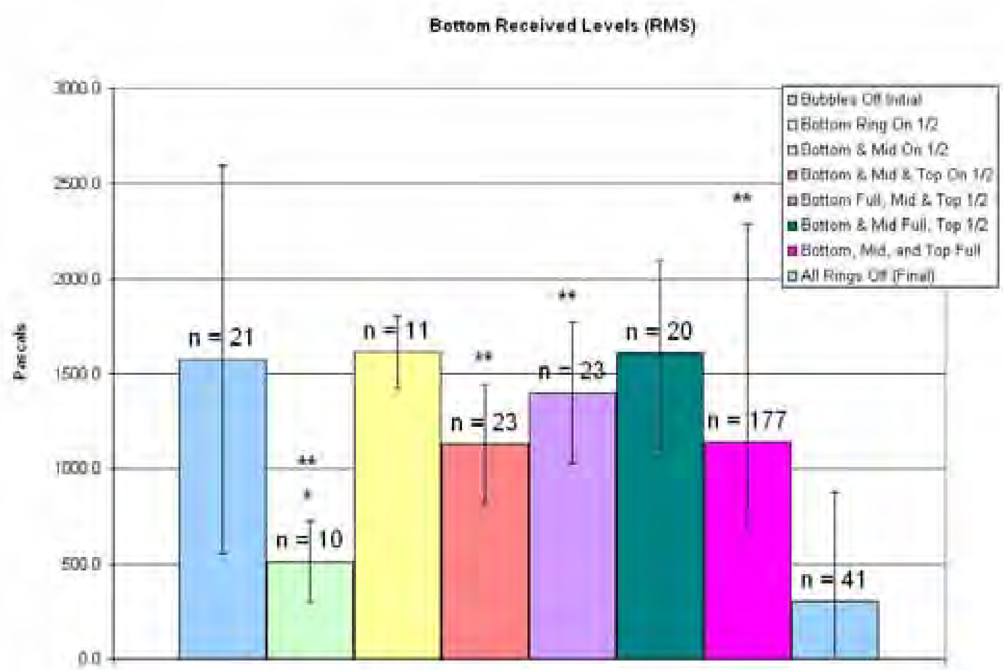


Figure 10: Pile 1, bottom average RMS received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05).

Figures 11 and 12 below show the acoustical frequency content of the absolute peak pile strike for each bubble ring air flow condition. Figure 11a compares the differences between the acoustical frequency content with all rings off and with bottom, mid, and top rings sequentially at ½ air flow rate. As can be seen in the figure, the upper frequencies are reduced with the bubble curtain rings at ½ air flow. This indicates that the bubble curtain was effective in reducing the overall noise levels although not as much as during the initial bubble curtain testing phase. Figure 11b compares the bubble curtain off condition to the averaged spectrum for all rings at ½ flow rate again indicating that the bubble curtain was effective in reducing the overall noise levels.

Figure12a compares the bubble curtain off condition with the condition of all the bubble curtain rings at full air flow. As the figure indicates, there is not a substantial change in the overall noise levels when compared to the bubble curtain at ½ air flow rate (Figure 11b). This indicates that the bubble curtain did not perform better with increased air flow. Both figures show that the dominant energy in each pile strike is between about 50 and 600 Hz. This held true for all piles monitored.

Figure 12b compares the bubble curtain condition with the averaged spectra for peak strikes at ½ air flow rate between DC and 2 kHz (the range of fish hearing). As the figure indicates, there is some reduction at frequencies below about 1 kHz compared to the initial bubbles off condition.

Figure 11: Pile 1: a. Frequency Spectral Analysis Comparing All Rings Off with Various Rings at ½ Air Flow. b. Frequency Spectral Analysis Comparing All Rings Off with the Average of All Spectra with Rings at ½ Air Flow.

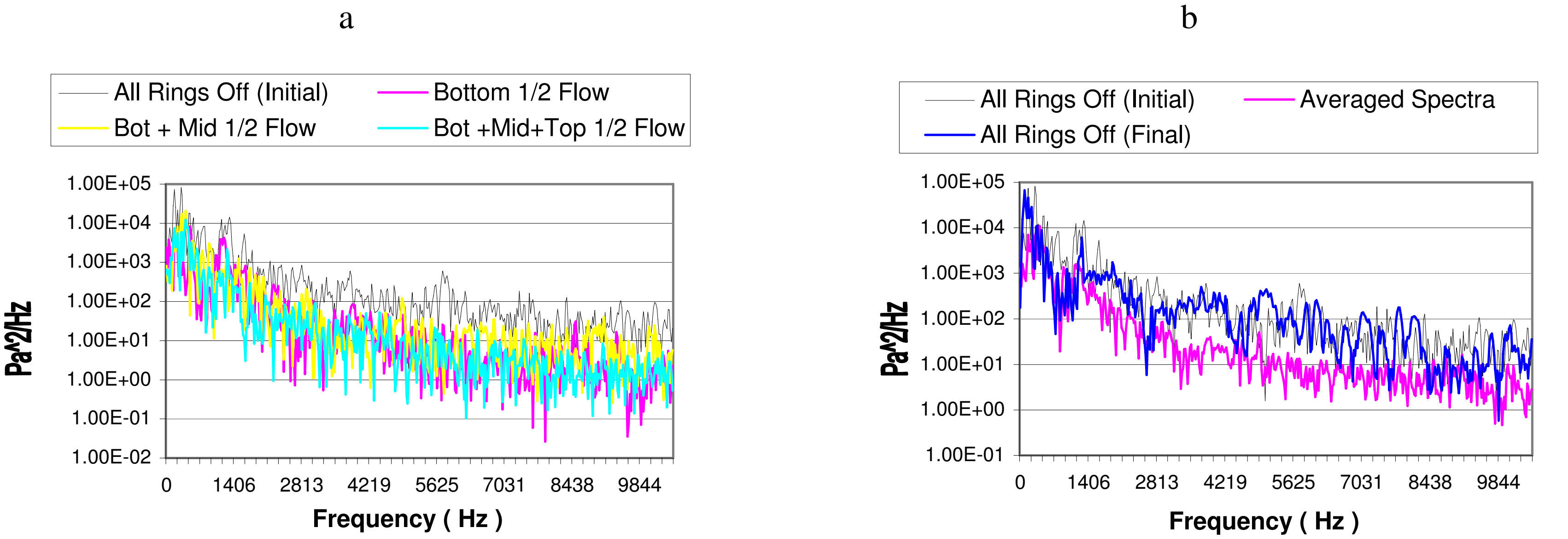
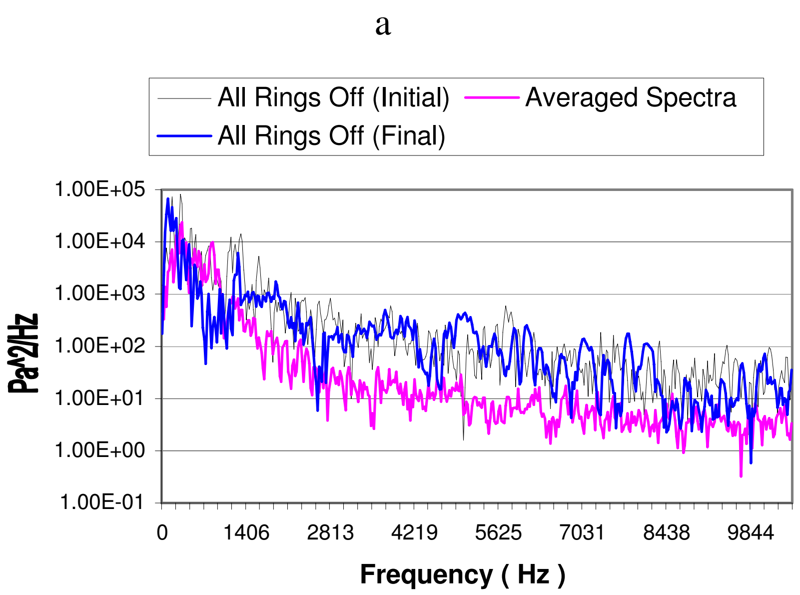
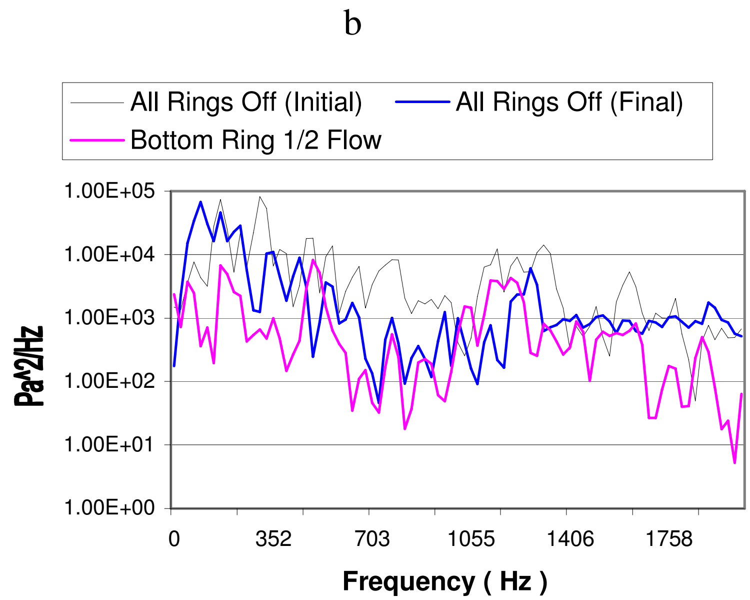


Figure 12: Pile 1: a. Frequency Spectral Analysis Comparing All Rings Off with All Rings at Full Air Flow. b. Frequency Spectral Analysis between DC and 2 kHz Comparing All Rings Off with ½ Flow for All Rings.





Pile 2 – Air Hammer

Table 4 summarizes the acoustical data collected for the Pile 2 at Dolphin #3. The peak values were generally higher at the bottom hydrophone. The sound received by the bottom hydrophone was only slightly attenuated by use of the bubble curtain. A modified bubble ring air flow pattern was used for this pile and all subsequent piles monitored. It was decided to use this modified pattern because no substantial change was observed in sound levels by turning on individual rings in succession. The pattern is as follows:

- All Rings Off
- Bottom Ring Full Flow 85 psi ~ 230 cfm
- All Rings Full Flow 70 psi ~ 225 cfm
- All Rings Off

The absolute peak values ranged from 197 dB_{peak} to 206 dB_{peak} at midwater and 198 dB_{peak} to 209 dB_{peak} at the bottom. There is no apparent effect of the bubble curtain on the average peak values when compared to the initial bubbles-off condition. The average peak levels were actually four to eight decibels higher with the bubble curtain on at the midwater hydrophone and six to ten decibels higher at the bottom hydrophone. Because these tests were not controlled we cannot be certain that all conditions, with the exception of the bubble curtain, were the same for each sequence of impacts. It will be necessary to analyze the dynamic pile driving data along with the acoustical data to provide a better context for assessment of test conditions. It is likely that other unmeasured variables are responsible for some of the observations made.

Table 4: Summary of Underwater Sound Level Impacts and Mitigation for Pile 2 at Dolphin #3.

Pile #	Date	Hammer Type	Hydrophone Depth	Bubble Curtain Rings On	Absolute Peak (dB)	Average Peak (dB ± s.d.)	n	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	% Strikes Exceeding 180 dBpeak
2	2/11/05	Air	24 feet	All Rings Off (Initial)	197	194 ± 186	8	-	178 ± 170	171	6.7	100
				Bottom Ring Full Flow	202	199 ± 188	138	0	182 ± 170	174	7.3	100
				All Rings Full Flow	202[1]	198 ± 183	233	0	181 ± 166	174	8.7	100
				All Rings Off (Final)	206[1]	202 ± 188	98	-	185 ± 170	178	2.3	100
			44 feet	All Rings Off (Initial)	198	195 ± 185	8	-	180 ± 170	174	3.2	100
				Bottom Ring Full Flow	207[1]	201 ± 191	138	0	184 ± 172	178	2.4	100
				All Rings Full Flow	207	203 ± 190	233	0	185 ± 170	178	3.1	100
				All Rings Off (Final)	209	205 ± 192	98	-	186 ± 172	179	2.9	100

[1] – Absolute peak value is peak underpressure for this category.

Figure 13 shows the average peak underwater sound pressure levels for Pile 2 (± one standard deviation). Midwater received peak level statistical comparisons made to the initial bubbles off condition indicated that none were significant (Figure 13). When compared to the final bubbles off condition all were significantly less indicating little difference between the bottom ring on only and all rings on.

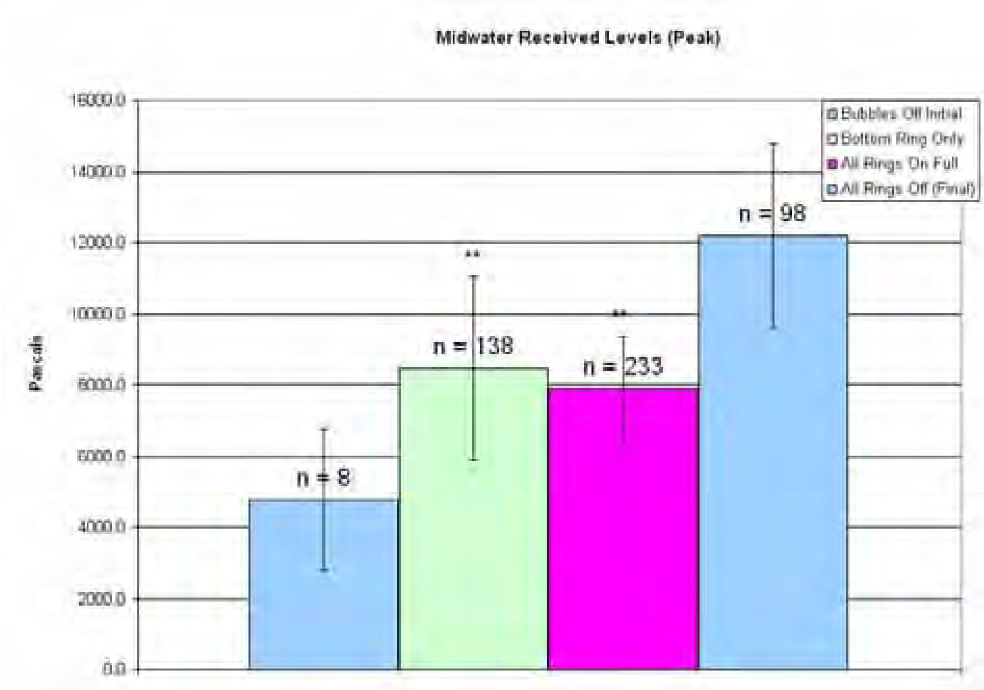


Figure 13: Pile 2, midwater average peak received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

Bottom received peak level comparisons (Figure 14) indicated progressively increasing peak values with none significant.

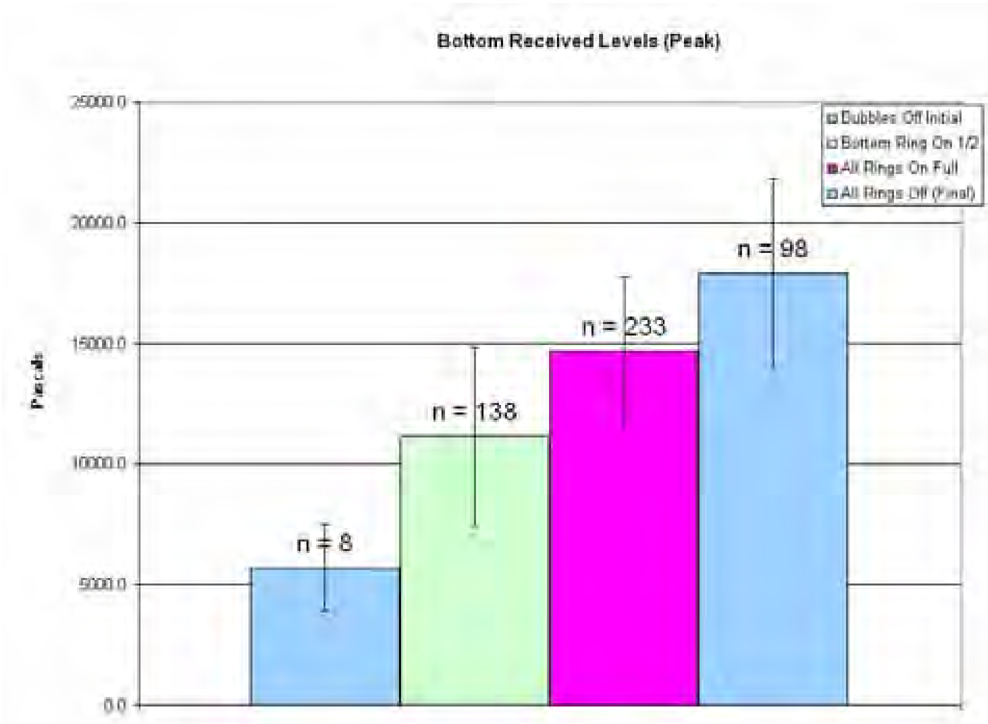


Figure 14: Pile 2, bottom average peak received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

RMS values are less variable than the peak values and when compared statistically with the initial bubbles off condition none were significant. Figure 15 shows the average midwater RMS values (± one standard deviation). Midwater received RMS level statistical comparisons made to the initial bubbles off condition indicated that none were significant. However, when compared to the final bubbles off condition both bottom ring only and all rings on were significantly less.

Bottom received RMS level statistical comparisons indicated that none were significantly different from the initial bubbles off condition (Figure 16). Both bottom ring only and all rings on were significantly less than the final bubbles of condition.

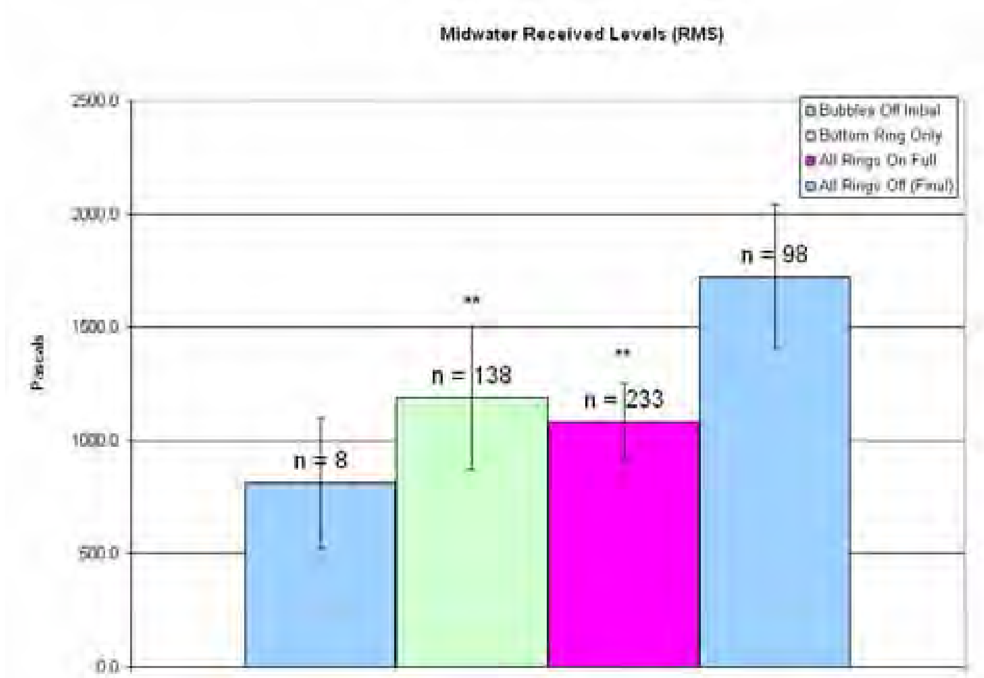


Figure 15: Pile 2, midwater average RMS received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

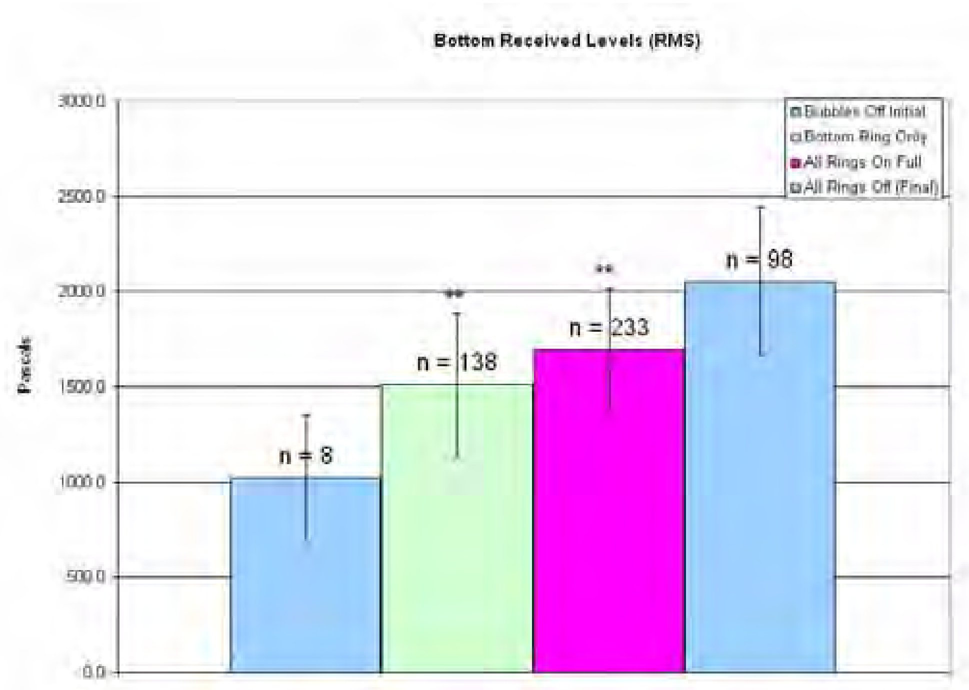


Figure 16: Pile 2, bottom average RMS received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

Pile 3 – Hydraulic Hammer

Table 5 summarizes the acoustical data collected for Pile 3 at Dolphin #3. The peak values were generally higher at the bottom hydrophone. The sound received by the bottom hydrophone was only slightly attenuated by use of the bubble curtain.

The absolute peak values ranged from 201 dB_{peak} to 204 dB_{peak} at mid water and 203 dB_{peak} to 207 dB_{peak} at the bottom. There is no apparent effect of the bubble curtain on the peak average values when compared to the initial bubbles-off condition. The peak levels were actually one to three decibels higher with the bubble curtains on at the midwater hydrophone and three to four decibels higher at the bottom hydrophone. Because these tests were not controlled we cannot be certain that all conditions, with the exception of the bubble curtain, were the same for each sequence of impacts. It will be necessary to analyze the dynamic pile driving data along with the acoustical data to provide a better context for assessment of test conditions. It is likely that other unmeasured variables are responsible for some of the observations recorded.

Table 5: Summary of Underwater Sound Level Impacts and Mitigation for Pile 3 at Dolphin #3.

Pile #	Date	Hammer Type	Hydrophone Depth	Bubble Curtain Rings On	Absolute Peak (dB)	Average Peak (dB ± s.d.)	n	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	% Strikes Exceeding 180 dBpeak
3	2/12/05	Hydraulic	25 feet	All Rings Off	201	197 ± 186	24	-	182 ± 172	174	1.2	100
				Bottom Ring Full Flow	204	200 ± 188	61	0	182 ± 166	173	6.9	100
				All Rings Full Flow	204	201 ± 182	60	0	182 ± 166	173	6.8	100
				All Rings Off	202[1]	200 ± 182	58	-	183 ± 166	174	0.6	100
			47 Feet	All Rings Off	203	199 ± 187	24	-	184 ± 170	176	3.0	100
				Bottom Ring Full Flow	206[1]	203 ± 189	61	0	186 ± 170	179	1.0	100
				All Rings Full Flow	207	203 ± 188	60	0	186 ± 170	178	1.6	100
				All Rings Off	207[1]	204 ± 187	58	-	186 ± 172	179	0.7	100

[1] – Absolute peak value is peak underpressure for this category.

Figure 17 shows the average peak underwater sound pressure levels for Pile 3 (± one standard deviation). Midwater received peak level statistical comparisons made to the initial bubbles off condition indicated that all with air flow on were significantly higher. When compared to the final bubbles off condition none were significant.

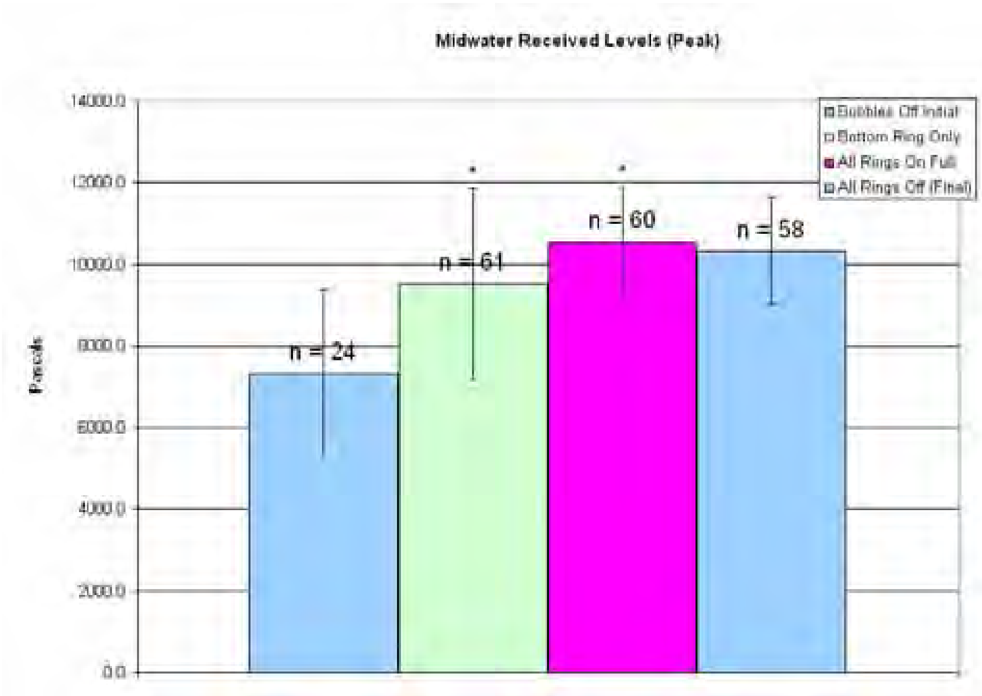


Figure 17: Pile 3, midwater average peak received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

Figure 18 indicates the average peak underwater sound pressure levels for Pile 3 (± one standard deviation). Bottom received peak level statistical comparisons made to the initial bubbles off condition indicated that all with air flow on were significantly higher. When compared to the final bubbles off condition only the all rings full on was significantly less.

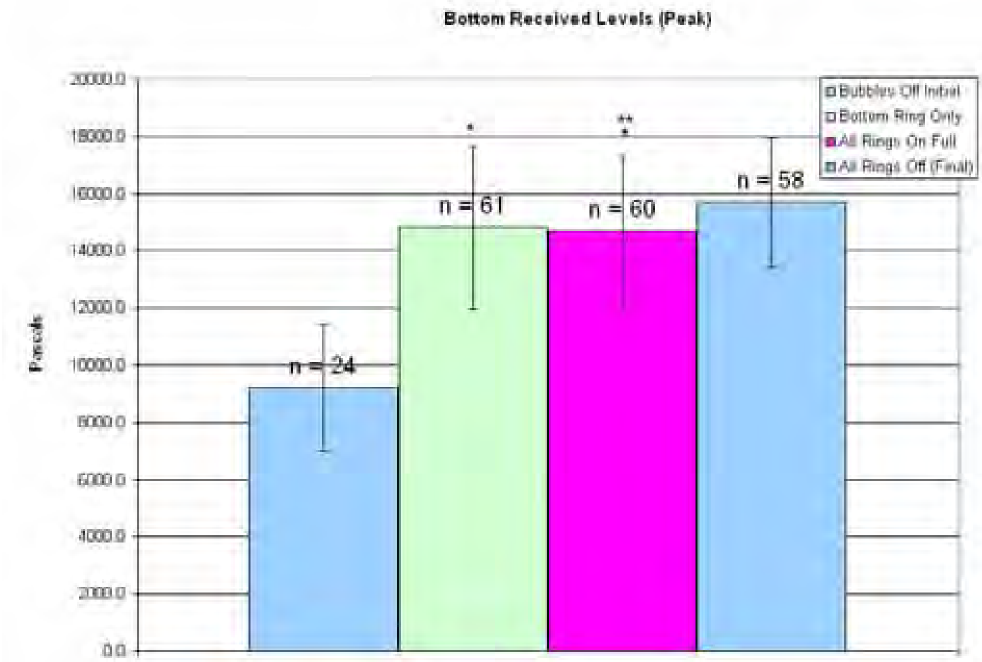


Figure 18: Pile 3, bottom average peak received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

RMS values are less variable than the peak values and when the midwater received RMS levels were compared statistically with the initial bubbles off condition none were significant (Figure 19). When compared to the final bubbles off condition none were significant.

Bottom received RMS level statistical comparisons indicated that all were significantly higher than the initial bubbles off condition. When compared to the final bubbles off condition none were significant (Figure 20).

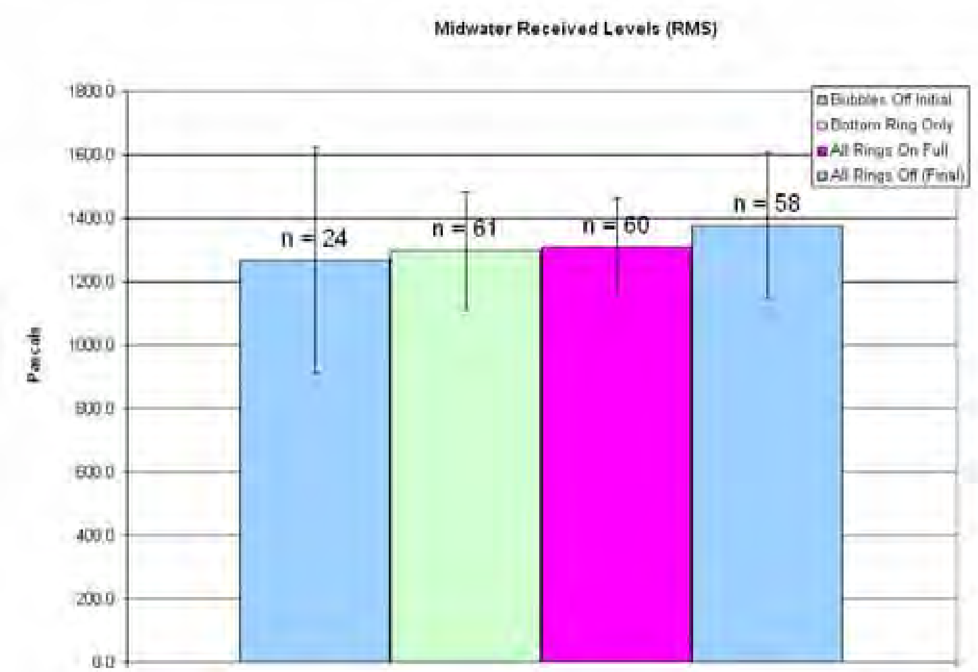


Figure 19: Pile 3, midwater average RMS received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

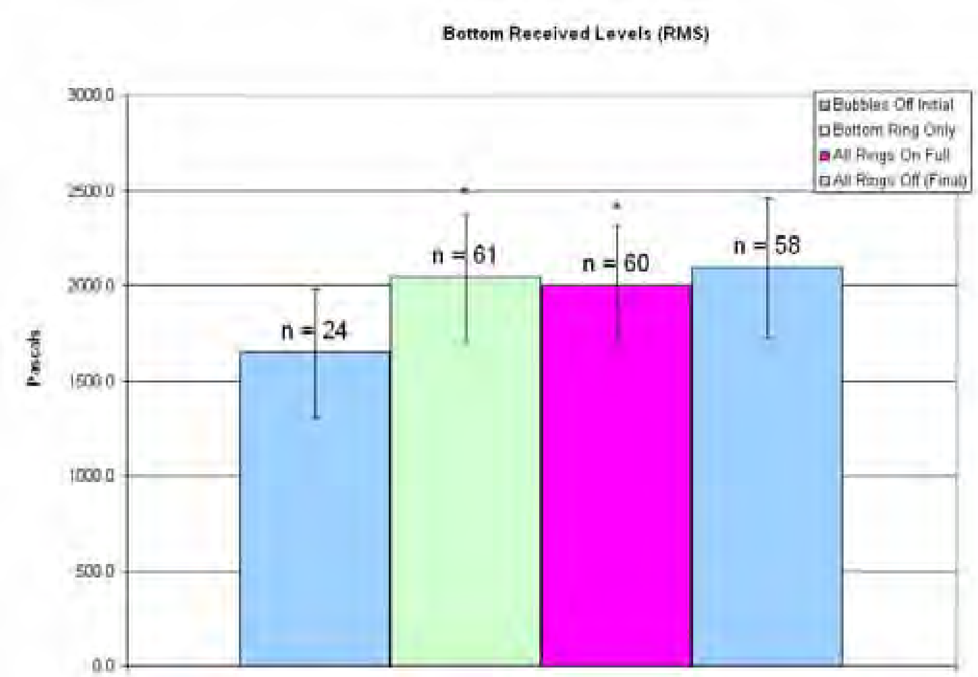


Figure 20: Pile 3, bottom average RMS received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

Pile 4 – Diesel Hammer

Figure 21 is a diagrammatic drawing of the hydrophone monitoring location in relation to the shoreline and other structures in the water for piles 4, 5 and 6. The drawing is not to scale.

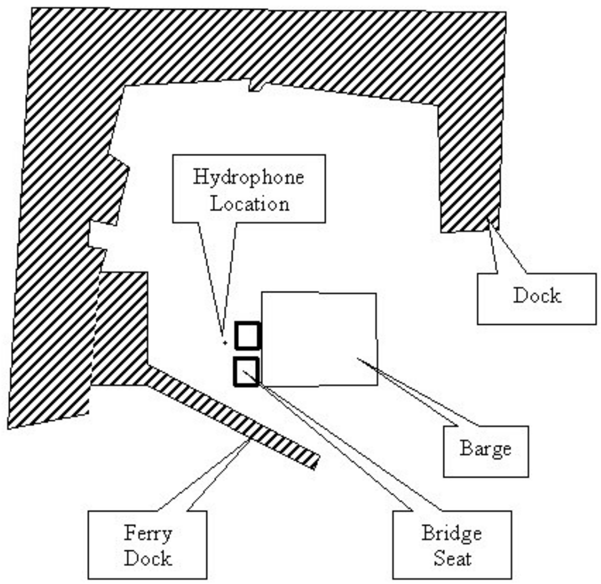


Figure 21. Diagram of Monitoring Location in Relation to the Shoreline and Other Nearby Structures.

Table 6 summarizes the acoustical data collected for the Pile 4 at the Slip Bridge Seat. The pile was driven into solid rock the last few feet of the drive and the sensitivity of the monitoring equipment was set incorrectly. Thus all of the peaks that were above 210 dB were truncated at 210 dB. Therefore the highest peak values recorded for Pile 4 were 210 dB_{peak}. The peak values were generally higher at the bottom hydrophone. The sound received by the bottom hydrophone was only slightly attenuated by use of the bubble curtain.

The absolute peak values ranged from 204 dB_{peak} to 210 dB_{peak} at mid water and 210 dB_{peak} at the bottom. There is only a modest reduction in the average peak values between the air curtain on and off conditions. The peak levels were actually higher with the bubble curtain on at the midwater and bottom hydrophones. It is possible that this is the result of the hammer striking the pile harder as it is driven deeper into the sediment but it is unclear. Because these results were anticipated dynamic pile testing was performed on the pile itself to help assess the dynamics between pile energy and sound metrics. However, the dynamic pile data analysis is beyond the scope of this report.

Because these tests were not controlled we cannot be certain that all conditions, with the exception of the bubble curtain, were the same for each sequence of impacts. It will be necessary to analyze the dynamic pile driving data along with the acoustical data to provide a better context for assessment of test conditions. It is likely that other unmeasured variables are responsible for some of the observations recorded

Table 6: Summary of Underwater Sound Level Impacts and Mitigation for Pile 4 at Slip Bridge Seat.

Pile #	Date	Hammer Type	Hydrophone Depth	Bubble Curtain Rings On	Peak (dB)	Average Peak (dB ± s.d.)	n	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	% Strikes Exceeding 180 dB Peak
4	2/23/05	Diesel	16 feet	Bottom Ring On Full	210[2]	208 ± 197	44	0	184 ± 170	176	8.4	100
				All Rings On Full	210[2]	206 ± 194	74	0	189 ± 177	182	0.6	100
				All Rings Off	210 [1,2]	209 ± 198	12	-	192 ± 172	185	0.6	100
			33 feet	Bottom Ring On Full	210[1]	208 ± 197	44	0	190 ± 178	184	1.2	100
				All Rings On Full	210[1]	210 ± 126	74	0	194 ± 174	185	0.6	100
				All Rings Off	210[1]	210 ± 130	12	-	194 ± 176	185	0.6	100

[1] – Peak exceed 210 dB, however, because equipment was not set properly the peaks were clipped at 210 dB.
[2] – Absolute peak value is peak underpressure for this category.

Figure 22 shows the average peak underwater sound pressure levels for Pile 4 (± one standard deviation). Midwater received peak level statistical comparisons made to the final bubbles off condition indicated that all with air flow on were significantly lower. The all rings on full condition was slightly lower than having just the bottom ring on full.

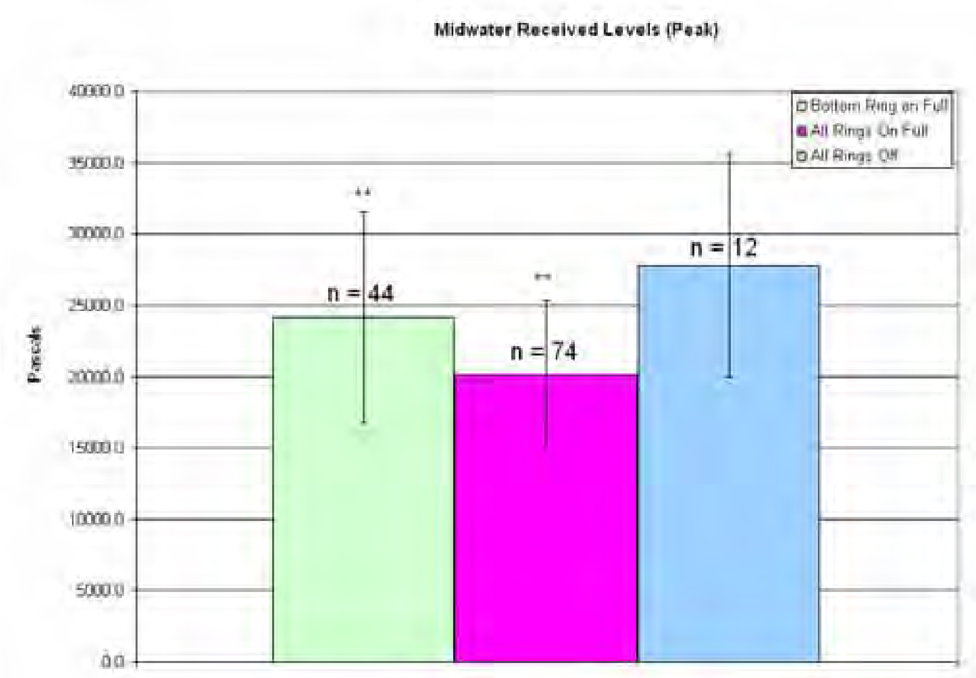


Figure 22: Pile 4, midwater average peak received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

Figure 23 indicates the average peak underwater sound pressure levels for Pile 4 (± one standard deviation). Bottom received peak level statistical comparisons made to the final bubbles off condition indicated that all with air flow on were significantly lower. However, because the peaks were clipped at 210 dB the variability is artificially small, with the exception of the bottom ring on only condition. Therefore, the statistical significance is likely artificial as well.

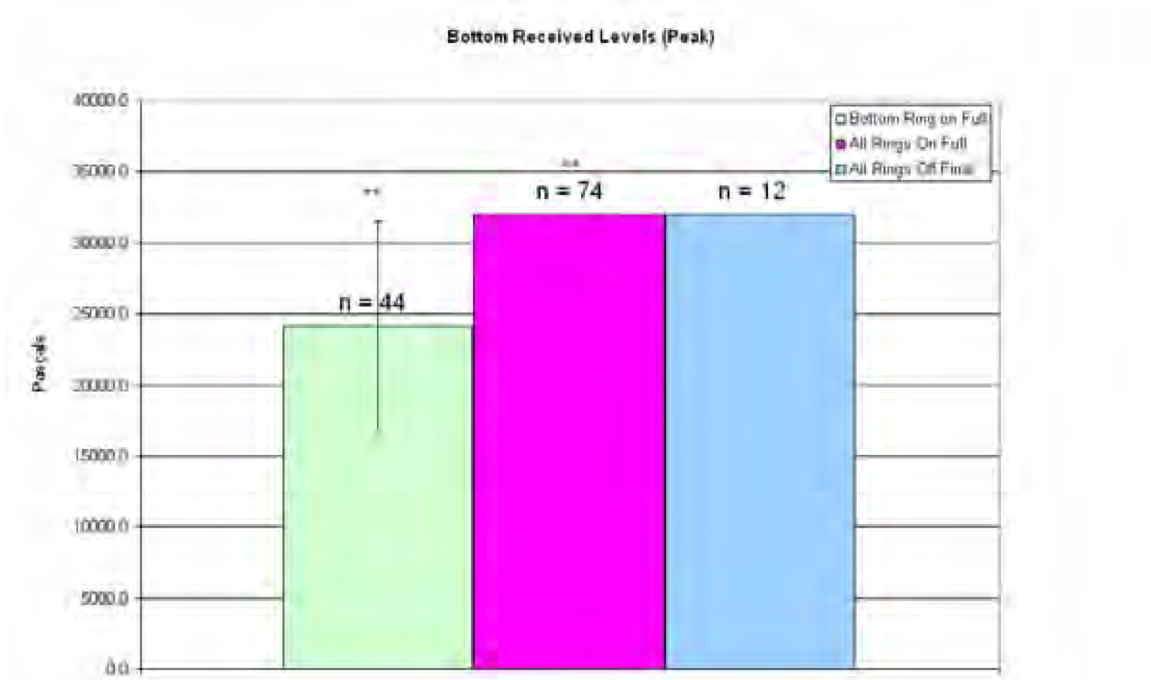


Figure 23: Pile 4, bottom average peak received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

RMS and SEL values are less variable than peak values. Both hydrophones indicated an inverse reduction in sound levels with increasing air flow. Midwater received RMS levels were compared statistically with the final bubbles off condition and all were significant (Figure 24). Bottom received RMS levels were statistically compared with the final bubbles off condition and all were significant (Figure 25). In both cases the greatest reduction in RMS values occurred with the bottom ring only on full.

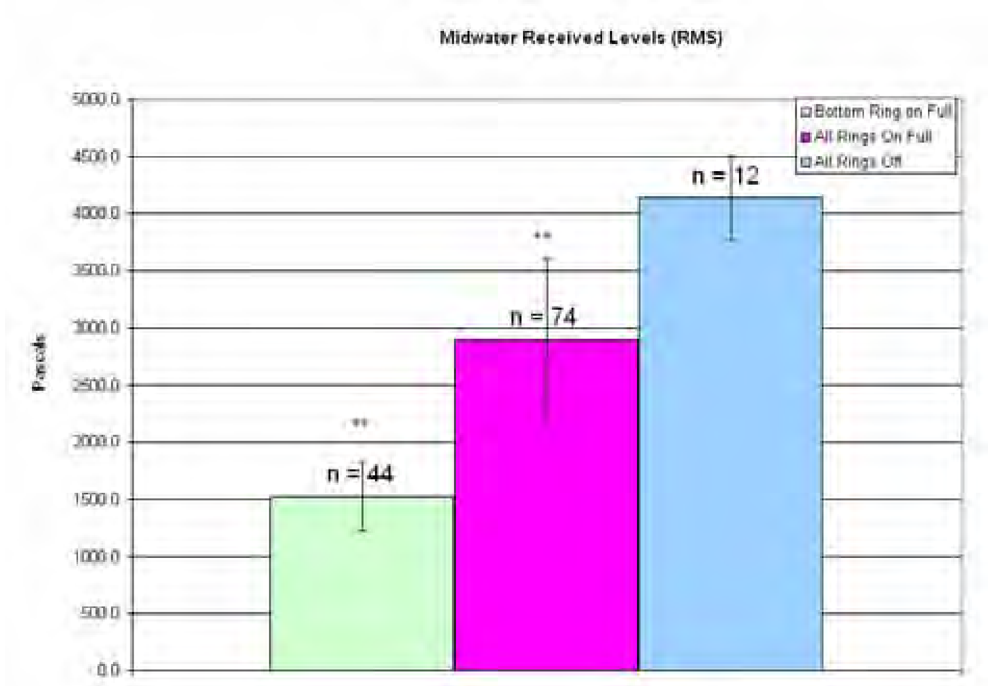


Figure 24: Pile 4, midwater average RMS received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

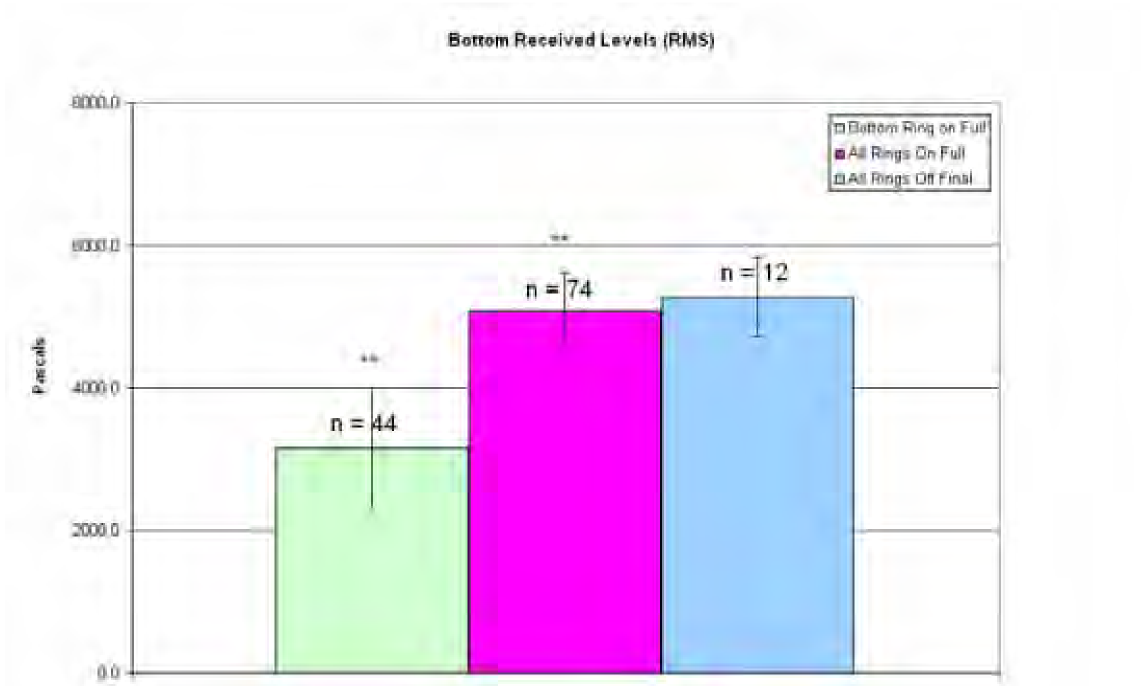


Figure 25: Pile 4, bottom average RMS received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

Pile 5 – Diesel Hammer

Table 7 summarizes the acoustical data collected for Pile 5 at the Slip Bridge Seat. The peak values were generally higher at the bottom hydrophone. The bottom hydrophone was only moderately affected by the use of the bubble curtain.

The amplifier gain was reset prior to recording sound levels to avoid saturation of impact signals for this pile and subsequent piles. This pile was also driven into solid rock the last few feet of the drive and thus the absolute peak values ranged from 209 dB_{peak} to 212 dB_{peak} at mid water and 215 dB_{peak} to 217 dB_{peak} at the bottom. There is only a modest reduction in the average peak values between the air curtain on and off conditions with the maximum average reduction occurring when the bottom ring only was at full flow.

Because these tests were not controlled we cannot be certain that all conditions, with the exception of the bubble curtain, were the same for each sequence of impacts. It will be necessary to analyze the dynamic pile driving data along with the acoustical data to provide a better context for assessment of test conditions. It is likely that other unmeasured variables are responsible for some of the observations recorded

Table 7: Summary of Underwater Sound Level Impacts and Mitigation for Pile 5 at Slip Bridge Seat.

Pile #	Date	Hammer Type	Hydrophone Depth	Bubble Curtain Rings On	Peak (dB)	Average Peak (dB ± s.d.)	n	Average Decibel Reduction	Average RMS (dB ± s.d.)	SEL (dB)	Rise Time (msec)	% Strikes Exceeding 180 dB Peak
5	2/24/05	Diesel	16 feet	Bottom Ring On Full	209	206 ± 191	42	2	190 ± 172	182	4.4	100
				All Rings On Full	210[2]	209 ± 186	191	0	191 ± 174	182	22.0[1]	100
				All Rings Off	212[2]	208 ± 198	38	-	189 ± 174	181	0.5	100
			33 feet	Bottom Ring On Full	215[2]	214 ± 192	42	2	196 ± 178	188	1.0	100
				All Rings On Full	216[2]	216 ± 185	191	1	197 ± 177	187	1.1	100
				All Rings Off	217	215 ± 176	38	-	195 ± 178	187	1.1	100

[1] – Based on higher secondary peak likely the result of ringing of the pile.
[2] – Absolute peak value is peak underpressure for this category

Figure 26 shows the average peak underwater sound pressure levels for Pile 5 (± one standard deviation). Midwater received peak level statistical comparisons made to the final bubbles off condition indicated that only the all rings on full condition was significantly higher. Although not significant, the bottom ring only on condition average peak was lower.

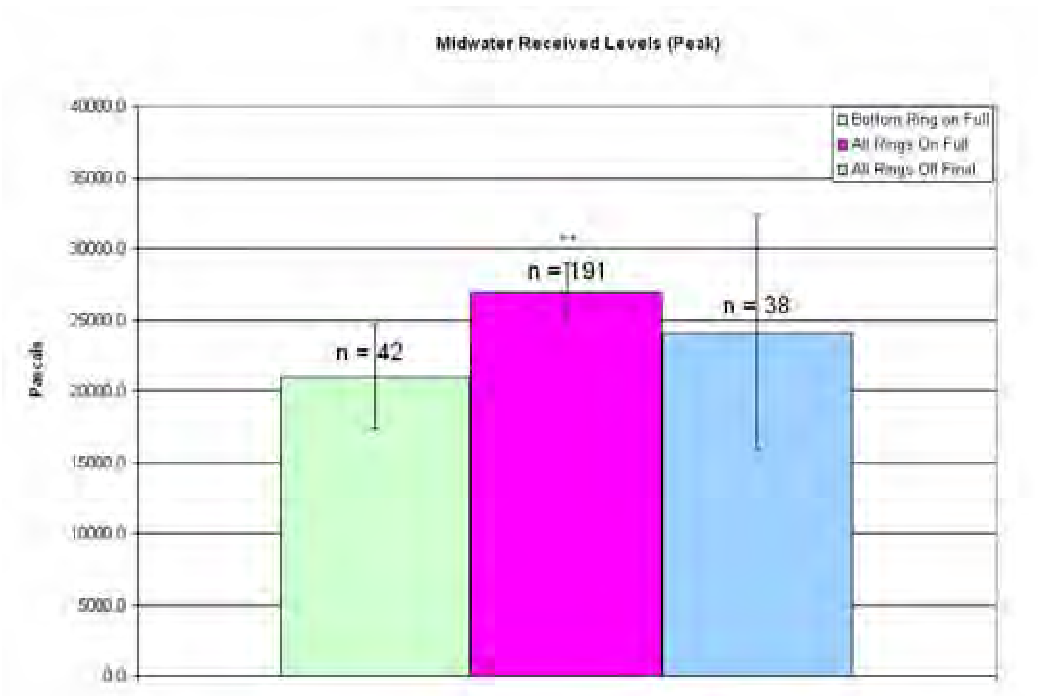


Figure 26. Pile 5, midwater average peak received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

Figure 27 indicates the average peak underwater sound pressure levels for Pile 5 (± one standard deviation). Bottom received peak level statistical comparisons made to the final bubbles off condition indicated that all rings on full was significantly higher but the bottom ring only on full was significantly lower.

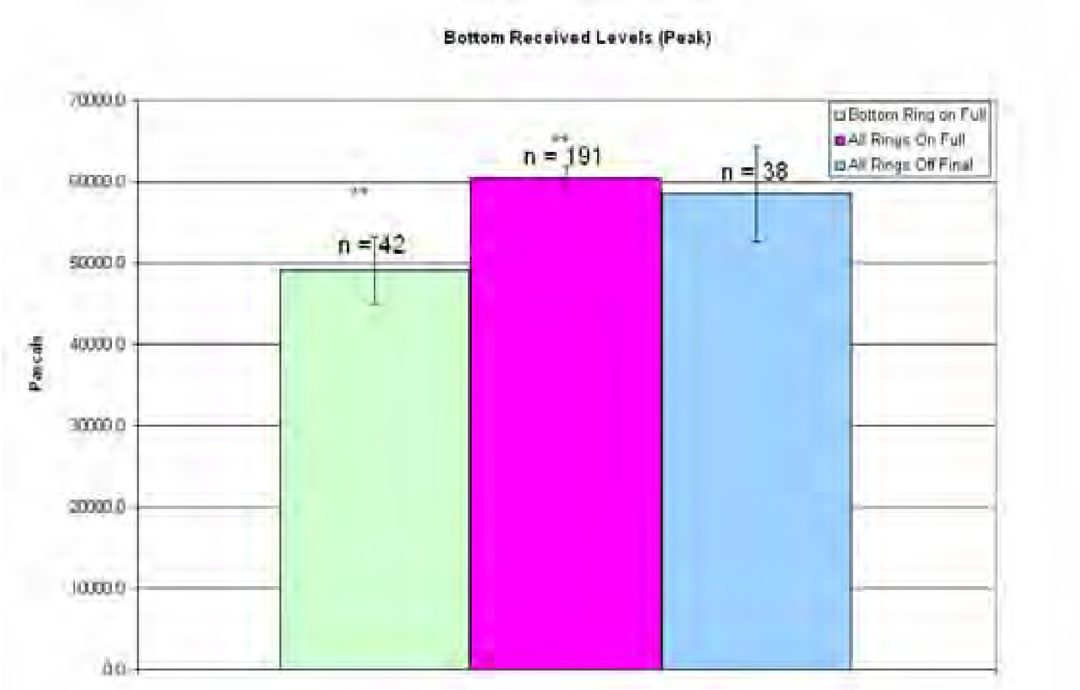


Figure 27. Pile 5, midwater average peak received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

RMS and SEL values are less variable than peak values. Both hydrophones indicated an inverse reduction in sound levels with increasing air flow. Midwater received RMS levels were compared statistically with the final bubbles off condition and all were significantly higher (Figure 28). Bottom received RMS levels were statistically compared with the final bubbles off condition and all were significantly higher (Figure 29). In both cases the smallest increase in RMS values occurred with the bottom ring only on full.

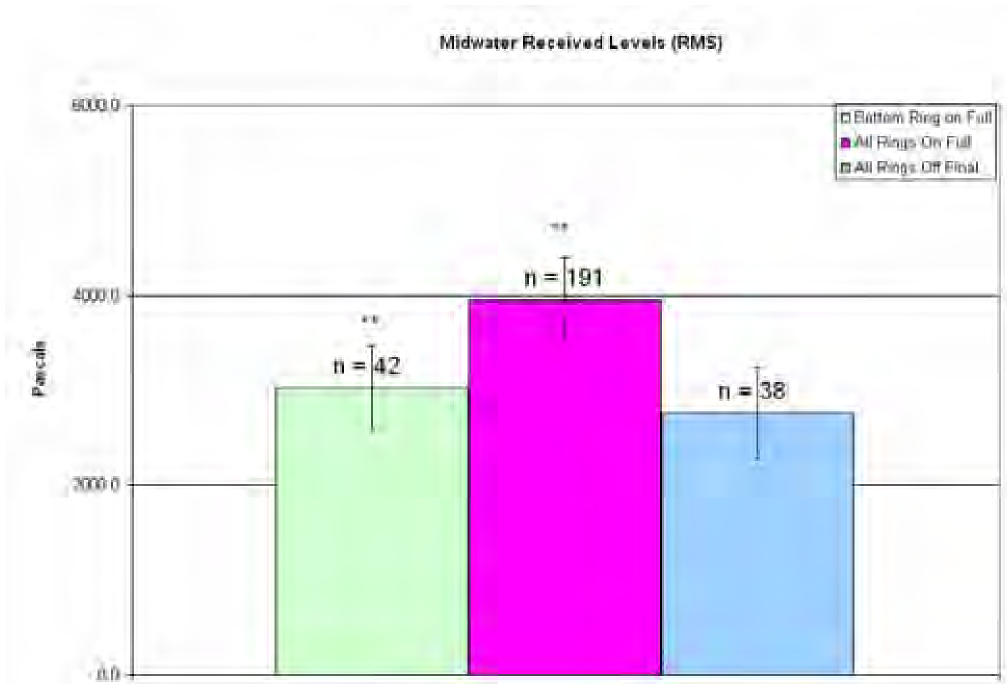


Figure 28. Pile 5, midwater average RMS received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

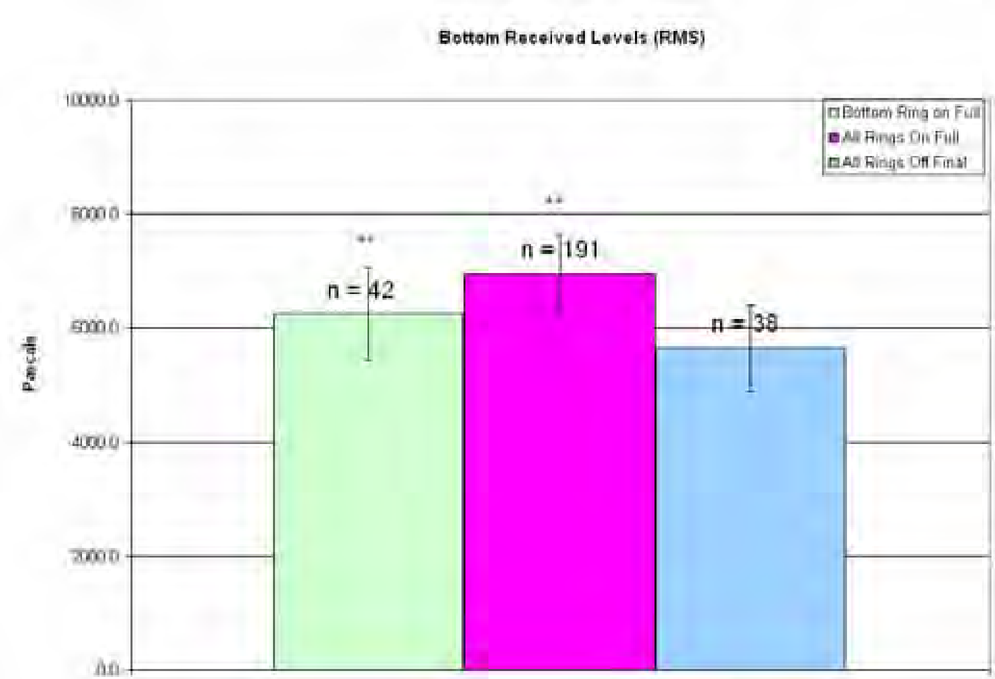


Figure 29. Pile 5, bottom average RMS received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

Pile 6 – Hydraulic Hammer

Table 8 summarizes the acoustical data collected for the Pile 6 at the Slip Bridge Seat. The peak values were generally higher at the bottom hydrophone.

This pile was driven into solid rock for the last few feet of the drive. Therefore, the absolute peak values were relatively high ranging from 196 dB_{peak} to 208 dB_{peak} at mid water and 198 dB_{peak} to 214 dB_{peak} at the bottom. There is a substantial reduction in average peak values between the all rings on full and all air off. There is a slightly less reduction in peak values between the bottom ring only on full and all off conditions.

Because these tests were not controlled we cannot be certain that all conditions, with the exception of the bubble curtain, were the same for each sequence of impacts. It will be necessary to analyze the dynamic pile driving data along with the acoustical data to provide a better context for assessment of test conditions. It is likely that other unmeasured variables are responsible for some of the observations recorded

Table 8: Summary of Underwater Sound Level Impacts and Mitigation for Pile 6 at the Slip Bridge Seat.

Pile #	Date	Hammer Type	Hydrophone Depth (ft)	Bubble Curtain Rings On	Absolute Peak (dB)	Average Peak (dB s.d.)	n	Average Decibel Reduction	Average RMS (dB ± s.d)	SEL (dB)	Rise Time (msec)	% Strikes Exceeding 180 dB Peak
6	2/24/05	Hydraulic	16 feet	Bottom Ring On Full	196[2]	193±180	44	12	178±164	167	37.7[1]	100
				All Rings On Full	205	202±192	162	3	186±176	178	5.6[1]	100
				All Rings Off	208[2]	204±191	172	-	188±174	180	0.7	100
			33 feet	Bottom Ring On Full	198[2]	196±184	44	16	181±168	174	28.0[1]	100
				All Rings On Full	214	211±203	162	0	192±182	184	2.0	100
				All Rings Off	214	212±197	172	-	193±179	184	2.2	100

[1] - Secondary spike used as peak to calculate rise time and is most likely an indication of ringing of the pile.
[2] – Absolute peak value is peak underpressure for this category

Figure 30 shows the average peak underwater sound pressure levels for Pile 6 (± one standard deviation). Midwater received peak level statistical comparisons made to the final bubbles off condition indicated that all were significantly lower. The greatest sound reduction was measured when only the bottom ring was on full.

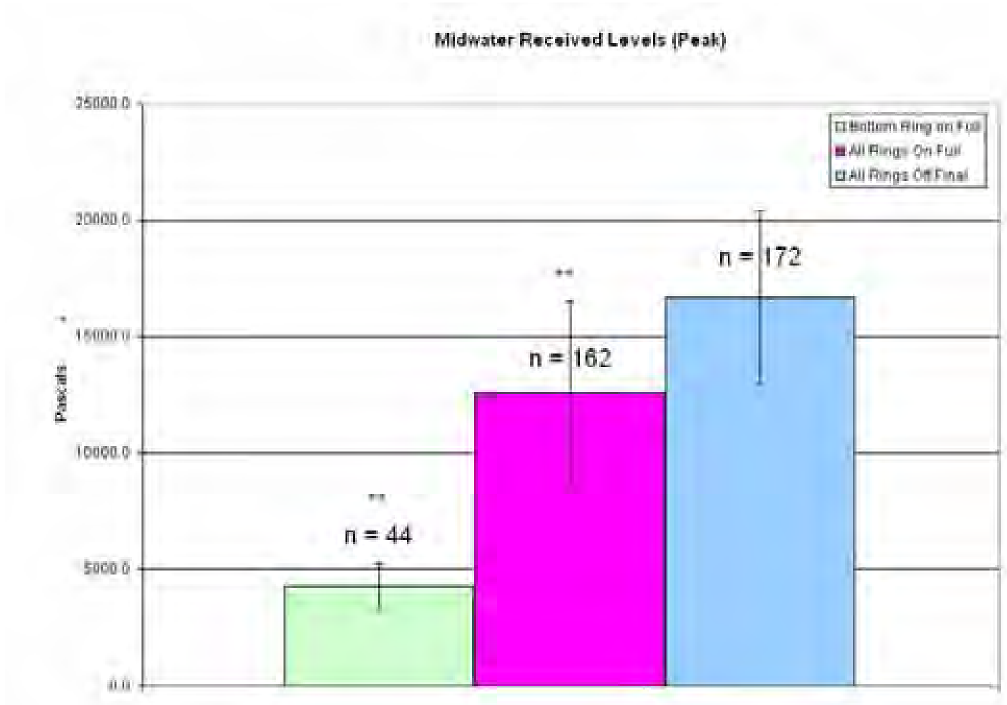


Figure 30. Pile 6, midwater average peak received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

Figure 31 indicates the average peak underwater sound pressure levels for Pile 6 (± one standard deviation). Bottom received peak level statistical comparisons made to the final bubbles off condition indicated that all were significantly lower.

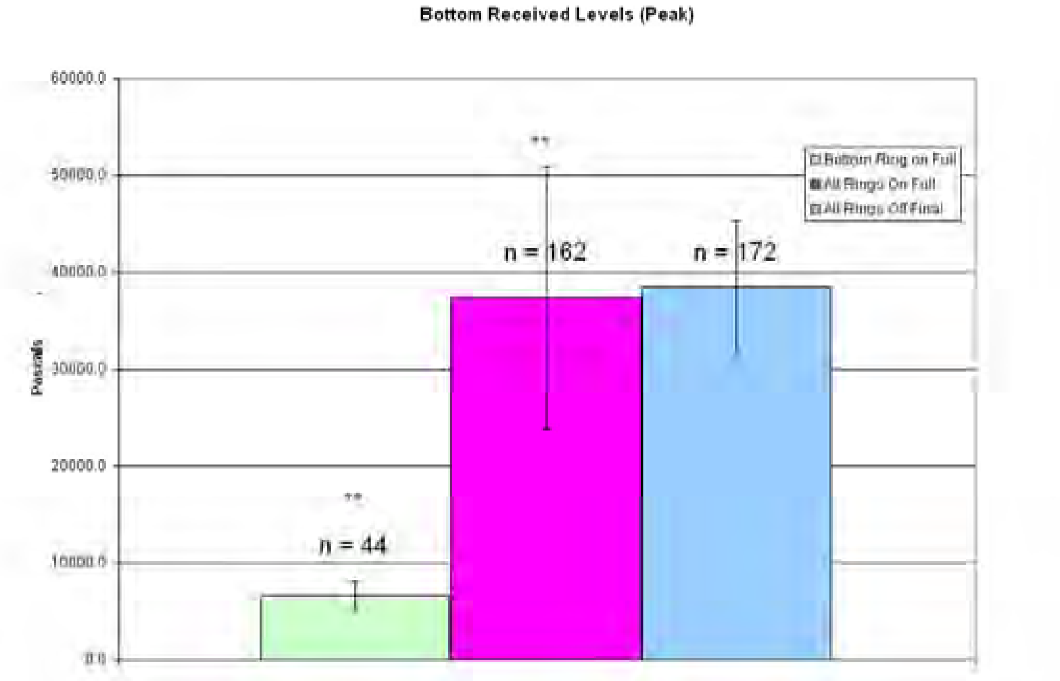


Figure 31. Pile 6, bottom average peak received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

RMS and SEL values indicated sound reduction as well with the greatest reduction seen with only the bottom ring air flow on. This follows the same trend seen at other piles and was true for both hydrophones.

Midwater received RMS levels were compared statistically with the final bubbles off condition and all were significantly lower (Figure 32). Bottom received RMS levels were statistically compared with the final bubbles off condition and only the bottom ring only on full was significantly lower (Figure 33).

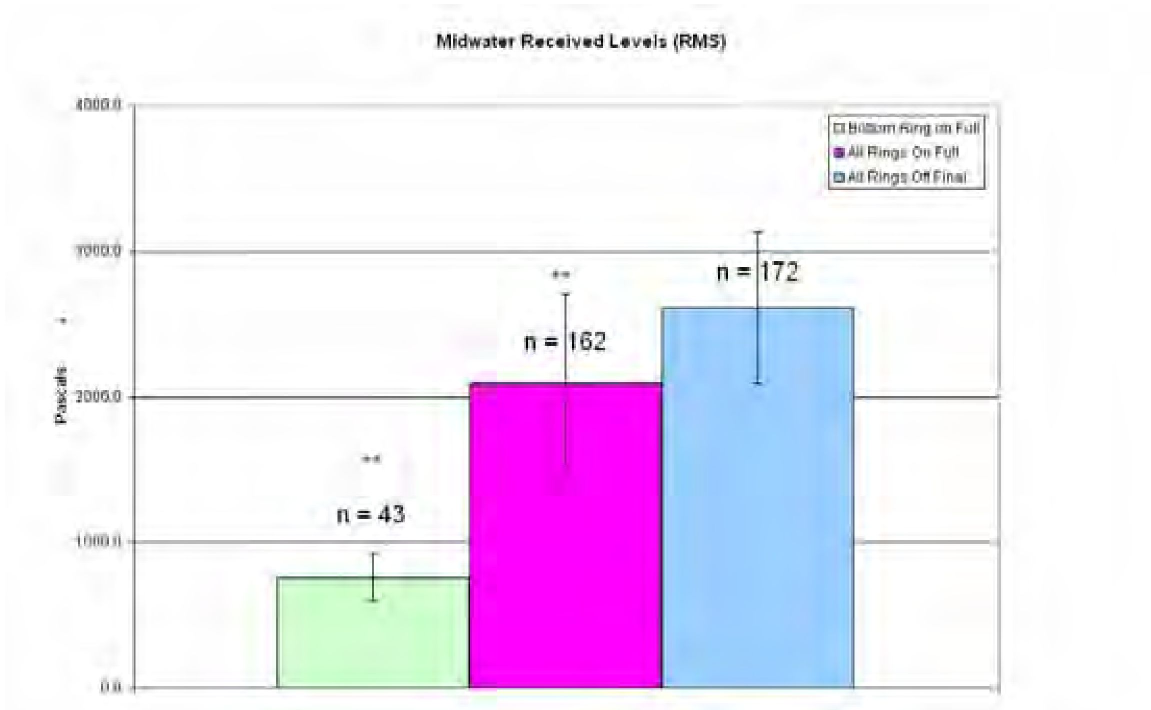


Figure 32. Pile 6, midwater average RMS received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

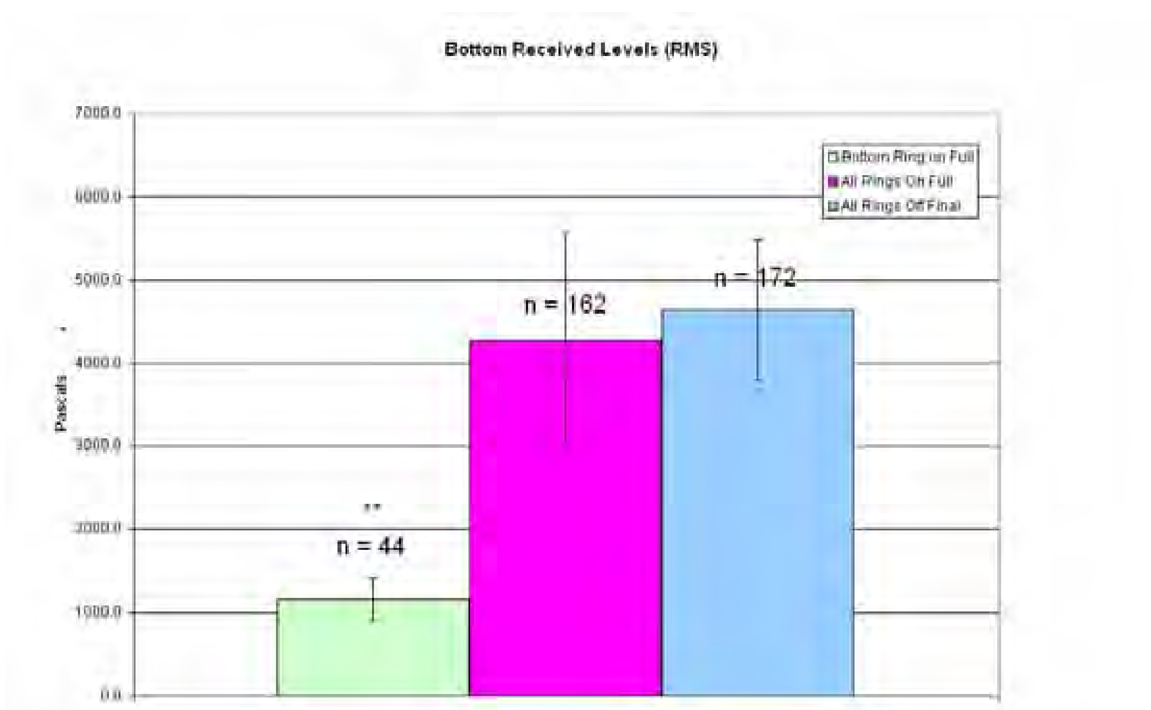


Figure 33. Pile 6, bottom average RMS received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05

Pile 7 – Diesel Hammer

Figure 34 is a diagrammatic drawing of the hydrophone monitoring location in relation to the shoreline and other structures in the water for piles 7 and 8. The drawing is not to scale.

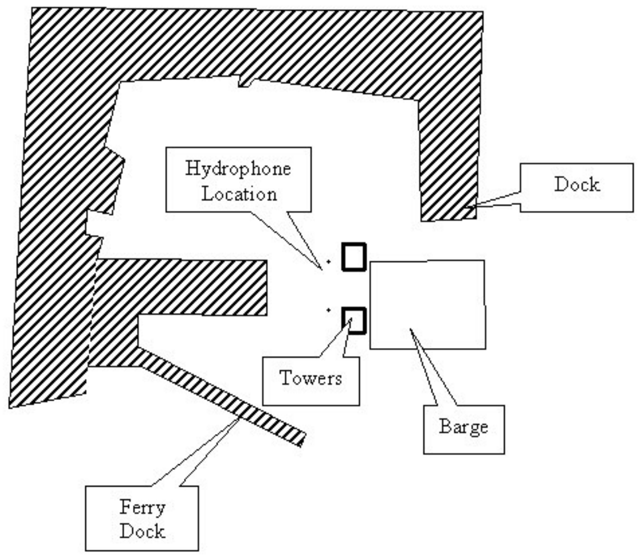


Figure 34. Diagram of Monitoring Location in Relation to the Shoreline and Other Nearby Structures.

Table 9 summarizes the acoustical data collected for Pile 7 at the southwest Tower. The peak values were generally higher at the bottom hydrophone.

The absolute peak values ranged from 205 dB_{peak} at mid water and 204 dB_{peak} to 211 dB_{peak} at the bottom. Sound level reduction comparisons between bubble curtain on and off are not possible for this pile since the bubble curtain was never turned off during the pile driving event.

Because these tests were not controlled we cannot be certain that all conditions, with the exception of the bubble curtain, were the same for each sequence of impacts. It will be necessary to analyze the dynamic pile driving data along with the acoustical data to provide a better context for assessment of test conditions. It is likely that other unmeasured variables are responsible for some of the observations recorded

Table 9: Summary of Underwater Sound Level Impacts and Mitigation for Pile 7 at the Southwest Tower.

Pile #	Date	Hammer Type	Hydrophone Depth	Bubble Curtain Rings On	Absolute Peak (dB)	Average Peak (dB ± s.d.)	n	Average Decibel Reduction	Average RMS (dB)	SEL (dB)	Rise Time (msec)	% Strikes Exceeding 180 dB Peak
7	3/3/05	Diesel	20 feet	Bottom Ring On Full	205	203 ± 190	53	-	189 ± 177	180	5.9	100
				All Rings On Full	205	202 ± 183	25	-	189 ± 172	181	41.3	100
			40 feet	Bottom Ring On Full	204	203 ± 191	53	-	189 ± 177	180	2.2	100
				All Rings On Full	211	209 ± 192	25	-	194 ± 178	186	2.4	100

Figure 35 shows the average peak underwater sound pressure levels for Pile 7 (± one standard deviation). Midwater received peak level statistical comparisons made between the bottom ring only and all rings on full indicate that the all rings on full condition was significantly lower.

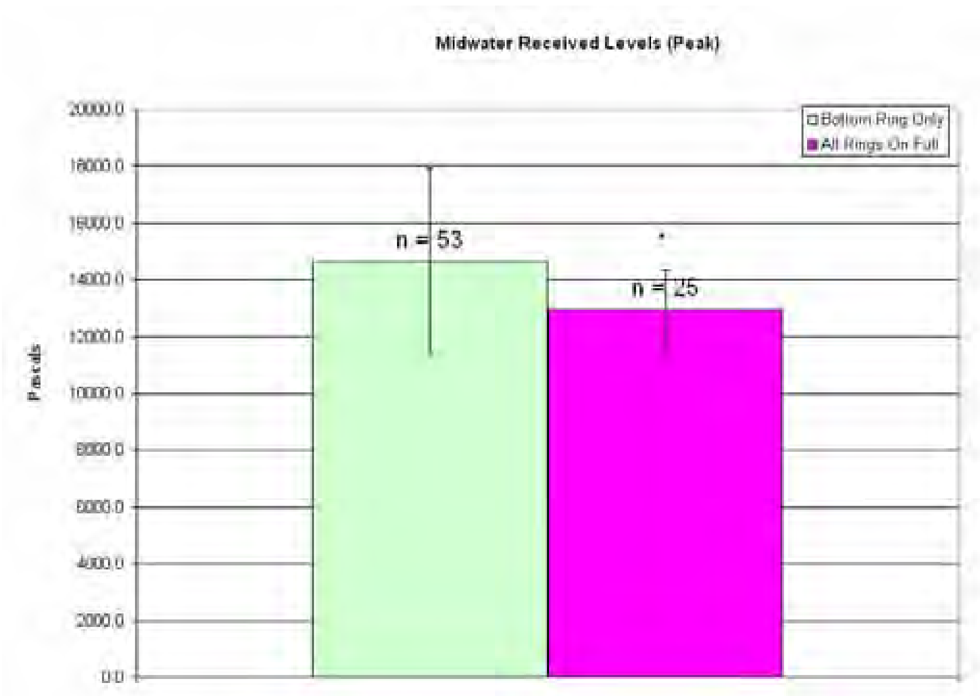


Figure 35. Pile 7, midwater average peak received levels. Error bars represent one standard deviation. * = Significant compared to bbottom ring on only (p<0.05).

Figure 36 indicates the average peak underwater sound pressure levels for Pile 7 (± one standard deviation). Bottom received peak level statistical comparisons made between the bottom ring only and all rings on full conditions indicate that the all rings on full was significantly higher.

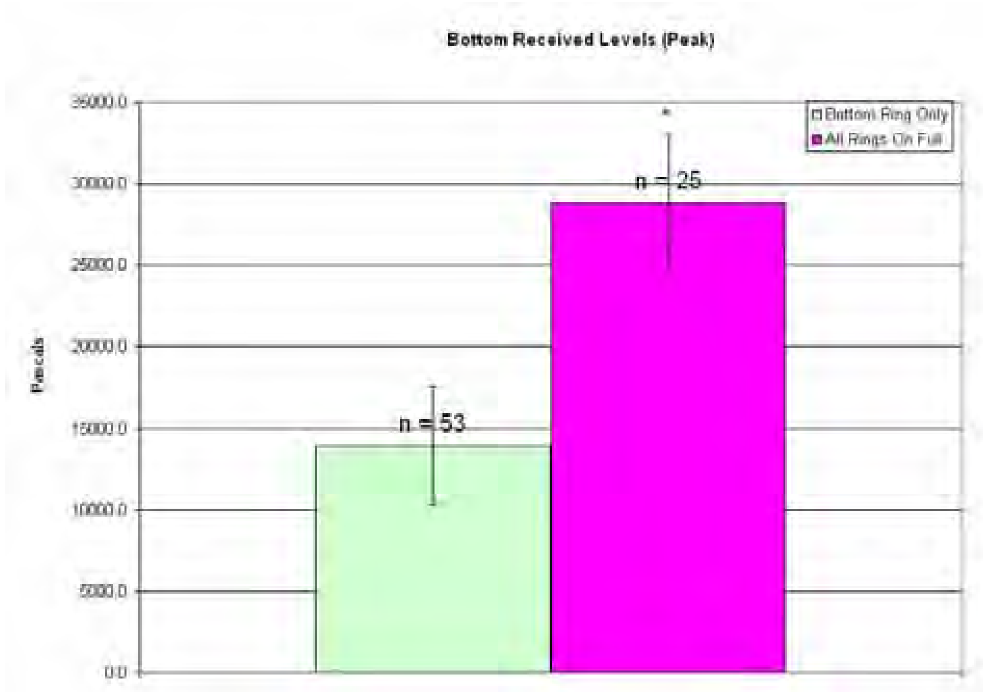


Figure 36. Pile 7, bottom average peak received levels. Error bars represent one standard deviation. * = Significant compared to bottom ring on only (p<0.05).

RMS and SEL values indicated very little difference between the bottom ring on only and the all rings on full conditions (Figure 37 & 38) for both midwater and bottom received RMS levels. Only the all rings on full condition at the bottom hydrophone was significantly greater than the bottom ring on only condition.

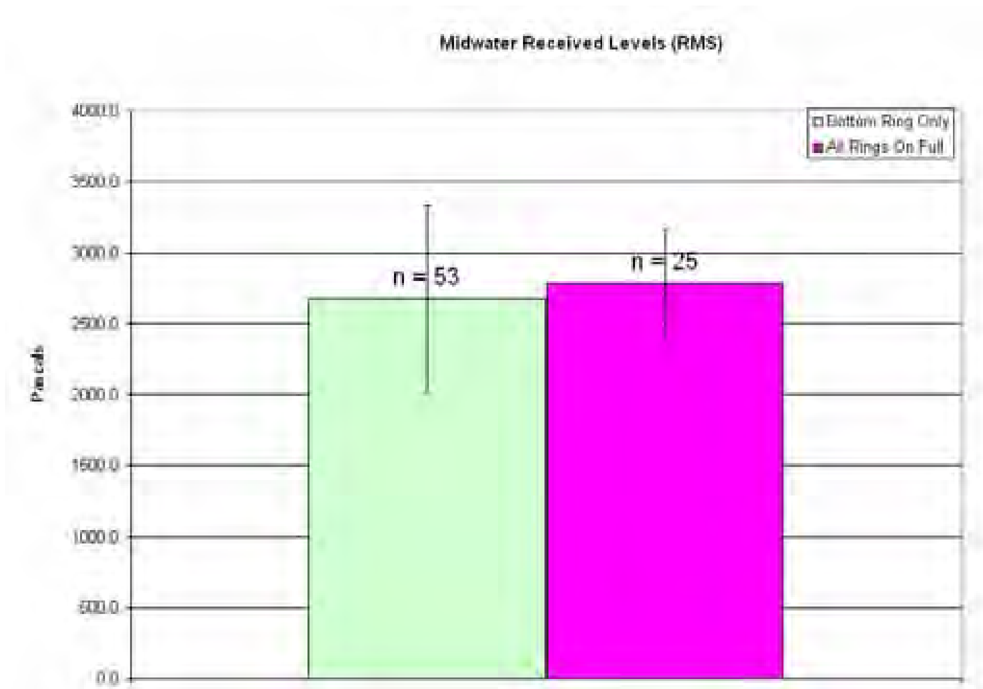


Figure 37. Pile 7, midwater average RMS received levels. Error bars represent one standard deviation. * = Significant compared to bottom ring on only (p<0.05).

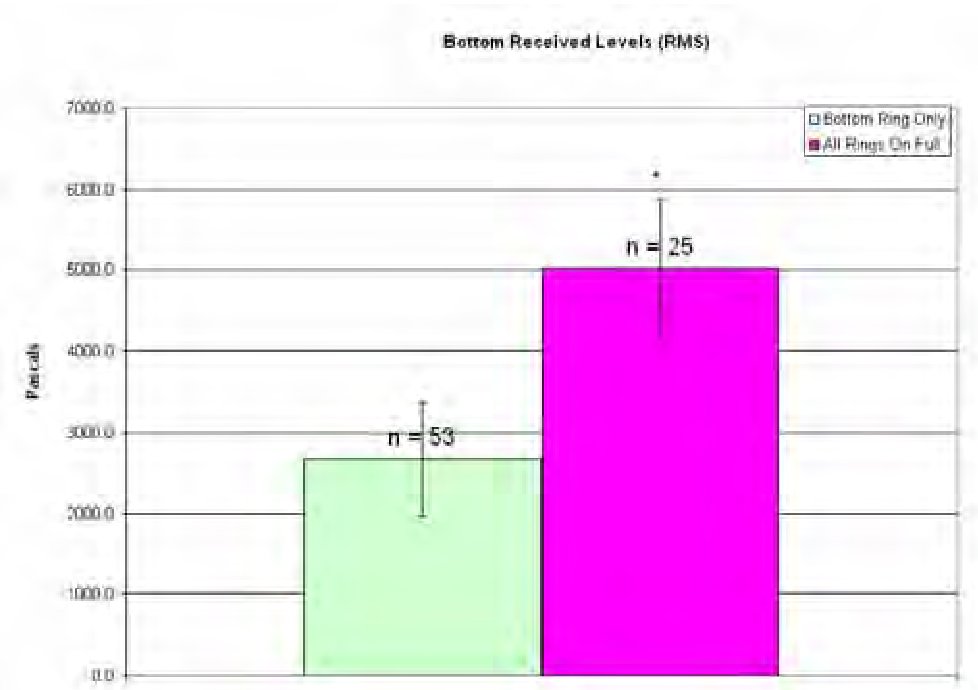


Figure 38. Pile 7, bottom average RMS received levels. Error bars represent one standard deviation. * = Significant compared to bottom ring on only ($p<0.05$).

Pile 8 – Diesel Hammer

Table 10 summarizes the acoustical data collected for the Pile 8 at the southwest Tower. The peak values were generally higher at the bottom hydrophone. The bottom hydrophone was only slightly affected by the use of the bubble curtain.

The absolute peak values ranged from 207 dB_{peak} to 212 dB_{peak} at mid water and 212 dB_{peak} to 215 dB_{peak} at the bottom. The peak values were generally higher at the bottom hydrophone. There is moderate reduction in the average peak values between the bubble curtain on and off conditions with the maximum average reduction occurring when the bottom ring only was at full flow.

Because these tests were not controlled we cannot be certain that all conditions, with the exception of the bubble curtain, were the same for each sequence of impacts. It will be necessary to analyze the dynamic pile driving data along with the acoustical data to provide a better context for assessment of test conditions. It is likely that other unmeasured variables are responsible for some of the observations recorded

Table 10: Summary of Underwater Sound Level Impacts and Mitigation for Pile 8 at the Southwest Tower.

Pile #	Date	Hammer Type	Hydrophone Depth (ft)	Bubble Curtain Rings On	Absolute Peak (dB)	Average Peak (db ± s.d.)	n	Average Decibel Reduction	Average RMS (dB)	SEL (dB)	Rise Time (msec)	% Strikes Exceeding 180 dB Peak
8	3/4/05	Diesel	14 feet	Bottom Ring On Full	208	207±185	49	2	190±172	181	6.5	100
				All Rings On Full	207	205±187	9	4	191±172	182	7.0	100
				All Rings Off	212	209±194	56	-	195±177	186	33.4[1]	100
			34 feet	Bottom Ring On Full	212	210±196	49	2	193±175	184	23.1[1]	100
				All Rings On Full	214	210±200	9	2	193±179	186	23.0[1]	100
				All Rings Off	215	212±194	56	-	196±178	187	23.1[1]	100

[1] - Secondary spike used as peak to calculate rise time and is most likely an indication of ringing of the pile.

Figure 39 shows the average peak underwater sound pressure levels for Pile 8 (± one standard deviation). Midwater received peak levels were statistically compared with the final bubbles off condition and all were significantly lower

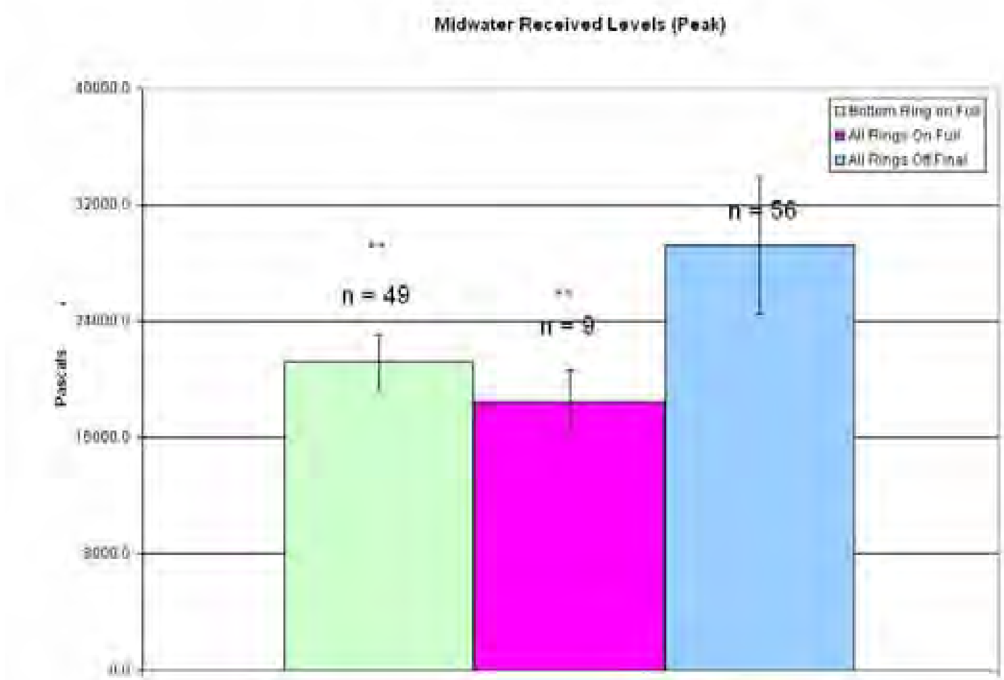


Figure 39. Pile 8, midwater average peak received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

Figure 40 indicates the average peak underwater sound pressure levels for Pile 8 (± one standard deviation). Bottom received peak levels were statistically compared with the final bubbles off condition and all were significantly lower

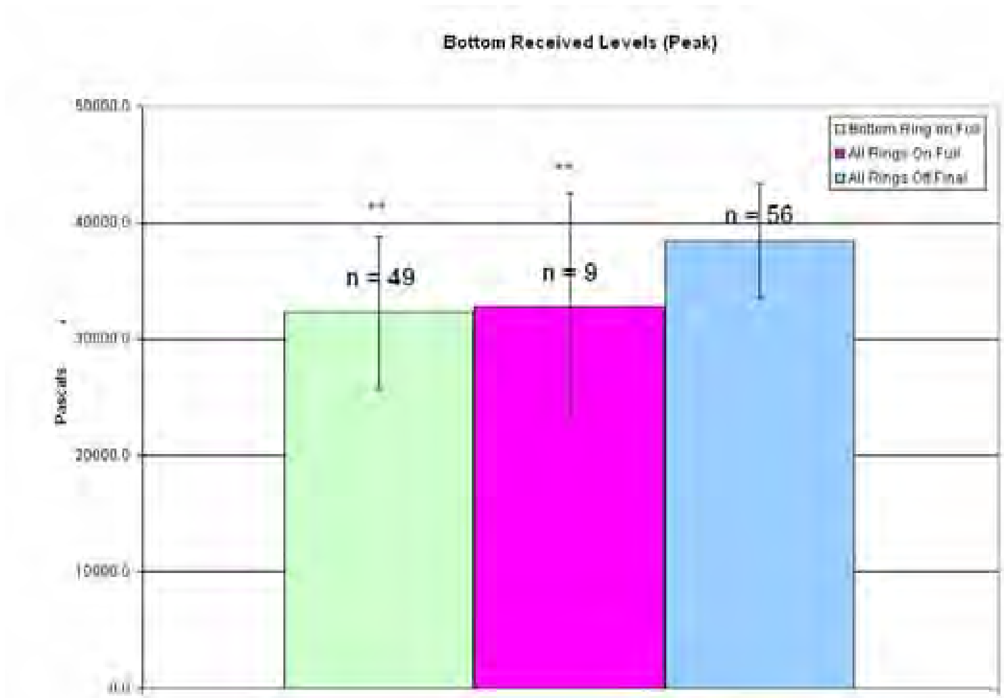


Figure 40. Pile 1, bottom average peak received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

RMS and SEL values indicated sound reduction as well with the greatest reduction seen with only the bottom ring air flow on. This follows the same trend seen at other piles and was true for both hydrophones.

Midwater received RMS levels were compared statistically with the final bubbles off condition and all were significantly lower (Figure 41). Bottom received RMS levels were statistically compared with the final bubbles off condition and all were significantly lower (Figure 42).

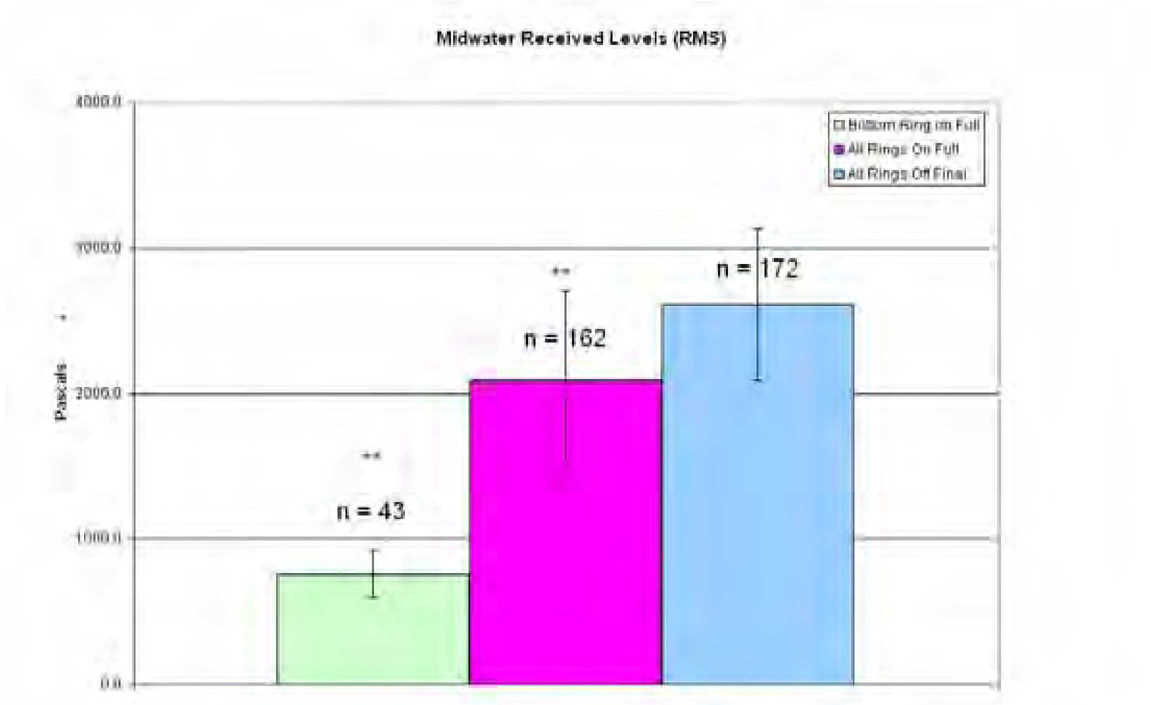


Figure 41. Pile 8, midwater average RMS received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

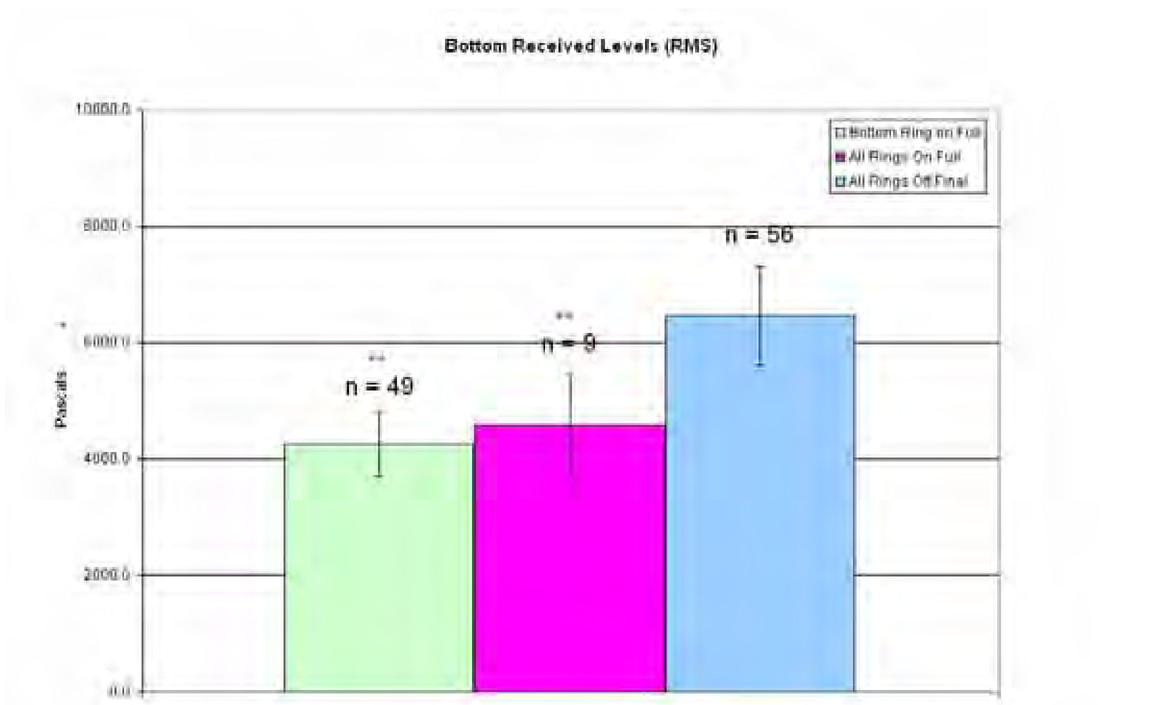


Figure 42. Pile 8, midwater average RMS received levels. Error bars represent one standard deviation. * = Significant compared to bubbles off initial (p<0.05). ** Significant compared to bubbles off final (p<0.05)

SEL

SEL was calculated for each of the absolute peak strikes for each pile and for each bubble curtain scenario. Figure 43 graphically shows the overall trend for SEL for each bubble curtain scenario. As can be seen in Figure 43 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 a substantially more energy to exceed this threshold. Although there is considerable variation between the individual strikes for each pile we have included a regression line indicating a general increase in SEL with increasing air flow.

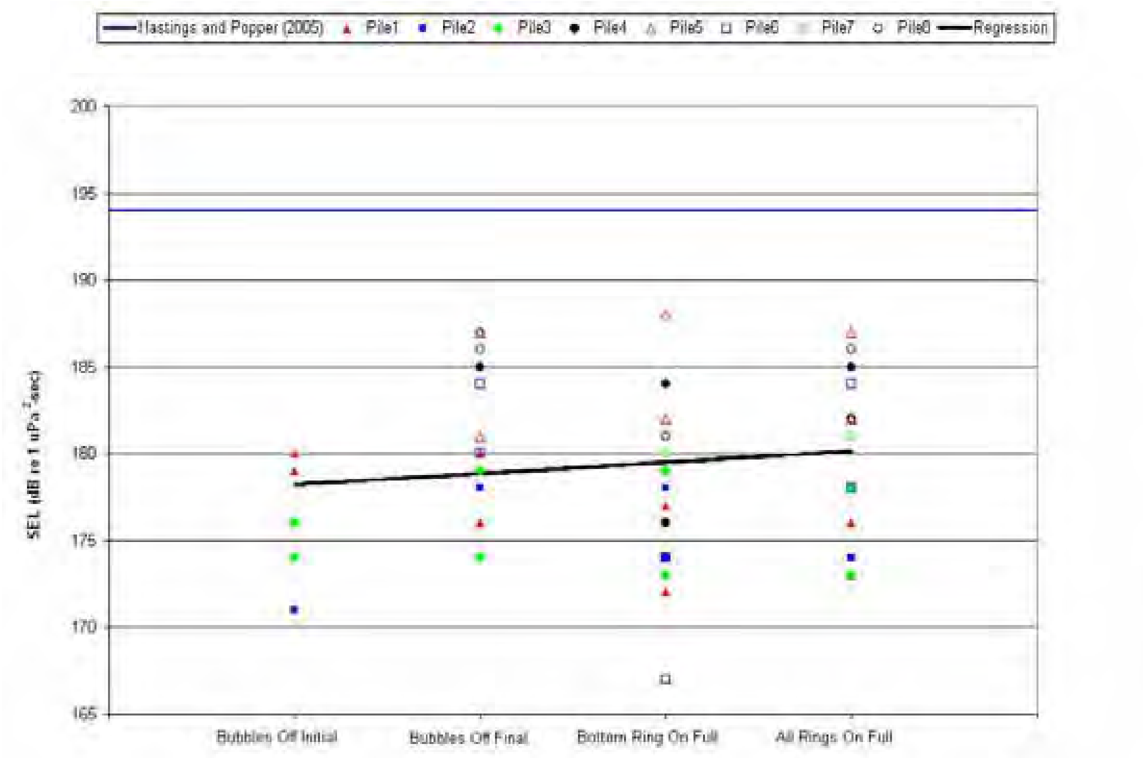


Figure 43. SEL values for each pile compared with the 194 dB SEL proposed threshold from Hastings and Popper (2005). Regression line formula is: y=0.639X + 177.6.

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 piles driven into solid rock and piles driven with a hydraulic hammer the absolute peak was observed to be at the front of the impulse wave. The highest absolute peak values were also recorded under these circumstances. However, no fish kills or distress of wildlife was observed.

Rise time, however, indicates a clear increase in the midwater received levels (Figure 44) as more air is supplied to the bubble curtain. Some of the highest rise times seen in Figure 44 are actually the ringing of the pile. However, for the bottom received levels, rise times were generally lower and this trend is not as clear (Figure 45). The bubble curtain differentially attenuates high frequencies. It is also possible that some sound may have "bounced" between the pile and the curtain before making it past the air curtain. This has the effect of stretching out the sound wave and slowing the rise time.

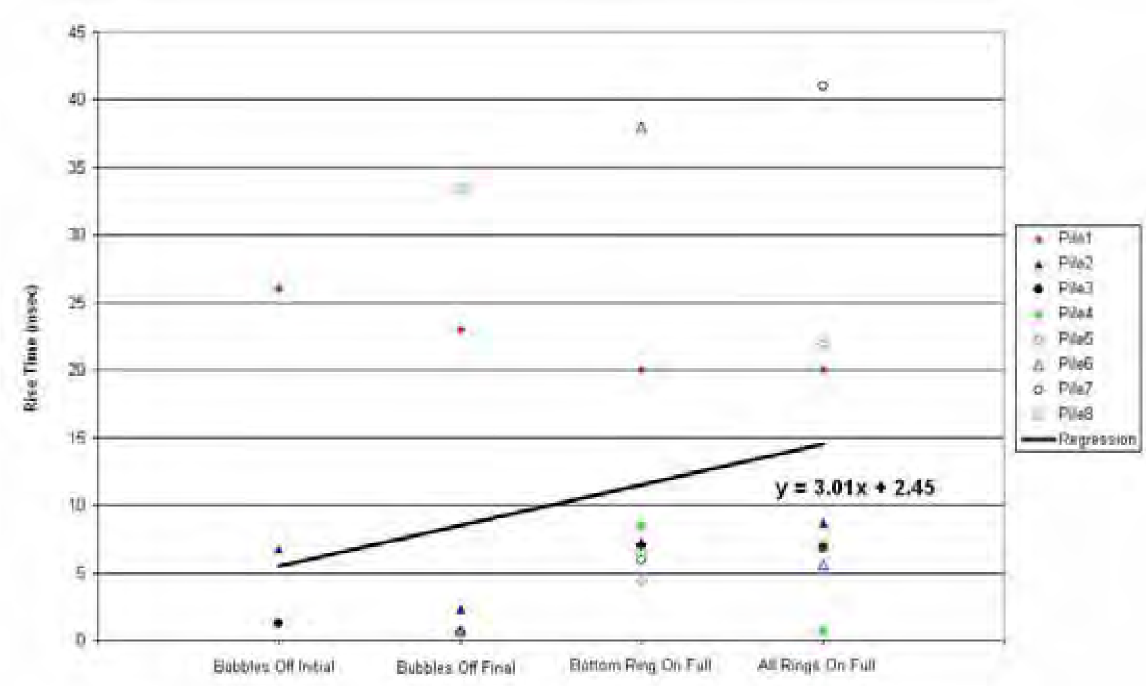


Figure 44. Rise times for each bottom received level peak pile strike with linear regression line

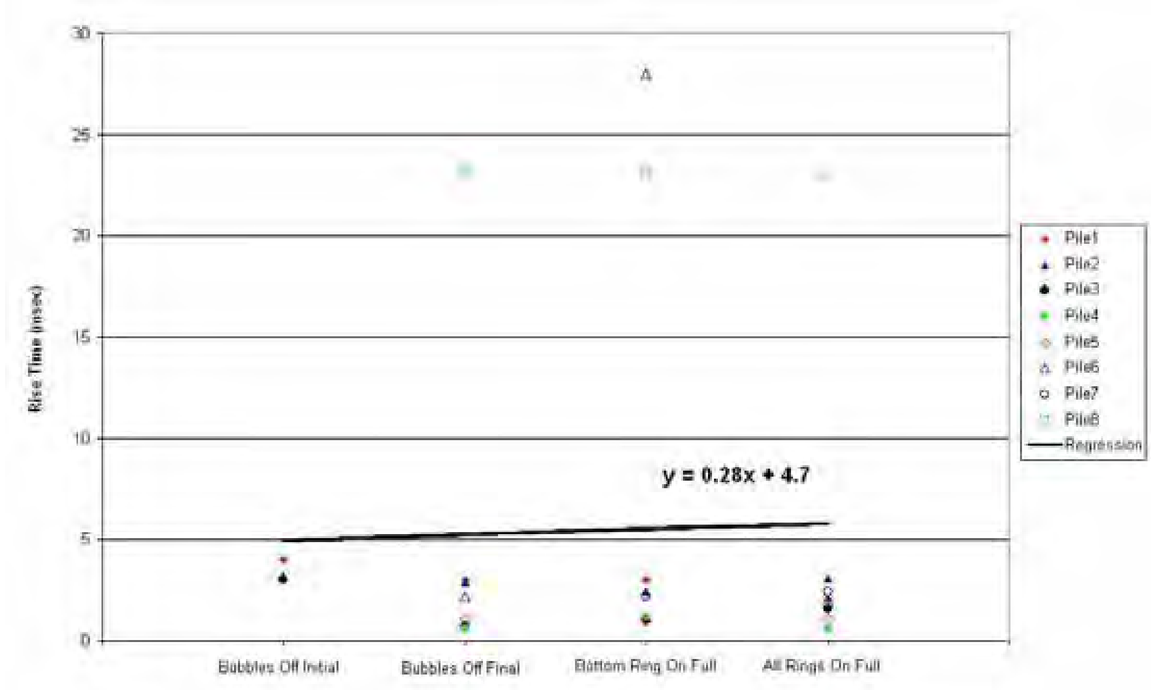


Figure 45. Rise times for each bottom received level peak pile strike with linear regression line.

Hammer Type Comparisons

Figure 46 appears to indicate that the diesel hammer created absolute peak levels that were higher than the other two hammer types. However, because of the large degree of variability indicated by the error bars it would appear that generally there was no substantial difference between the diesel hammer, the air hammer, and the hydraulic hammer.

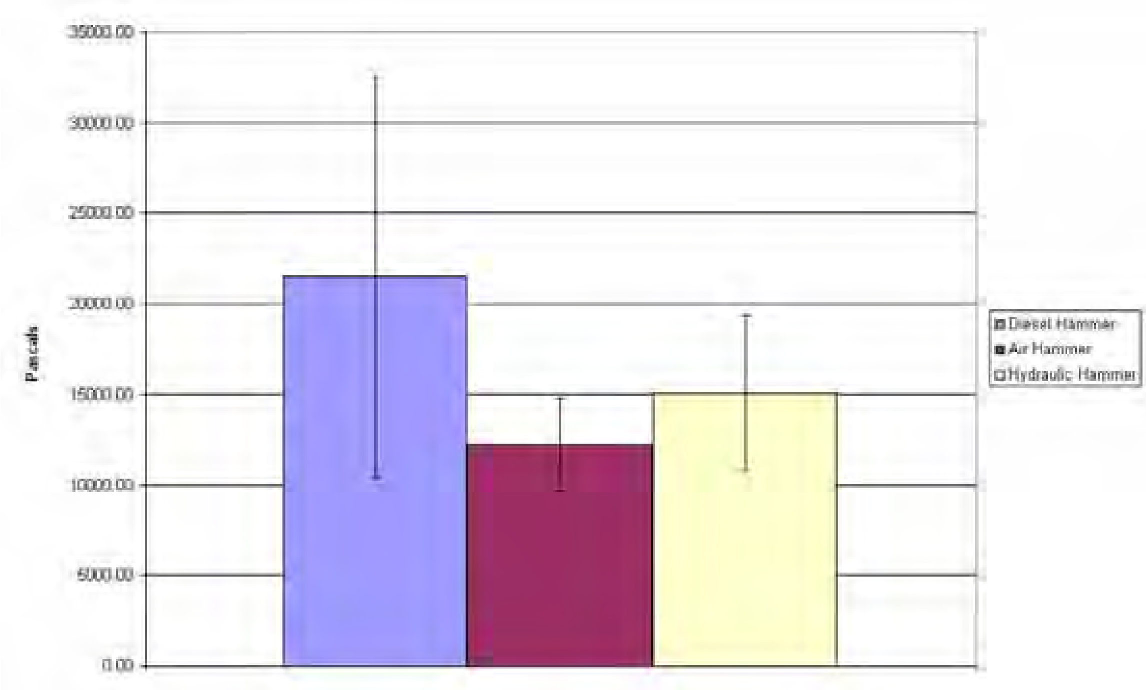


Figure 46. Average absolute peak midwater received values for each hammer type, all bubble rings off. Error bars are ± one standard deviation.

Average midwater received RMS values are shown in figure 47. The figure indicates that the diesel hammer had the highest RMS values. However, because of the large degree of variability between the samples there is no substantial difference between the three hammer types for RMS.

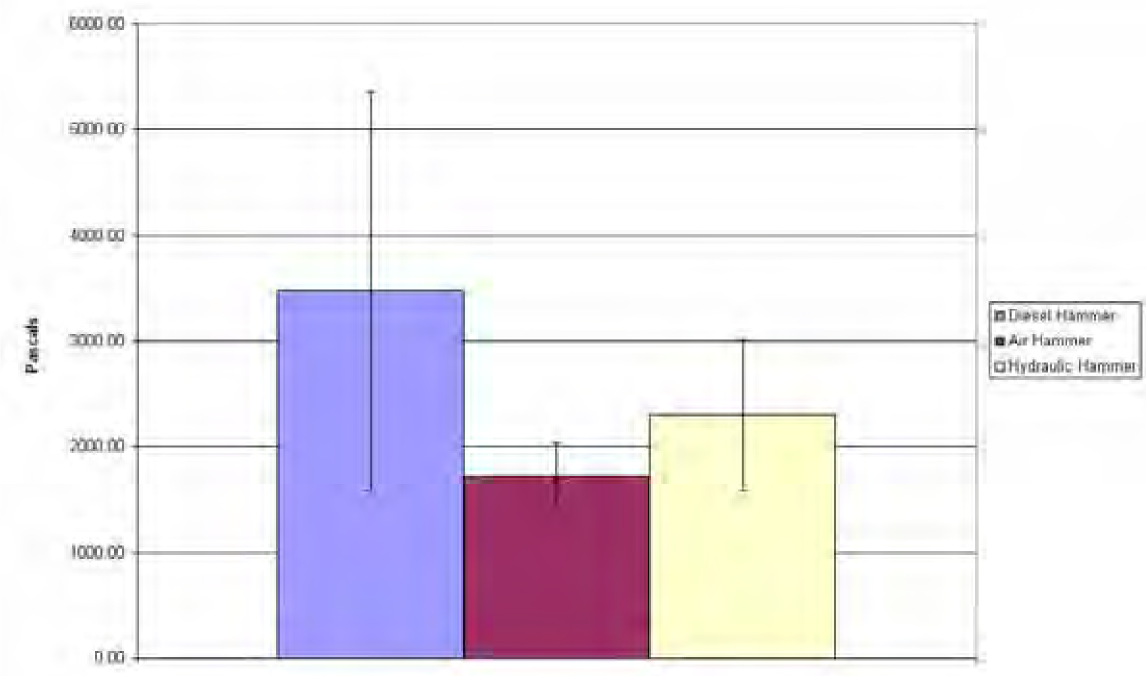


Figure 47. Average RMS midwater received values for each hammer type, all bubble rings off. Error bars are ± one standard deviation

Average midwater received SEL values shown in Figure 48 indicate that the diesel hammer had the highest SEL values. Again due to the relatively small sample size and the high degree of variability between values there is no substantial difference between the three hammer types for SEL.

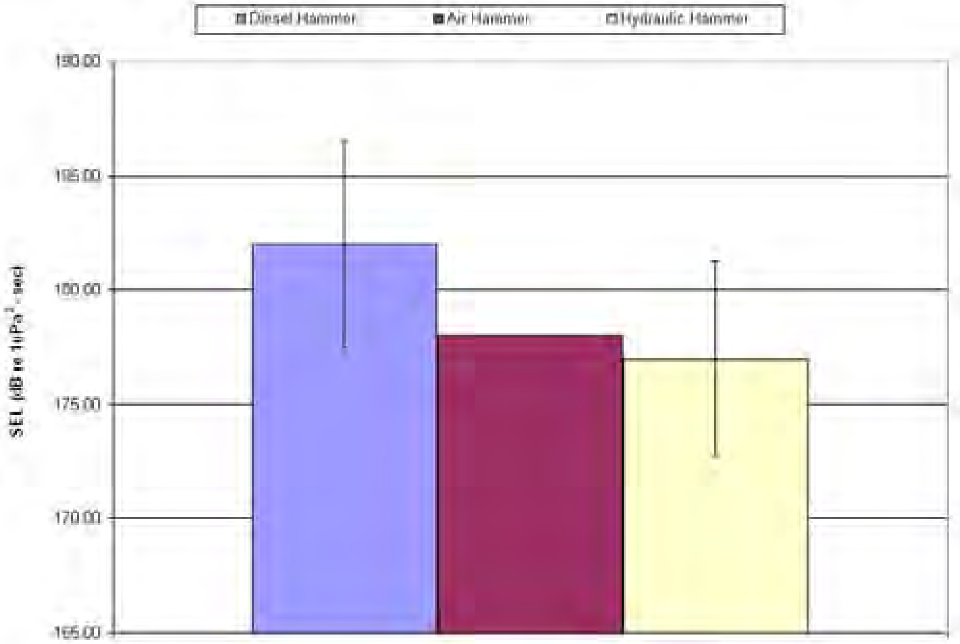


Figure 48. SEL midwater received values for each hammer type, all bubble rings off. Error bars are ± one standard deviation. SEL for the air hammer represents only one sample.

Looking at the individual peak waveforms in the appendix for the various hammer types there appears to be some differences. As the figures for the diesel hammer in the appendix indicate, the waveforms are typical of those we have seen for diesel hammers (piles 1, 4, 5, 7, and 8). The exception being the waveforms for piles 4 and 5. These latter two piles were driven into solid rock and the waveforms indicate a very sharp initial underpressure followed very rapidly by a shift to a very high overpressure. This is similar to what we see for hydraulic hammer waveforms. The SEL plots for the diesel hammers in Appendix A indicate a relatively moderate rise time and a fairly stable SEL between piles.

The waveform plots for the air hammer was similar to those seen for diesel hammers (pile 2). The rise times for the air hammer were generally higher than for the diesel or hydraulic hammer. This can be seen in the Pile 2 waveform plots in Appendix A where the waveforms appear more stretched out over time and the SEL plots indicate a moderate rise time.

The hydraulic hammer appeared to have a more explosive strike with the absolute peak at the front of the waveform. In other words the initial shock of the pile strike for the hydraulic hammer appeared more severe than that for the diesel or air hammers. The hydraulic hammer waveform plots in Appendix A (piles 3 and 6) indicate an initial steep underpressure followed by a rapid fluctuation to a sharp overpressure. In many cases a secondary peak was seen indicating a ringing of the pile. The SEL plots for hydraulic hammers indicate a relatively sharp rise time

Based on these results it appears that the hammer type may have no substantial influence on the peak, RMS, or SEL values. They also appear to not cause or contribute to the exceedence of the proposed threshold from Hastings and Popper (2005).

Underwater Ambient Noise Levels (No Construction Activity)

Ambient underwater sound levels were measured after construction activity had ceased for the day as well as during construction activity between pile drives. Ambient underwater noise levels with no construction activity ranged between 131 dB_{peak} and 136 dB_{peak}. With construction activity the ambient underwater noise levels ranged between 133 dB_{peak} and 140 dB_{peak}. This is comparable to what has been measured in other areas of Puget Sound with human activity.

AIRBORNE SOUND LEVELS

Airborne sound levels were measured with a standard airborne free field microphone. The microphone was mounted on a tripod approximately 5 feet above the water surface. Figure 8 presents the waveform analysis results of the airborne sound level measurements. The peak sound level was 116 dB_{peak} re: 20 micropascals. The RMS value 112 dB re: 20 micropascal and the SEL value was 106 dB re: 20 micropascals. The rise time was moderate at 5.7 seconds.

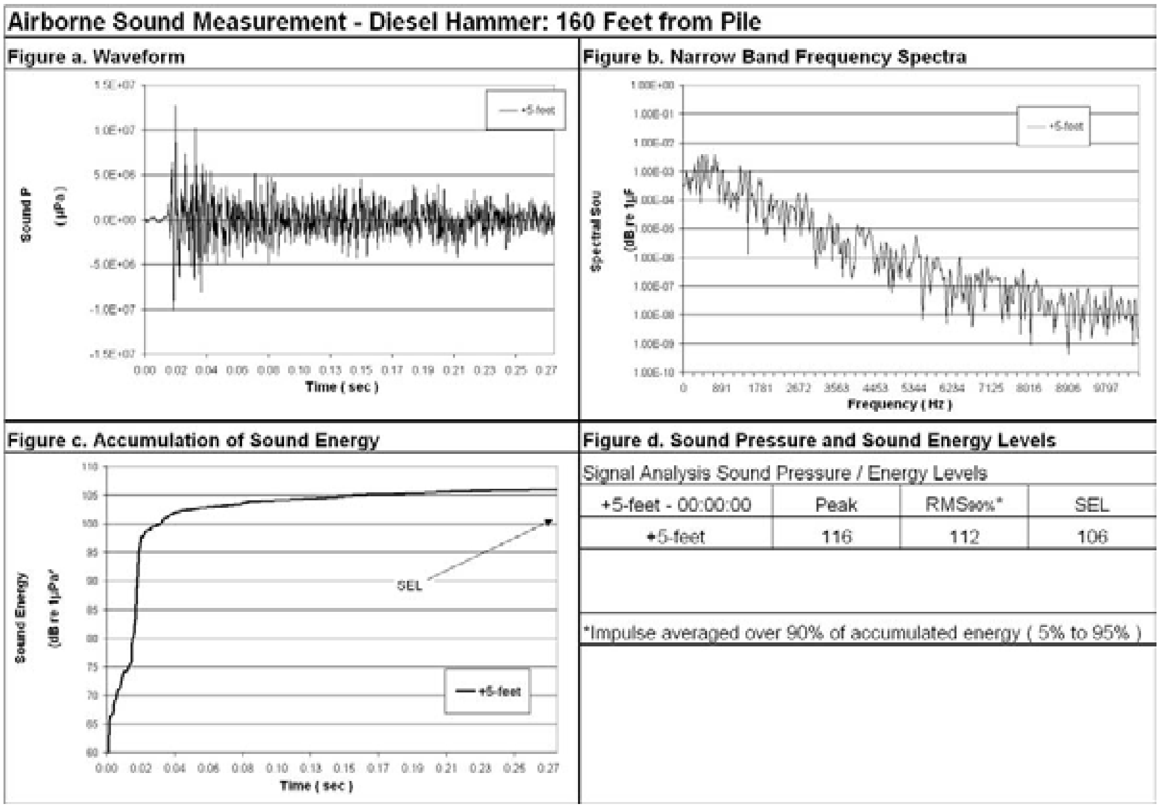


Figure 49: Airborne Sound Levels of a Diesel Pile Driver and Steel Pile , 160 feet from pile.

BIOLOGICAL OBSERVATIONS

A few pile perch were observed in the area around the pile driving activity in September. No fish mortality or distress was observed before, during, or after pile driving in September. No fish were observed in the immediate area around the pile driving activity in February and March. A few seagulls were observed in the area but not while pile driving was occurring. None of the seagulls were observed feeding on fish. One harbor seal was observed swimming through the project area on the second day but not during pile driving activity

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

These conclusions should be considered preliminary because the complete data set needed for a more complete analysis has not been assembled. This acoustical data should be analyzed with the dynamic pile driving data prior to drawing any definitive conclusions. This type of analysis is outside the scope of this report. In addition, some consideration of statistical analysis models for the data is needed to more fully utilize the data and to help direct future efforts to understand and evaluate bubble curtain performance.

That being said, what we did find was that out of eight piles that had the bottom ring only on seven had significantly lower absolute peak and RMS levels when compared to the bubbles off condition. The all rings on full condition was significantly less in only four out of eight piles and some were significantly greater. Even though the bubble curtain appeared to be deployed in the same way and we must assume it was functioning as designed, it did not reduce sound levels as effectively in February and March as it did in September. Therefore, it appears that use of more than just the bottom ring of the bubble curtain is not cost effective.

Use of more than just one ring on the bottom of the pile to mitigate noise levels from pile driving increases rise time in those instances when not driving into solid rock. The use of one ring can also decrease SEL in some cases. The importance of these factors in protecting fish appears to be significant according to Hastings and Popper (2005) and Reyff (2002). Whether the changes in rise time and SEL outweigh the reasonable cost of providing the mitigation is still open to debate.

It is recommended that future pile driving projects using open-ended steel piles use only one bubble ring on the bottom because of the only slight advantage of increased rise time that additional rings provide. If future research indicates that rise time is more important than it is currently thought to be, then more weight might be given to using more than one ring in a bubble curtain.

REFERENCES

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Zar, J.H., 1984. Biostatistical analysis (2^{nd} ed.). Englewood Cliffs, NJ: Prentice Hall.

APPENDIX A– WAVEFORM ANALYSIS FIGURES

SEPTEMBER BUBBLE CURTAIN TEST

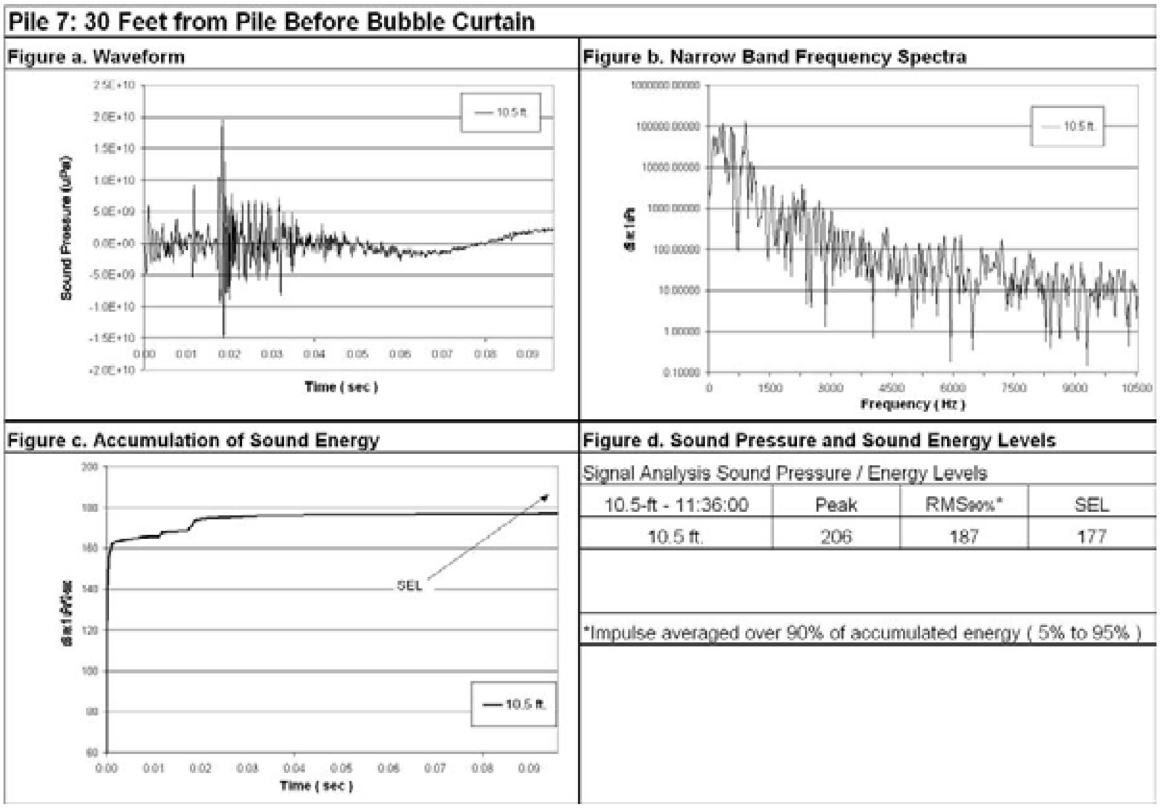


Figure 50: Results of Sound Pressure Levels without Bubble Curtain

In September of 2004 the newly designed bubble curtain system was tested on 24-inch steel piles and a diesel hammer. Results indicated that with the bubble curtain sound levels at the midwater hydrophone were reduced to 194 dB (re: 1 micropascal), RMS was 182 dB and the SEL was 171 dB. This was a 12 dB reduction in sound levels.

Sound levels for the hydrophone placed one foot from the bottom did not show any noticeable change in sound level. The reason for this difference between the two hydrophones is not clear, however, it could be that the bottom mounted hydrophone was measuring additional sound that was flanking through the sediment or was located in some unusual amplification node of sound reflected off of the various structures and bottom sediment in the area.

The waveform in Figure 45 indicates roughly a halving of the sound energy. The accumulation of sound energy in figure 44c indicate that without the bubble curtain the waveform has a much faster rise time than with the bubble curtain (figure 45c).

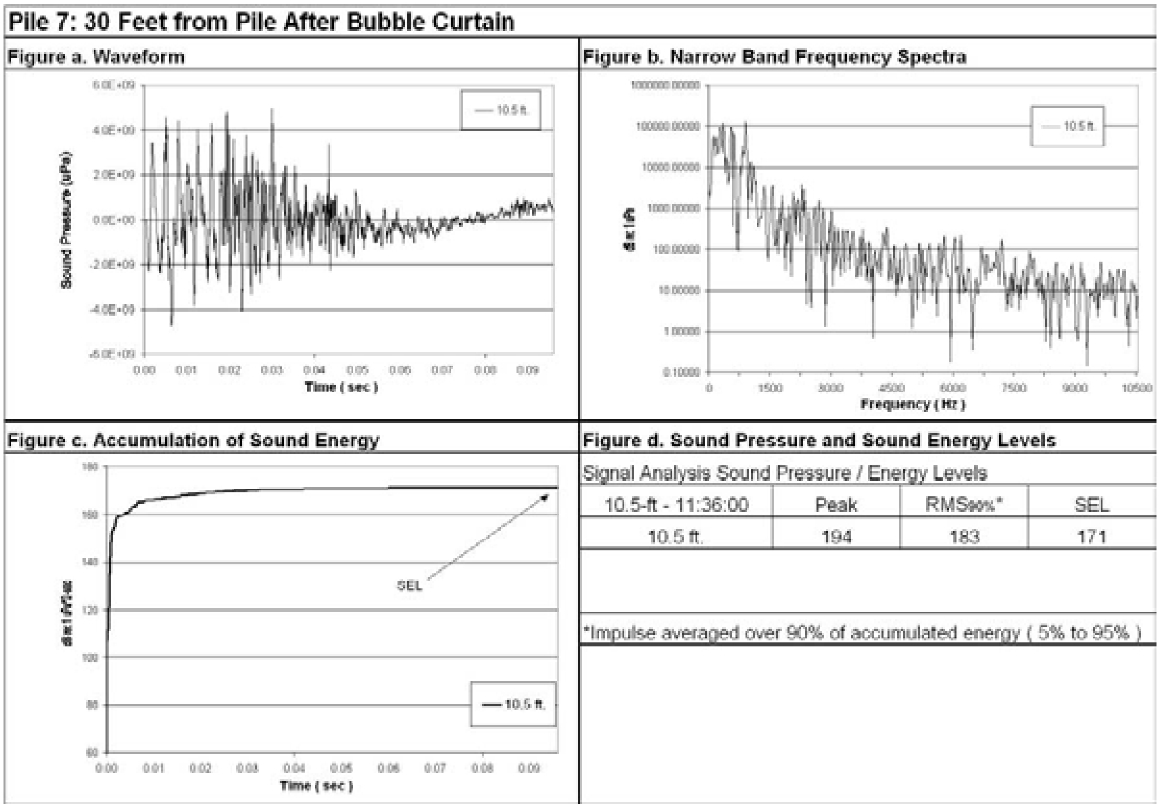


Figure 51: Results of Sound Pressure Levels with Bubble Curtain.

PILE 1 – DIESEL HAMMER

ALL RINGS OFF

Sound Pressure (µPa)

All Rings Off - Diesel Hammer: 33 Feet from Pile

Figure a. Waveform

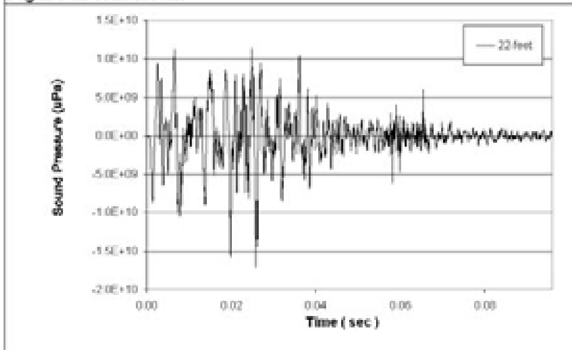


Figure b. Narrow Band Frequency Spectra

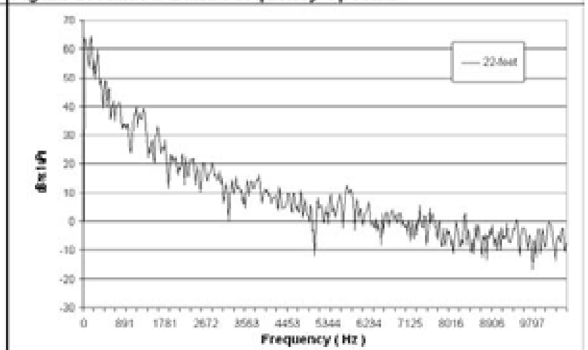


Figure c. Accumulation of Sound Energy

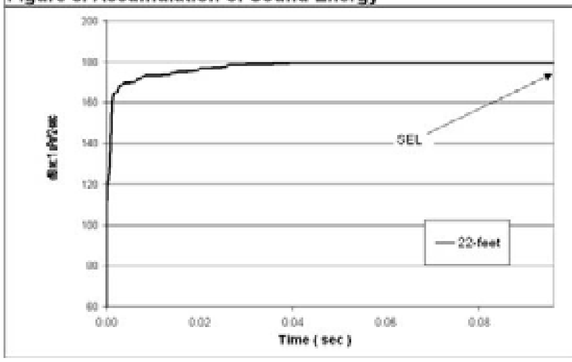


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

22-feet - 00:00:00	Peak	RMS90%*	SEL
22-feet	205	193	180

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

Figure 52: Waveform Analysis for Pile Number 1, 22-Feet Deep, 33-Feet from Pile, All Rings Off.

All Rings Off - Diesel Hammer: 33 Feet from Pile

Figure a. Waveform

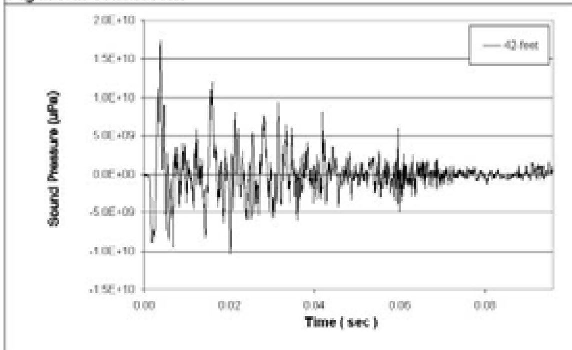


Figure b. Narrow Band Frequency Spectra

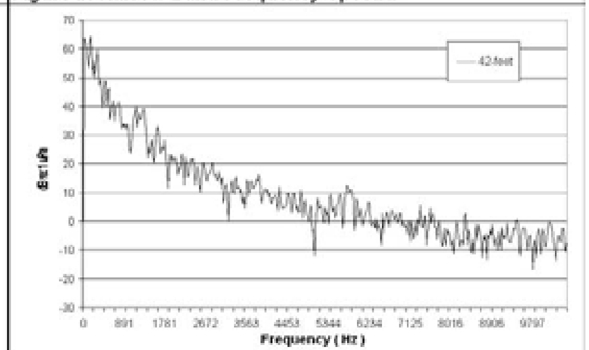


Figure c. Accumulation of Sound Energy

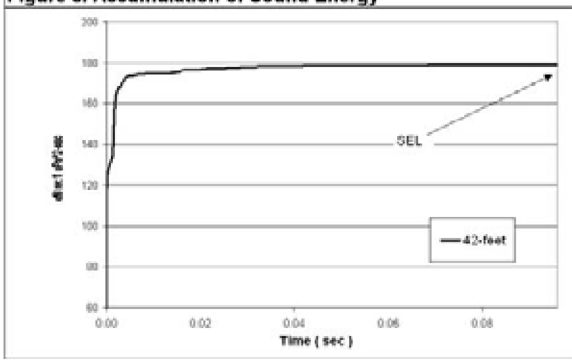


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

42-feet - 00:00:00	Peak	RMS90%*	SEL
42-feet	205	191	179

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

Figure 53: Waveform Analysis for Pile Number 1, 42-feet (Bottom), 33-Feet from Pile, All Rings Off.

BOTTOM RING ½ FLOW

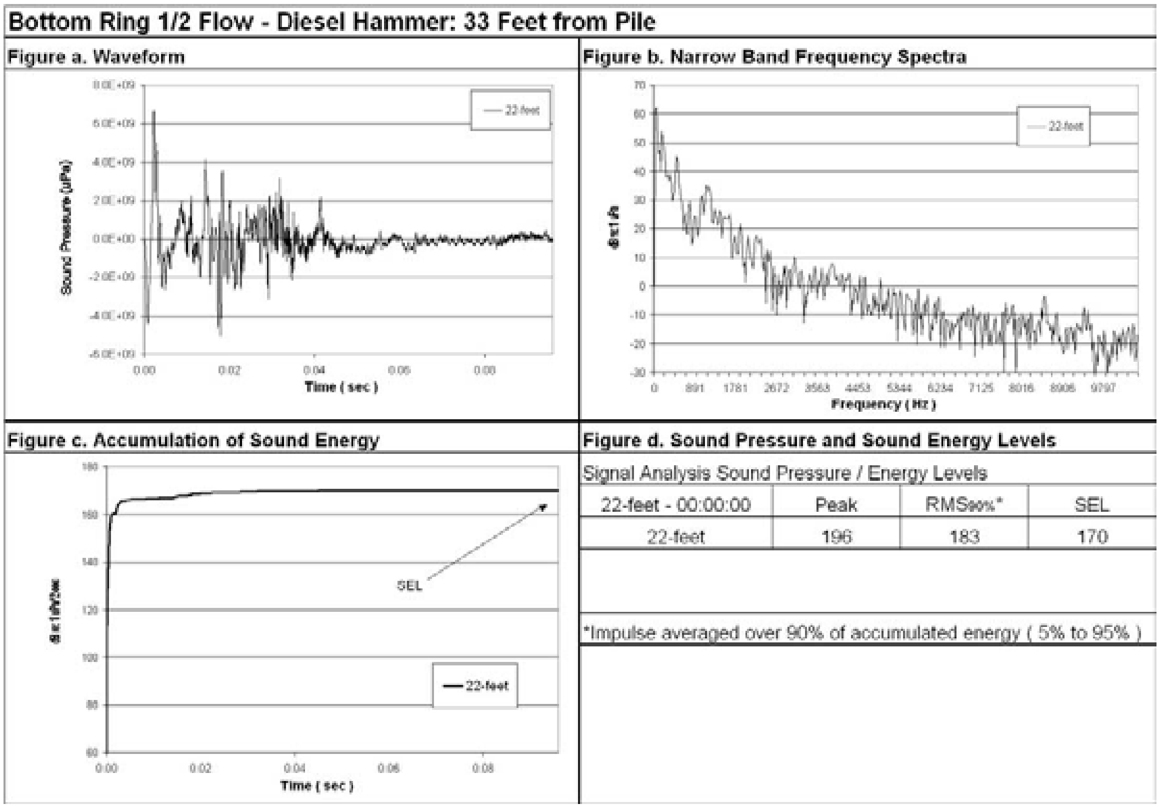


Figure 54: Waveform Analysis for Pile Number 1, 22-Feet Deep, 33-Feet from Pile, Bottom Ring ½ Flow.

Bottom Ring 1/2 Flow - Diesel Hammer: 33 Feet from Pile

Figure a. Waveform

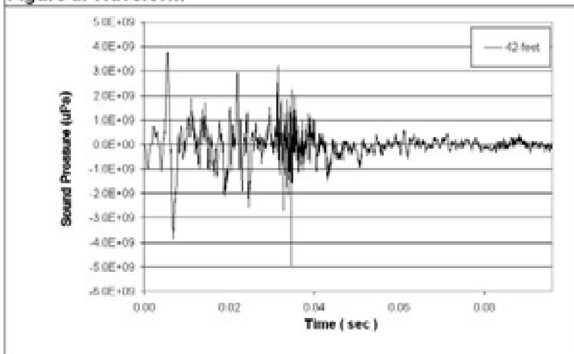


Figure b. Narrow Band Frequency Spectra

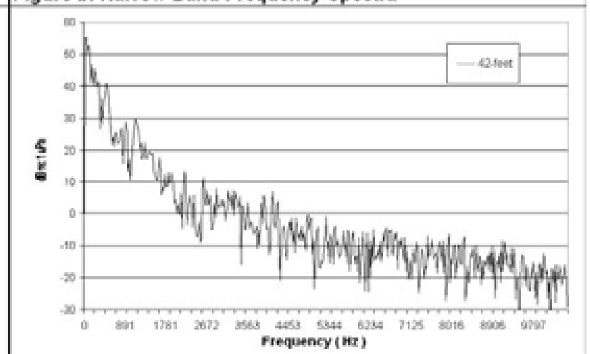


Figure c. Accumulation of Sound Energy

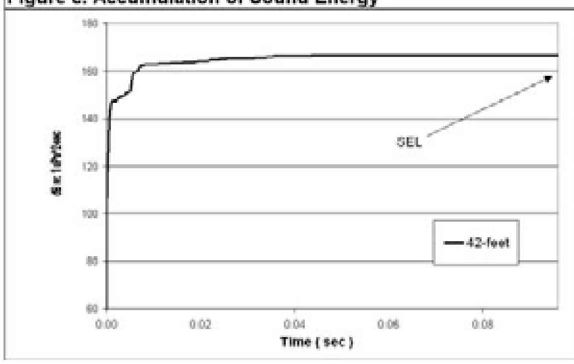


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

42-feet - 00:00:00	Peak	RMS90%*	SEL
42-feet	194	180	167

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

Figure 55: Waveform Analysis for Pile Number 1, 42-feet Deep (Bottom), 33-Feet from Pile, Bottom Ring ½ Flow.

BOTTOM AND MIDDLE RINGS AT ½ FLOW

Bottom & Middle Ring 1/2 Flow - Diesel Hammer: 33 Feet from Pile

Figure a. Waveform

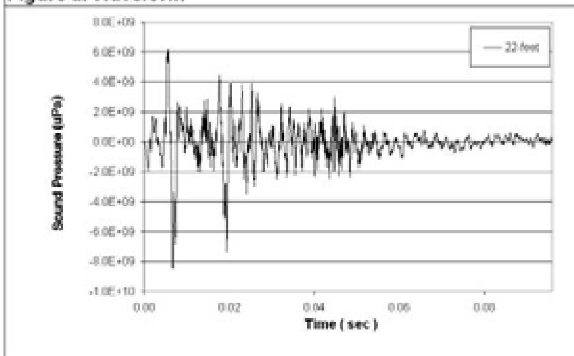


Figure b. Narrow Band Frequency Spectra

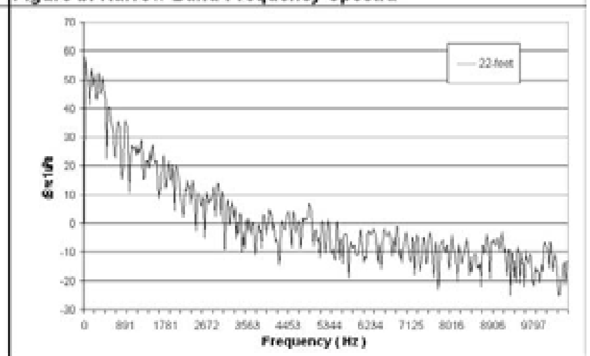


Figure c. Accumulation of Sound Energy

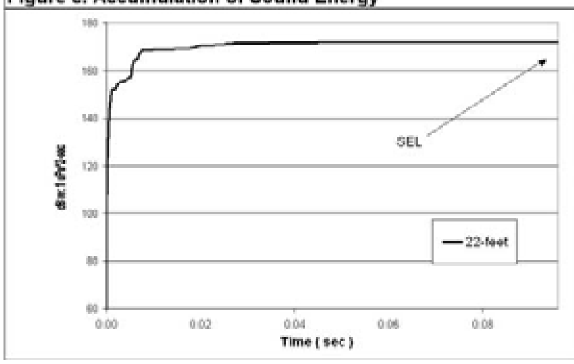


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

22-feet - 00:00:00	Peak	RMS90%*	SEL
22-feet	199	185	172

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

Figure 56: Waveform Analysis for Pile Number 1, 22-feet Deep, 33-Feet from Pile, Bottom and Middle Ring ½ Flow.

Bottom & Middle Ring 1/2 Flow - Diesel Hammer: 33 Feet from Pile

Figure a. Waveform | **Figure b. Narrow Band Frequency Spectra**

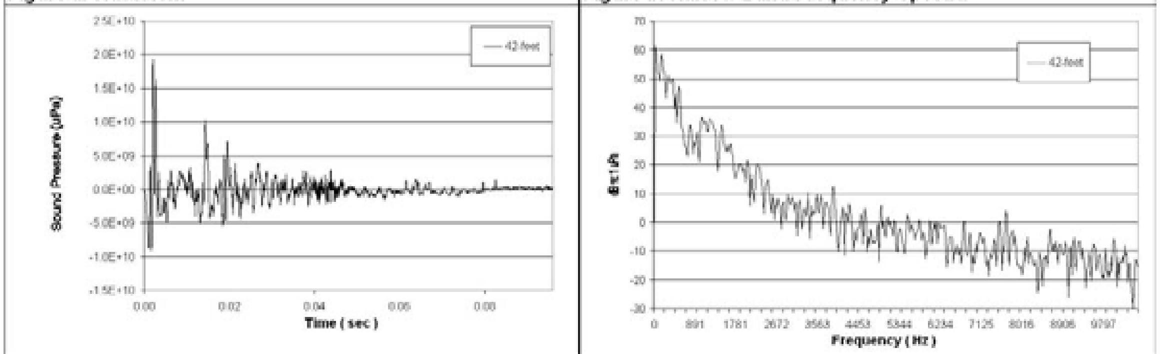


Figure c. Accumulation of Sound Energy

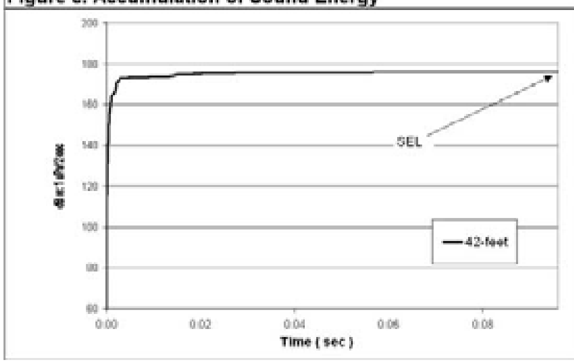


Figure d. Sound Pressure and Sound Energy Levels

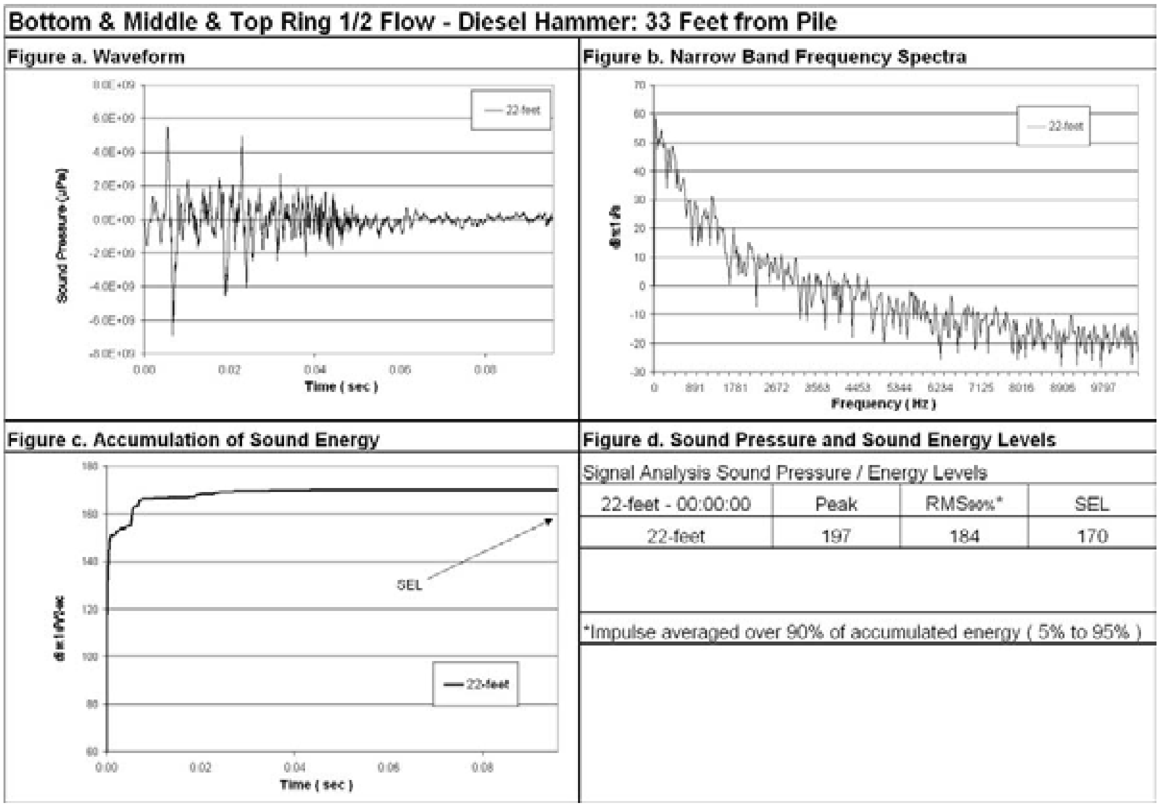
Signal Analysis Sound Pressure / Energy Levels

42-feet - 00:00:00	Peak	RMS90%*	SEL
42-feet	206	190	176

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

Figure 57: Waveform Analysis for Pile Number 1, 42-feet Deep (Bottom), 33-Feet from Pile, Bottom and Middle Ring ½ Flow.

BOTTOM, MIDDLE, AND TOP RINGS AT ½ FLOW



22-feet - 00:00:00	Peak	RMS90%*	SEL
22-feet	197	184	170

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

Figure 58 Waveform Analysis for Pile Number 1, 22-feet Deep, 33-Feet from Pile, Bottom, Middle, and Top Ring ½ Flow.

Bottom & Middle & Top Ring 1/2 Flow - Diesel Hammer: 33 Feet from Pile

Figure a. Waveform

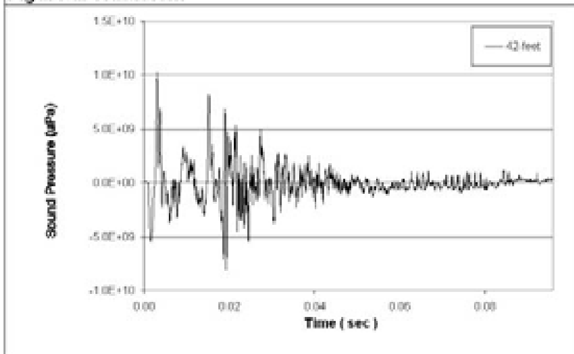


Figure b. Narrow Band Frequency Spectra

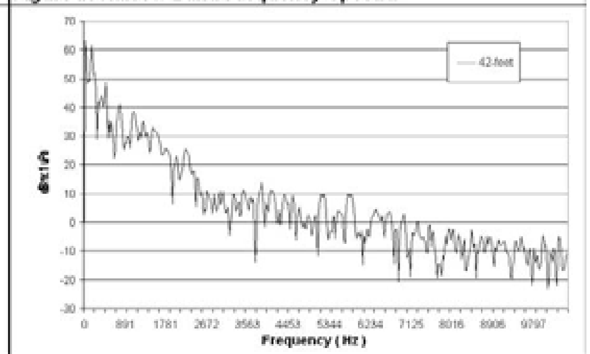


Figure c. Accumulation of Sound Energy

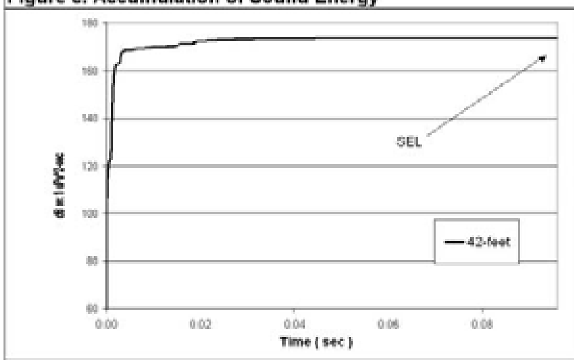


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

42-feet - 00:00:00	Peak	RMS90%*	SEL
42-feet	200	187	174

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

Figure 59 Waveform Analysis for Pile Number 1, 42-feet Deep (bottom), 33-Feet from Pile, Bottom, Middle, and Top Ring ½ Flow.

BOTTOM FULL FLOW, MIDDLE, AND TOP RINGS AT ½ FLOW

Bottom Full & Middle & Top Ring 1/2 Flow - Diesel Hammer: 33 Feet from Pile

Figure a. Waveform

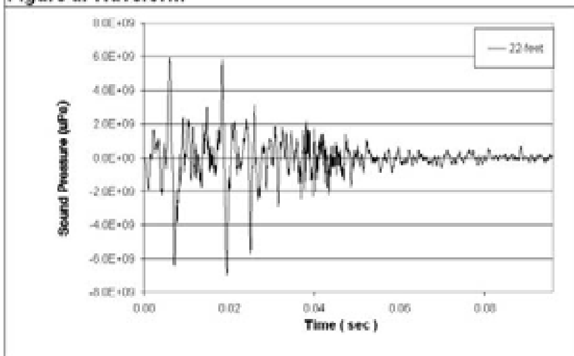


Figure b. Narrow Band Frequency Spectra

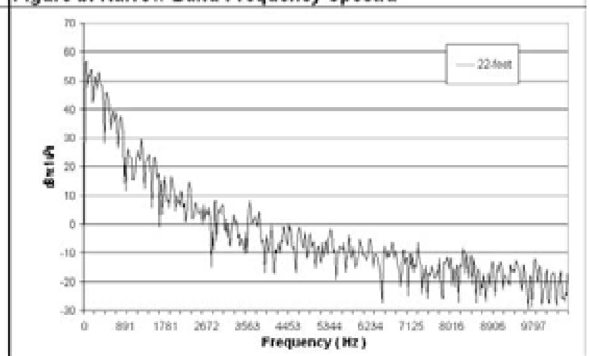


Figure c. Accumulation of Sound Energy

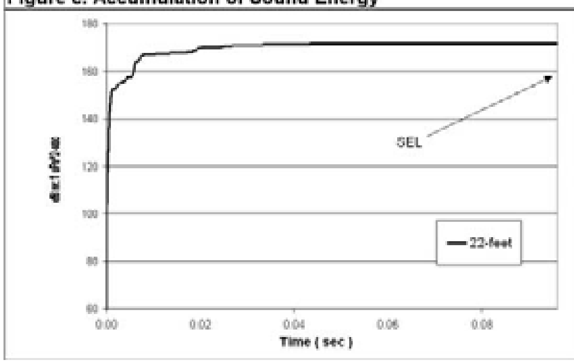


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

22-feet - 00:00:00	Peak	RMS90%*	SEL
22-feet	197	185	172

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

Figure 60 Waveform Analysis for Pile Number 1, 22-feet Deep, 33-Feet from Pile, Bottom Ring Full Flow, Middle, and Top Ring ½ Flow.

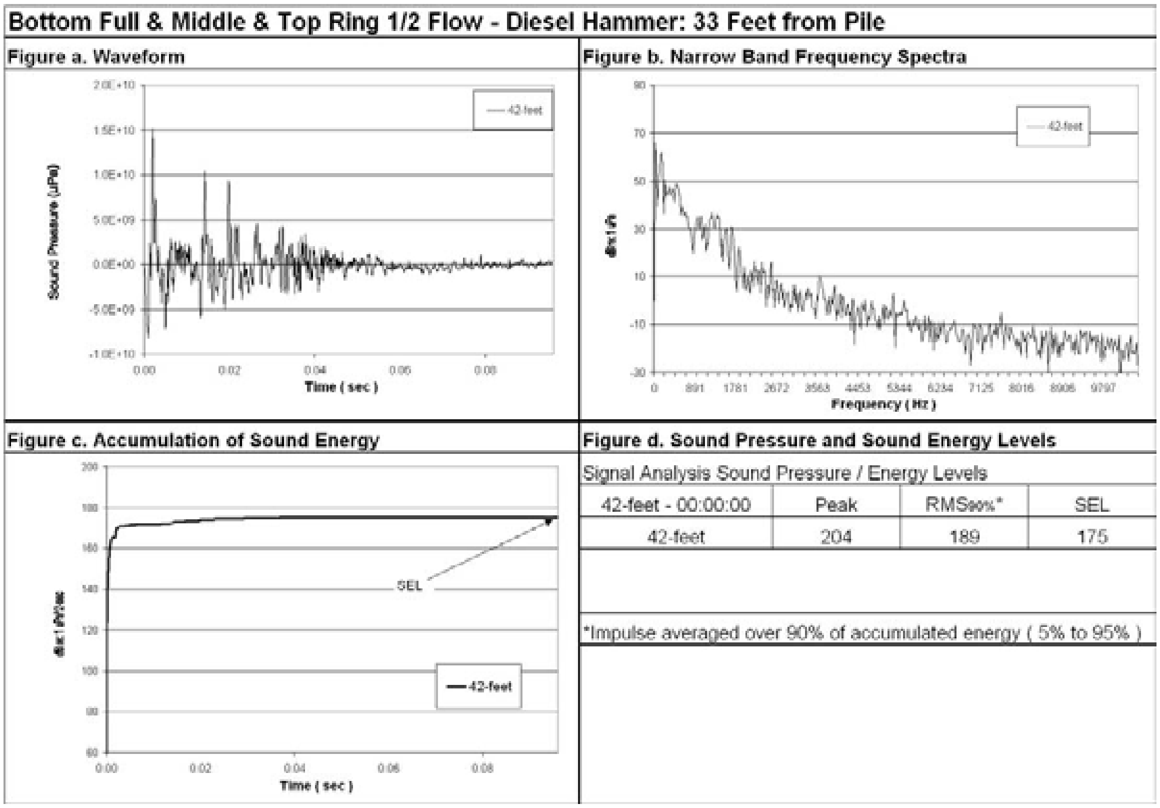


Figure 61 Waveform Analysis for Pile Number 1, 42-feet Deep (bottom), 33-Feet from Pile, Bottom Ring Full, Middle, and Top Ring ½ Flow.

BOTTOM AND MIDDLE FULL FLOW, TOP RING AT ½ FLOW

Bottom & Middle Full & Top Ring 1/2 Flow - Diesel Hammer: 33 Feet from Pile

Figure a. Waveform

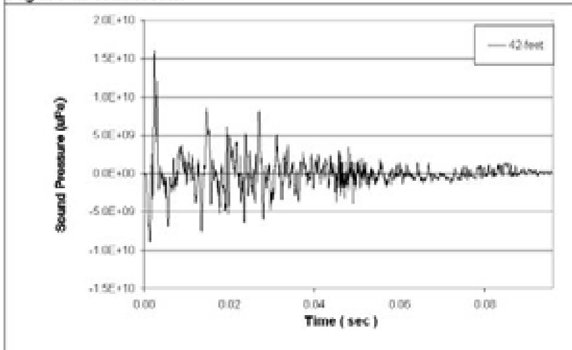


Figure b. Narrow Band Frequency Spectra

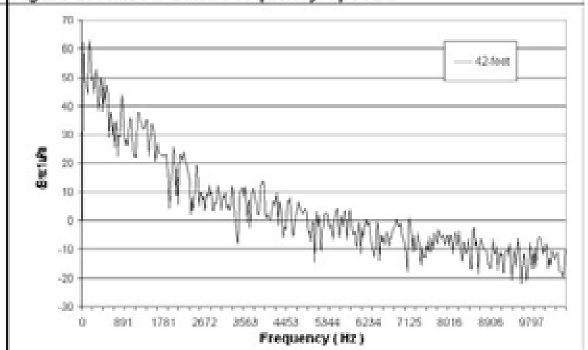


Figure c. Accumulation of Sound Energy

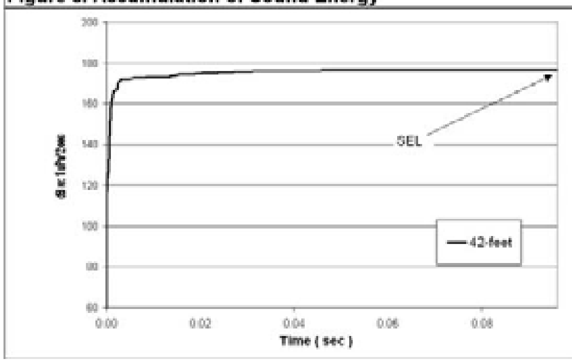


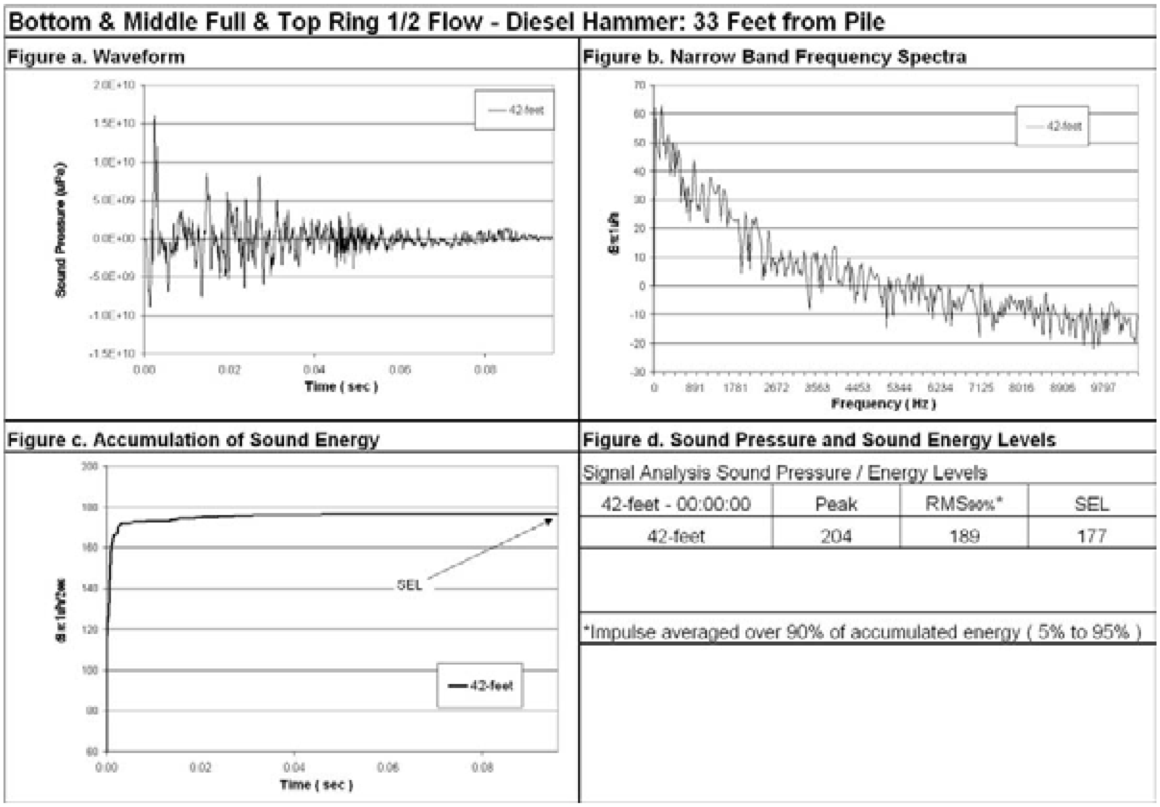
Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

42-feet - 00:00:00	Peak	RMS90%*	SEL
42-feet	204	189	177

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

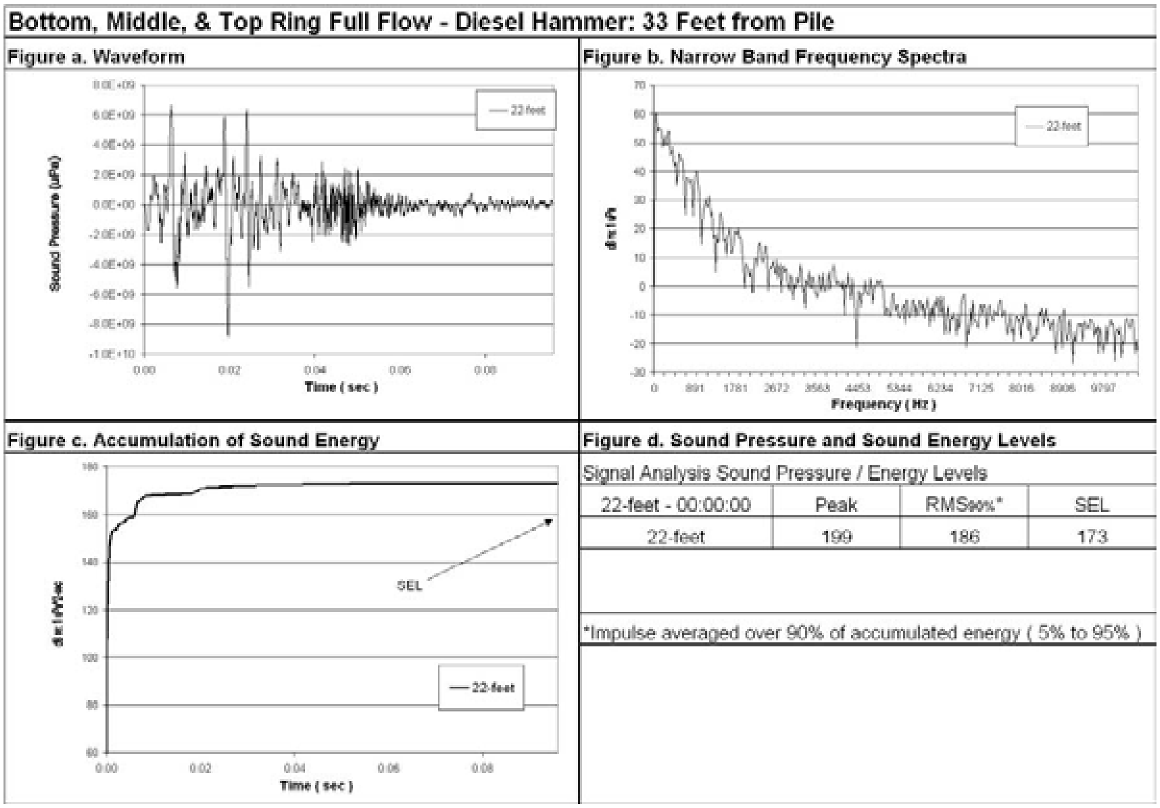
Figure 62 Waveform Analysis for Pile Number 1, 42-feet Deep (bottom), 33-Feet from Pile, Bottom Ring and Middle Full, Top Ring ½ Flow.



42-feet - 00:00:00	Peak	RMS90%*	SEL
42-feet	204	189	177

Figure 63 Waveform Analysis for Pile Number 1, 42-feet Deep (bottom), 33-Feet from Pile, Bottom and Middle Ring Full, Top Ring ½ Flow

BOTTOM, MIDDLE, AND TOP RING AT FULL FLOW



22-feet - 00:00:00	Peak	RMS90%*	SEL
22-feet	199	186	173

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

Figure 64 Waveform Analysis for Pile Number 1, 22-feet Deep, 33-Feet from Pile, Bottom Ring, Middle, and Top Ring Full Flow

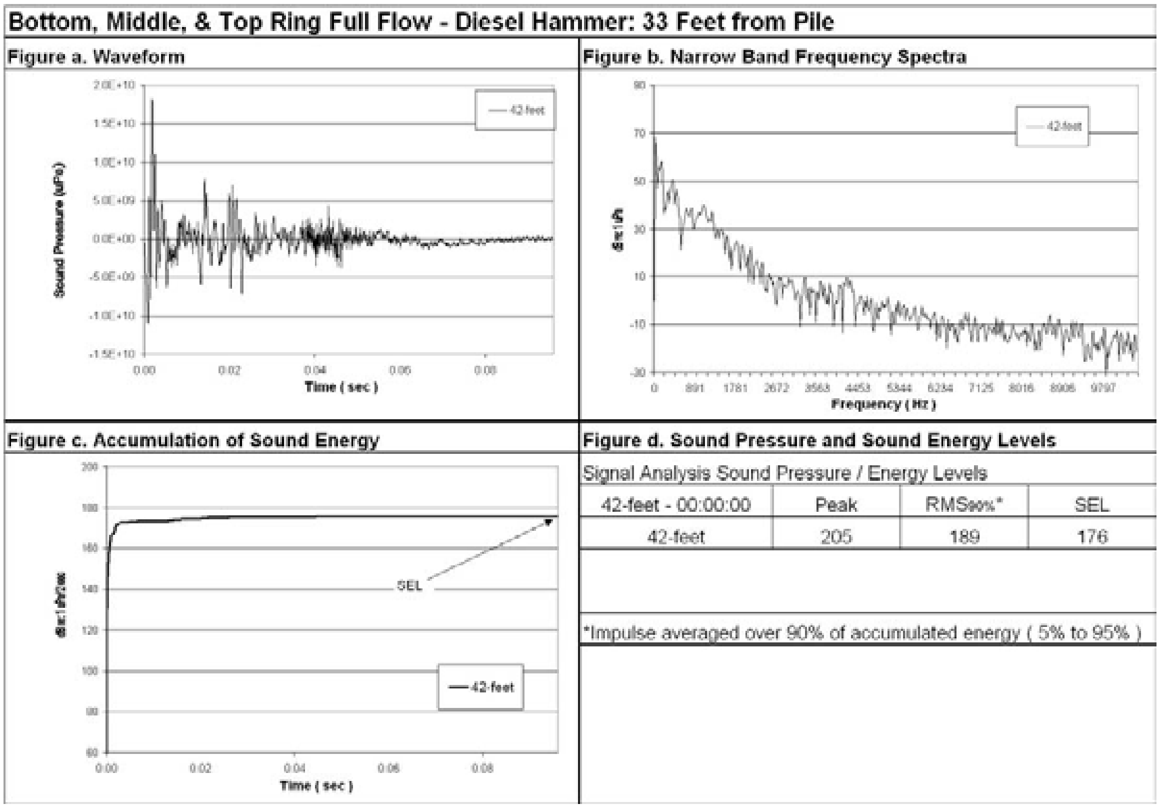


Figure 65 Waveform Analysis for Pile Number 1, 42-feet Deep (bottom), 33-Feet from Pile, Bottom, Middle, and Top Ring Full Flow

ALL RINGS OFF (FINAL)

All Rings Off (Final) - Diesel Hammer: 33 Feet from Pile

Figure a. Waveform

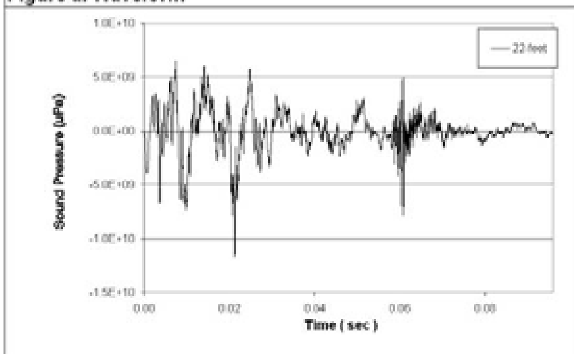


Figure b. Narrow Band Frequency Spectra

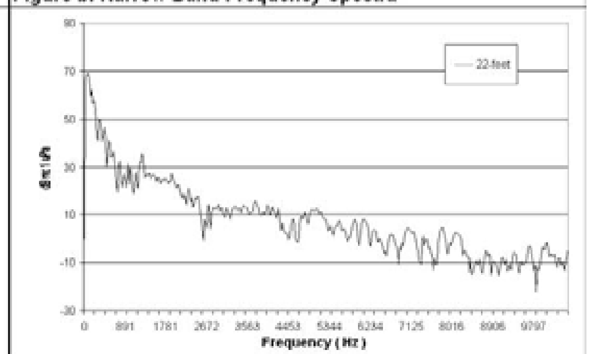


Figure c. Accumulation of Sound Energy

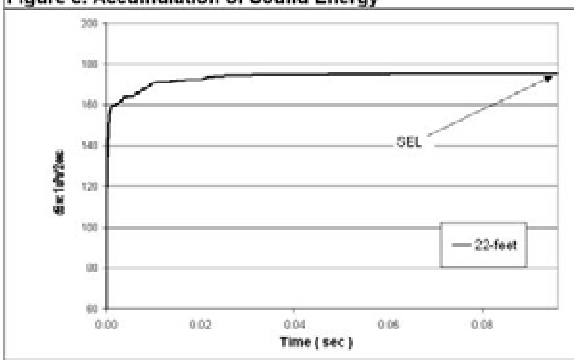


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

22-feet - 00:00:00	Peak	RMS90%*	SEL
22-feet	201	187	176

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

Figure 66 Waveform Analysis for Pile Number 1, 22-feet Deep, 33-Feet from Pile, All Rings Off (Final).

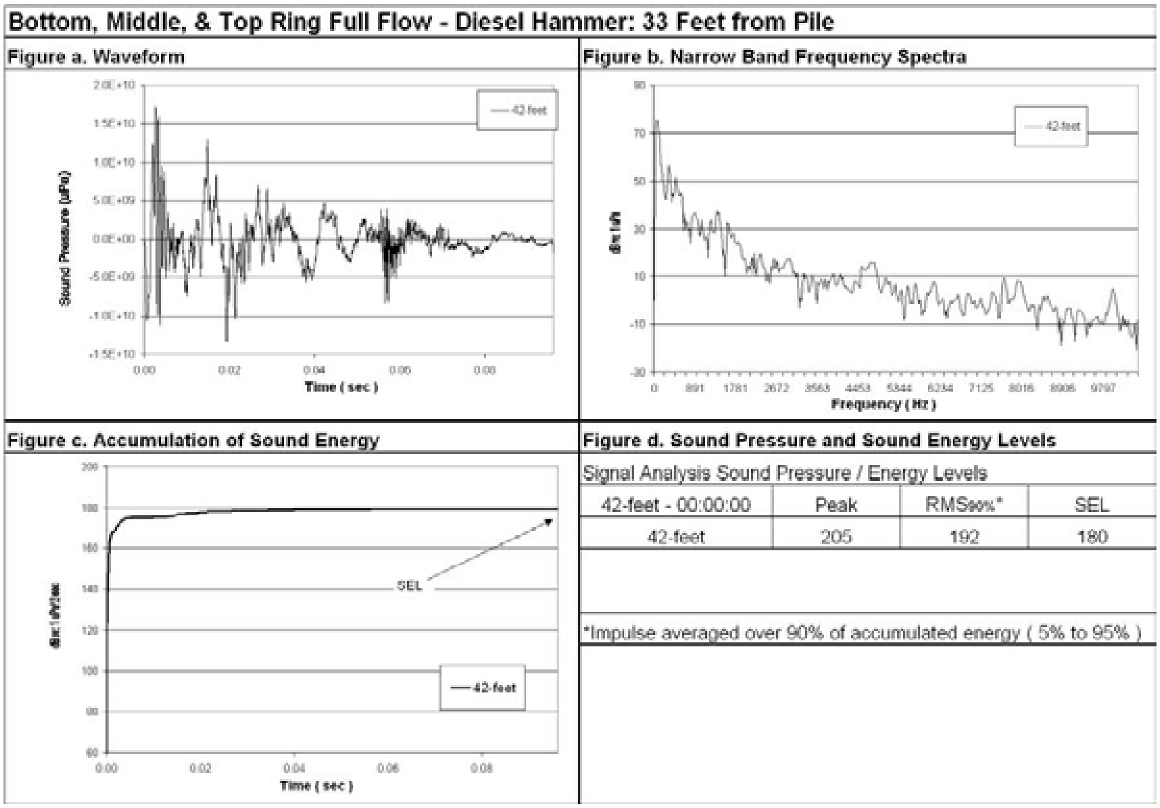


Figure 67 Waveform Analysis for Pile Number 1, 42-feet Deep (bottom), 33-Feet from Pile, All Rings Off (Final).

PILE 2 – AIR HAMMER

BUBBLE CURTAIN OFF

All rings off (initial) - Air Hammer: 33 Feet from Pile

Figure a. Waveform

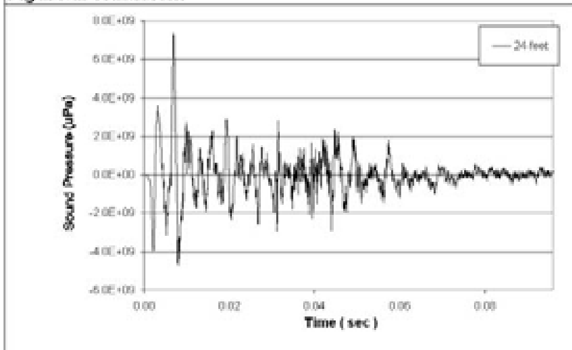


Figure b. Narrow Band Frequency Spectra

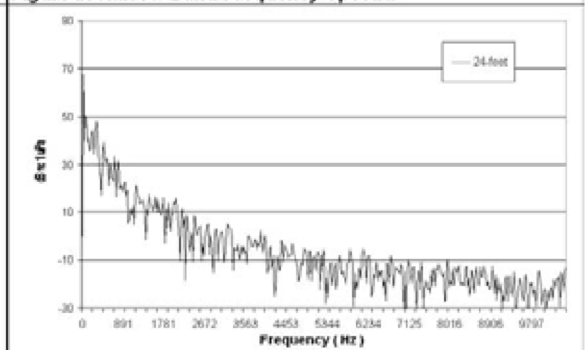


Figure c. Accumulation of Sound Energy

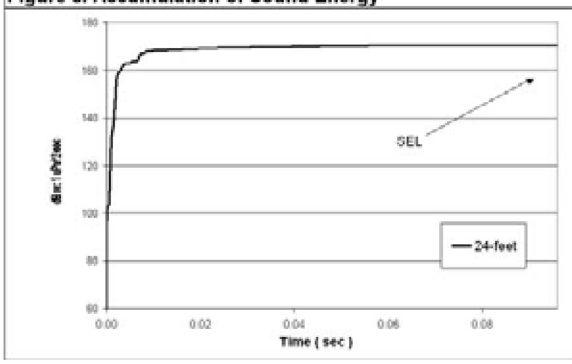


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

24-feet - 00:00:00	Peak	RMS90%*	SEL
24-feet	197	183	171

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

Figure 68: Waveform Analysis for Pile Number 2, 24-Feet Deep, 33-Feet from Pile, All Rings Off.

All rings off (initial) - Air Hammer: 33 Feet from Pile

Figure a. Waveform

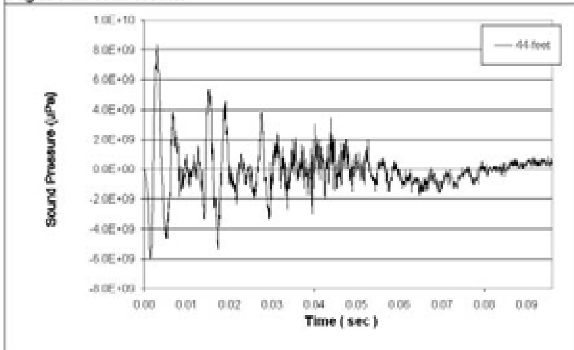


Figure b. Narrow Band Frequency Spectra

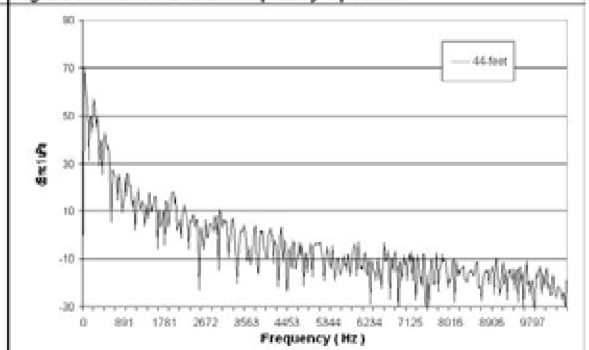


Figure c. Accumulation of Sound Energy

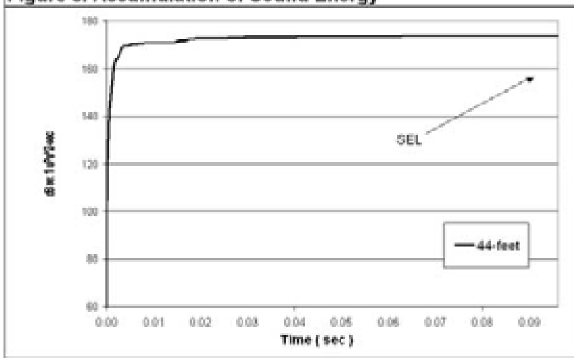


Figure d. Sound Pressure and Sound Energy Levels

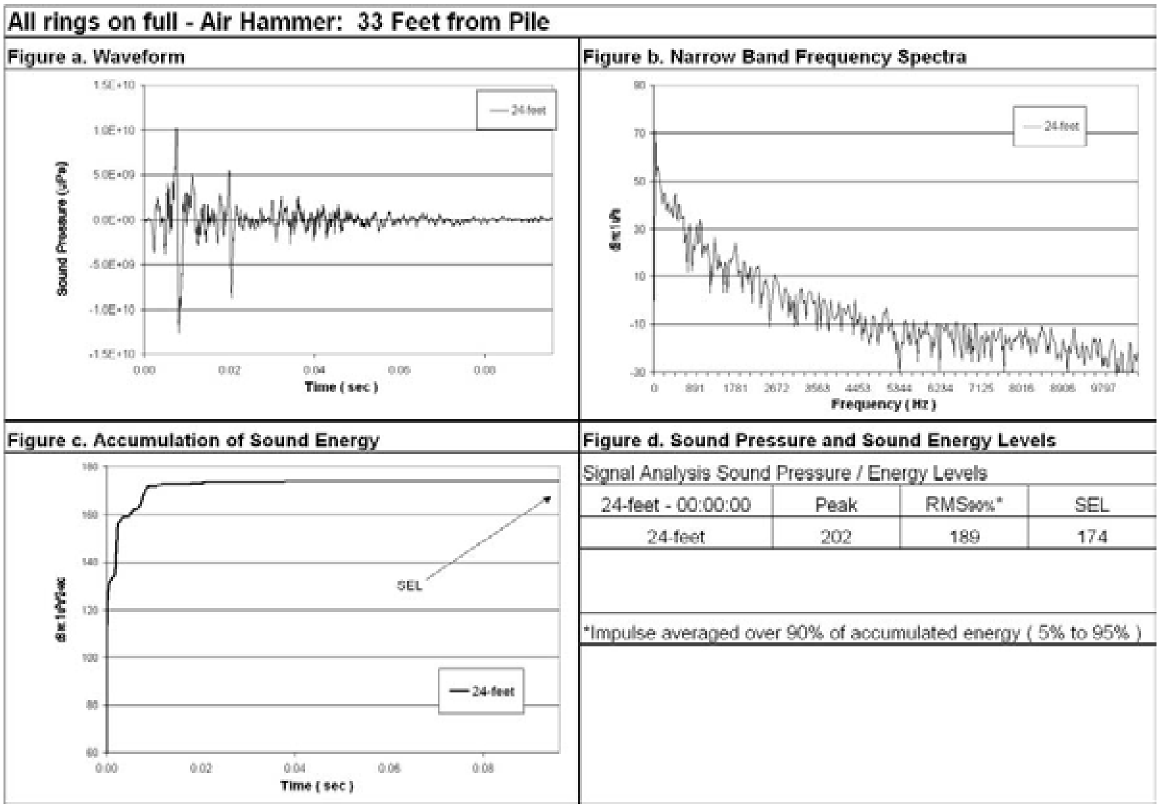
Signal Analysis Sound Pressure / Energy Levels

44-feet - 00:00:00	Peak	RMS90%*	SEL
44-feet	198	185	174

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

Figure 69: Waveform Analysis for Pile Number 2, 44-Feet Deep (bottom), 33-Feet from Pile, All Rings Off.

BOTTOM RING ON FULL



24-feet - 00:00:00	Peak	RMS90%*	SEL
24-feet	202	189	174

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

Figure 70 Waveform Analysis for Pile Number 2, 24-Feet Deep, 33-Feet from Pile, Bottom Ring On Full.

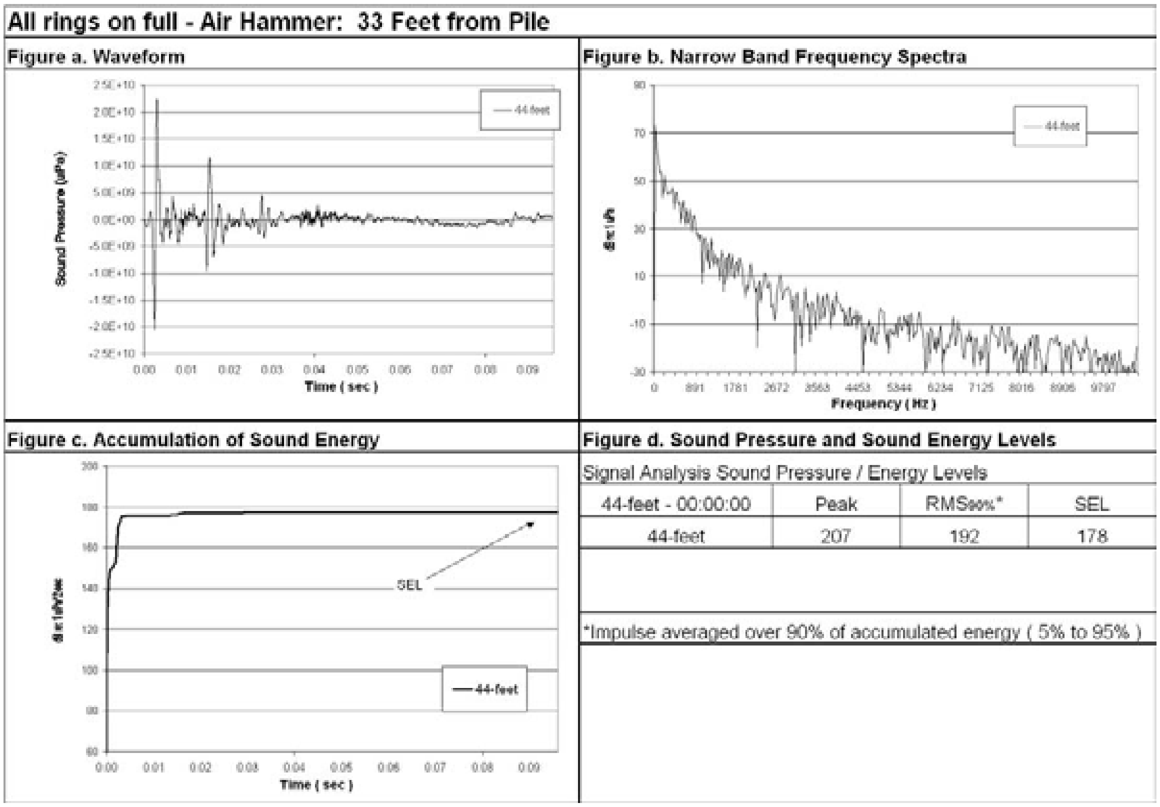


Figure 71 Waveform Analysis for Pile Number 2, 44-Feet Deep (bottom), 33-Feet from Pile, Bottom Ring On Full.

ALL RINGS ON FULL

All rings on full - Air Hammer: 33 Feet from Pile

Figure a. Waveform

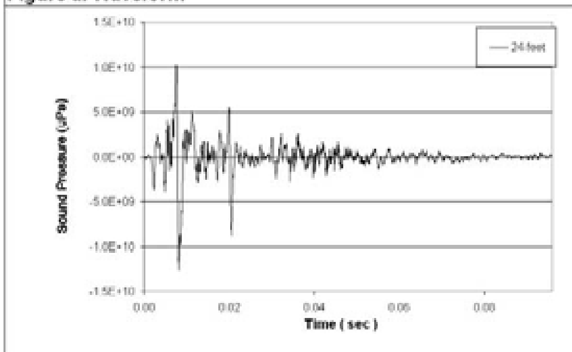


Figure b. Narrow Band Frequency Spectra

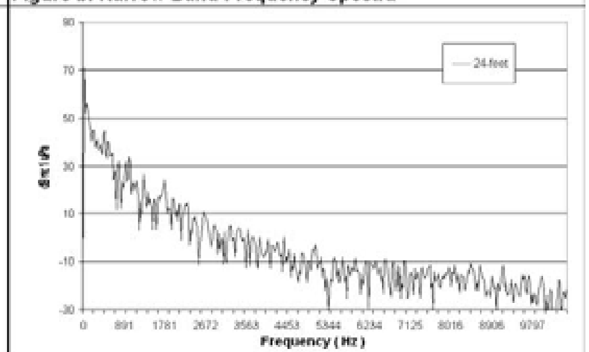


Figure c. Accumulation of Sound Energy

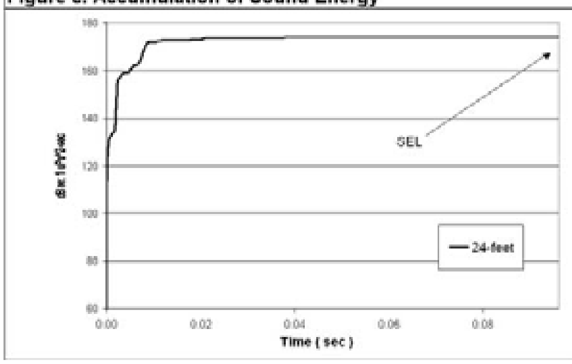


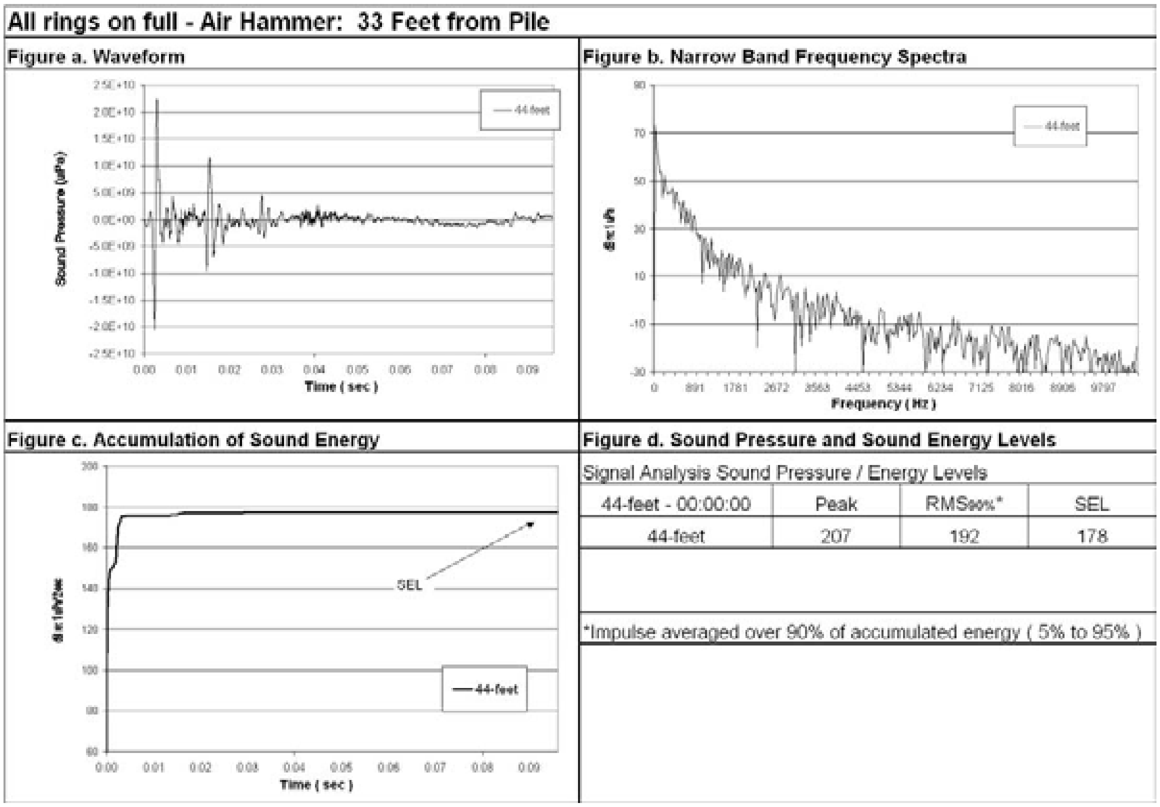
Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

24-feet - 00:00:00	Peak	RMS90%*	SEL
24-feet	202	189	174

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

Figure 72 Waveform Analysis for Pile Number 2, 24-Feet Deep, 33-Feet from Pile, All Rings On Full.



44-feet - 00:00:00	Peak	RMS90%*	SEL
44-feet	207	192	178

Figure 73 Waveform Analysis for Pile Number 2, 44-Feet Deep (Bottom), 33-Feet from Pile, All Rings On Full.

ALL RINGS OFF(FINAL)

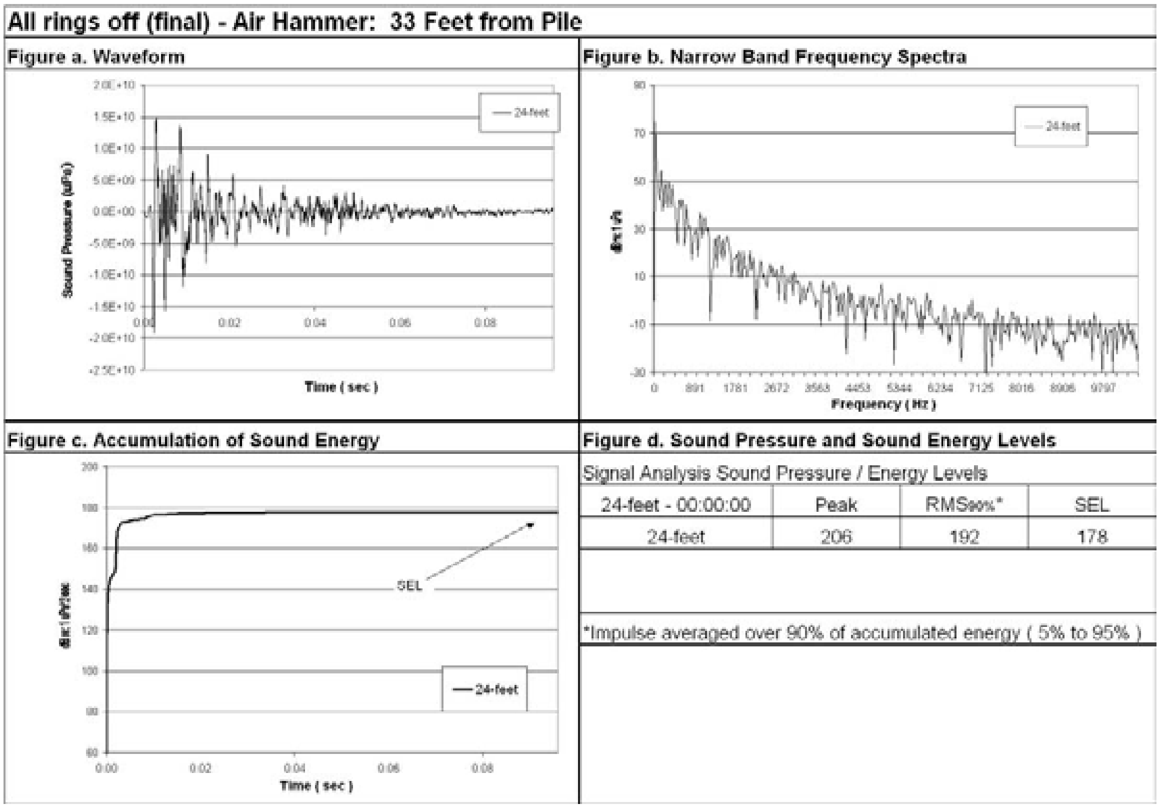


Figure 74 Waveform Analysis for Pile Number 2, 24-Feet Deep, 33-Feet from Pile, All Rings Off (Final).

All rings off (final)- Air Hammer: 33 Feet from Pile

Figure a. Waveform

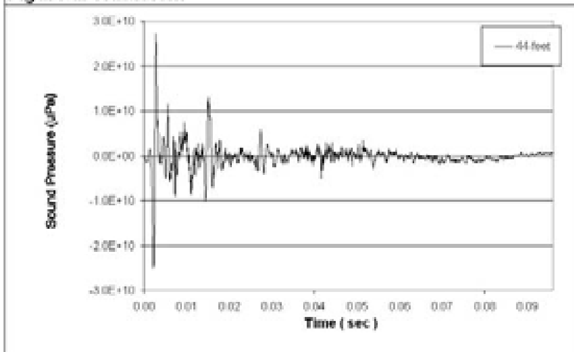


Figure b. Narrow Band Frequency Spectra

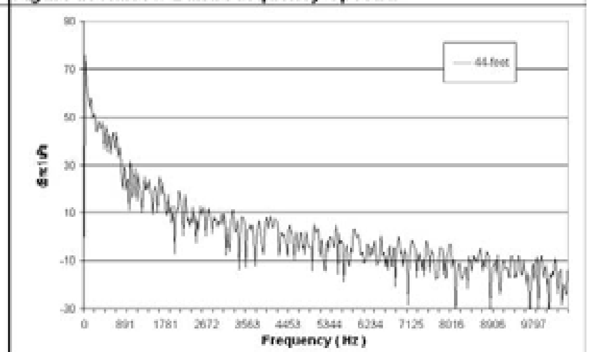


Figure c. Accumulation of Sound Energy

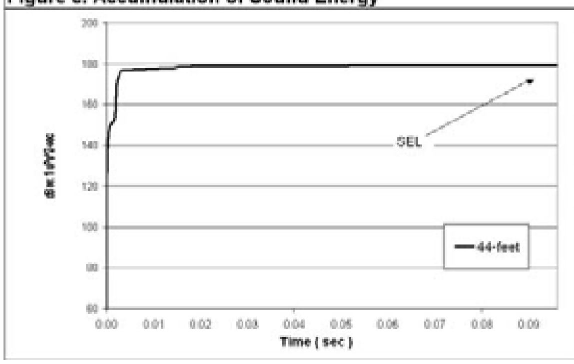


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

44-feet - 00:00:00	Peak	RMS90%*	SEL
44-feet	209	193	179

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

Figure 75 Waveform Analysis for Pile Number 2, 44-Feet Deep (Bottom), 33-Feet from Pile, All Rings Off (Final).

PILE 3 – HYDRAULIC HAMMER

ALL RINGS OFF (INITIAL)

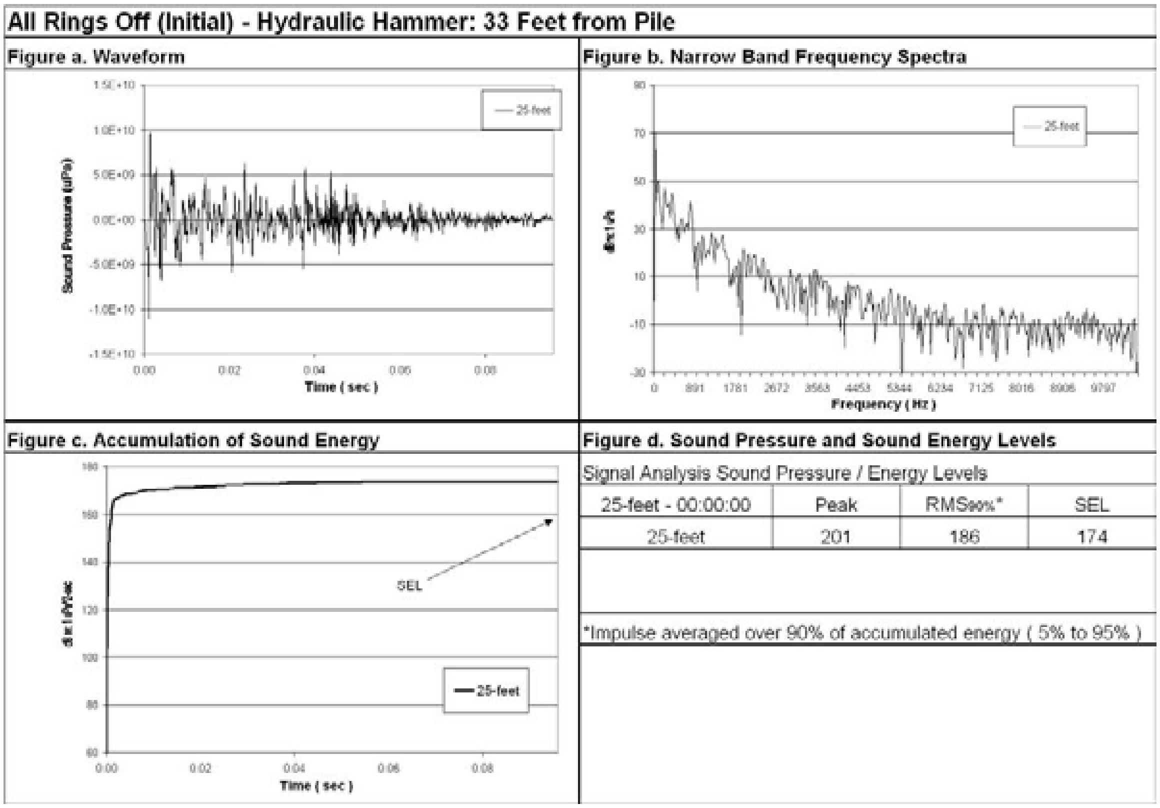
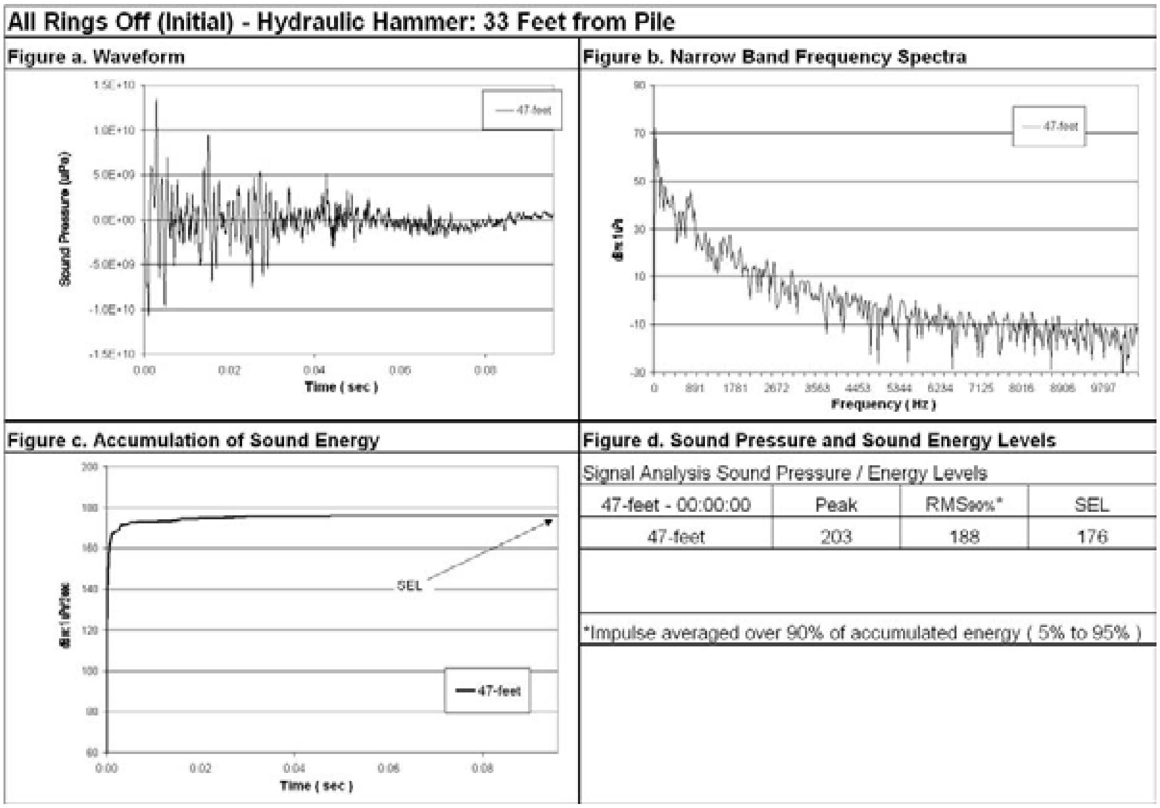


Figure 76 Waveform Analysis for Pile Number 3, 25-feet Deep, 33-Feet from Pile, All Rings Off (Initial).

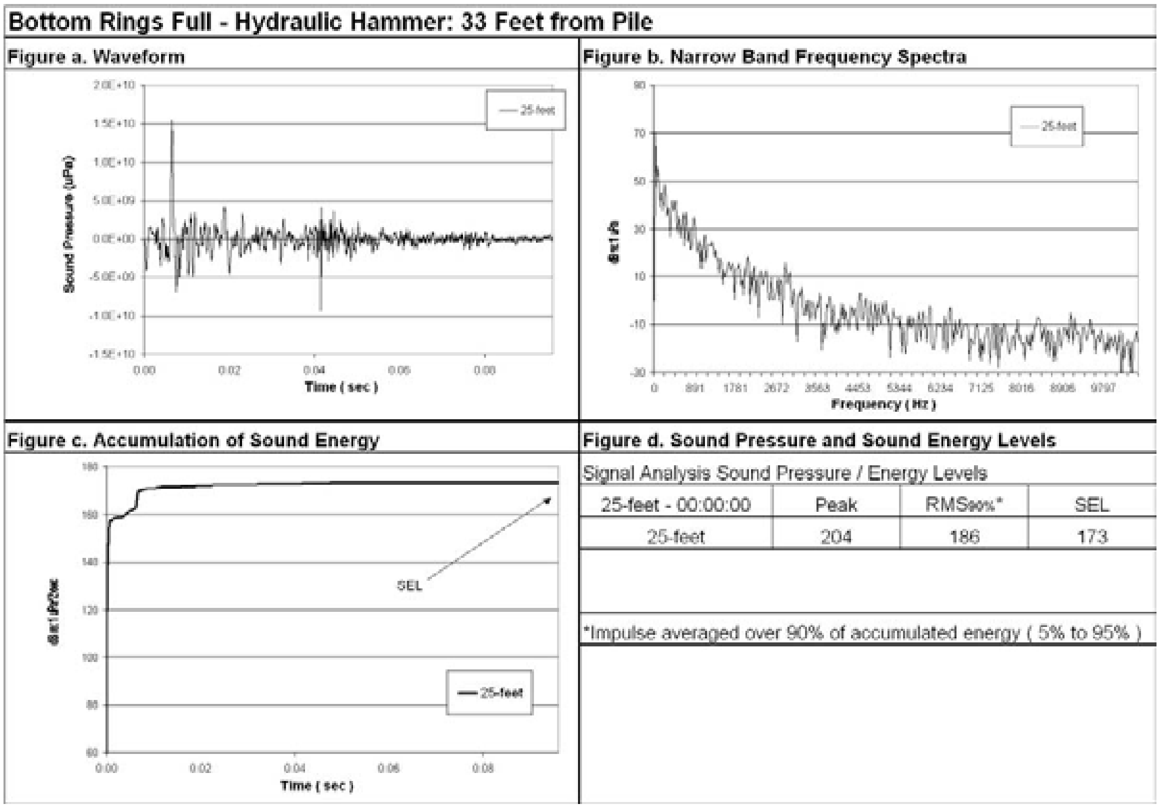


47-feet - 00:00:00	Peak	RMS90%*	SEL
47-feet	203	188	176

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

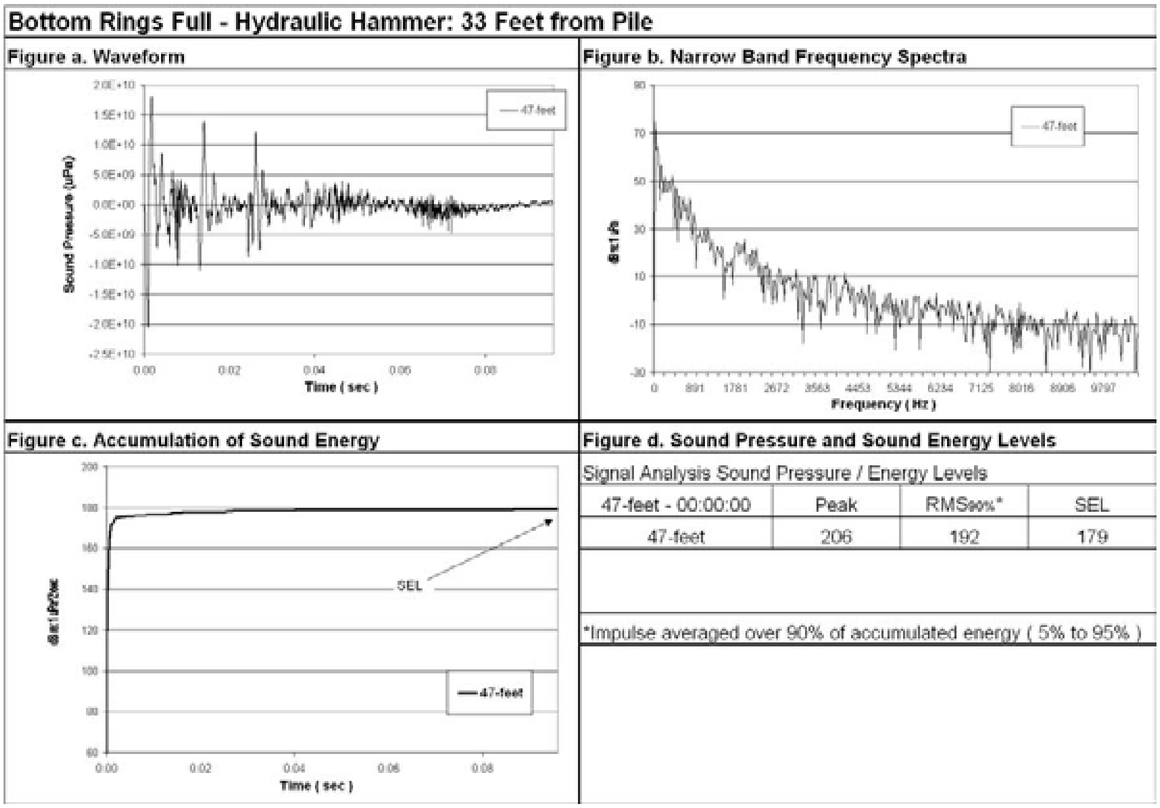
Figure 77 Waveform Analysis for Pile Number 3, 47-feet Deep (bottom), 33-Feet from Pile, All Rings Off.

BOTTOM RING ON FULL



25-feet - 00:00:00	Peak	RMS90%*	SEL
25-feet	204	186	173

Figure 78 Waveform Analysis for Pile Number 3, 25-feet Deep, 33-Feet from Pile, Bottom Ring On Full.



47-feet - 00:00:00	Peak	RMS90%*	SEL
47-feet	206	192	179

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

Figure 79 Waveform Analysis for Pile Number 3, 47-feet Deep (Bottom), 33-Feet from Pile, Bottom Ring On Full.

ALL RINGS ON FULL

All Rings Full - Hydraulic Hammer: 33 Feet from Pile

Figure a. Waveform

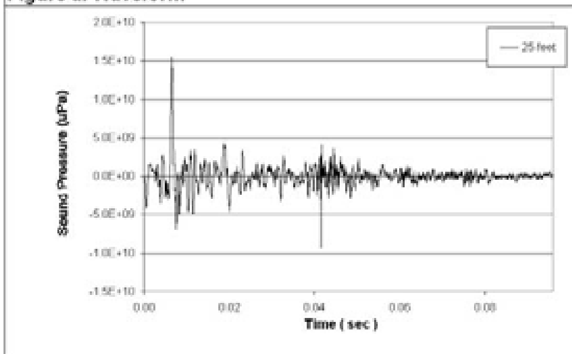


Figure b. Narrow Band Frequency Spectra

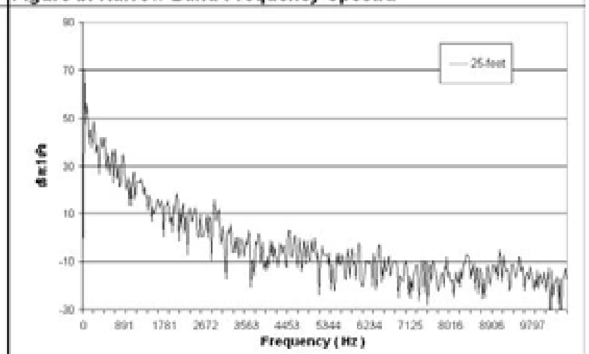


Figure c. Accumulation of Sound Energy

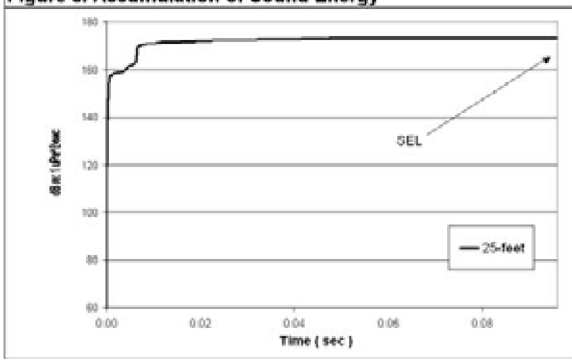


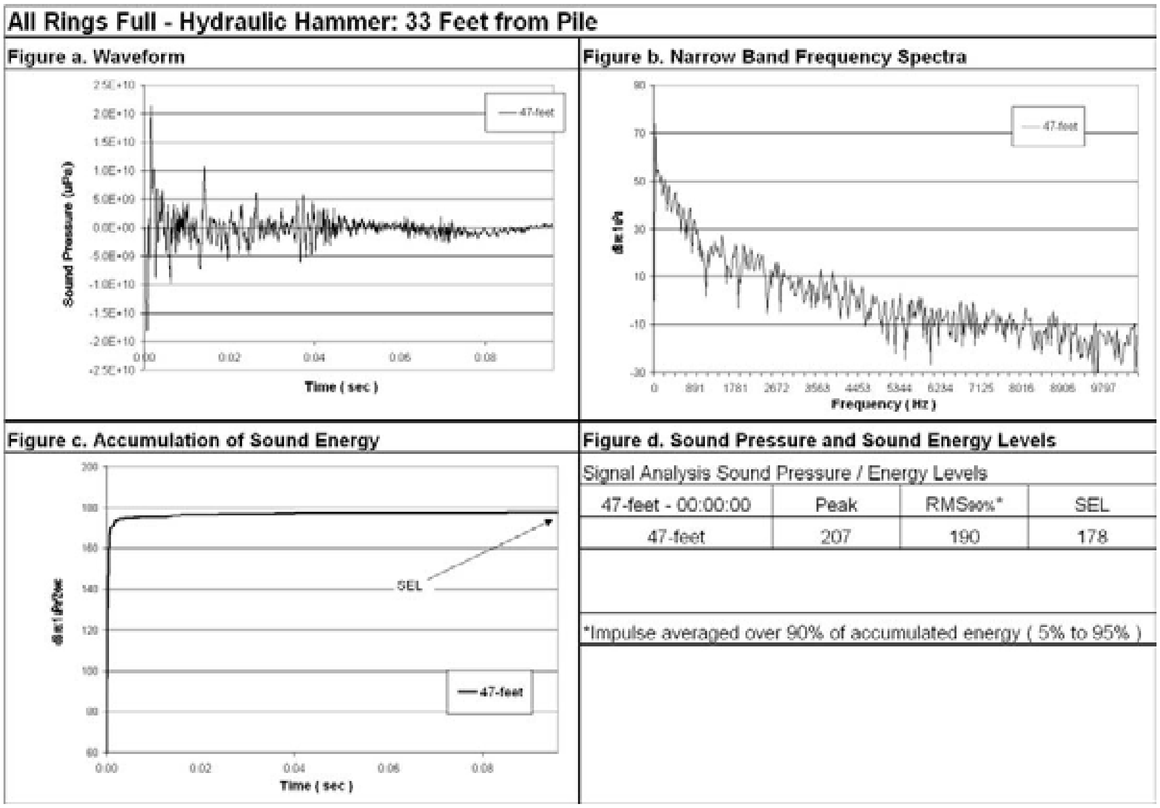
Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

25-feet - 00:00:00	Peak	RMS90%*	SEL
25-feet	204	186	173

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

Figure 80 Waveform Analysis for Pile Number 3, 25-feet Deep, 33-Feet from Pile, All Rings Full.



47-feet - 00:00:00	Peak	RMS90%*	SEL
47-feet	207	190	178

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

Figure 81 Waveform Analysis for Pile Number 3, 47-feet Deep (Bottom), 33-Feet from Pile, All Rings Full.

ALL RINGS OFF (FINAL)

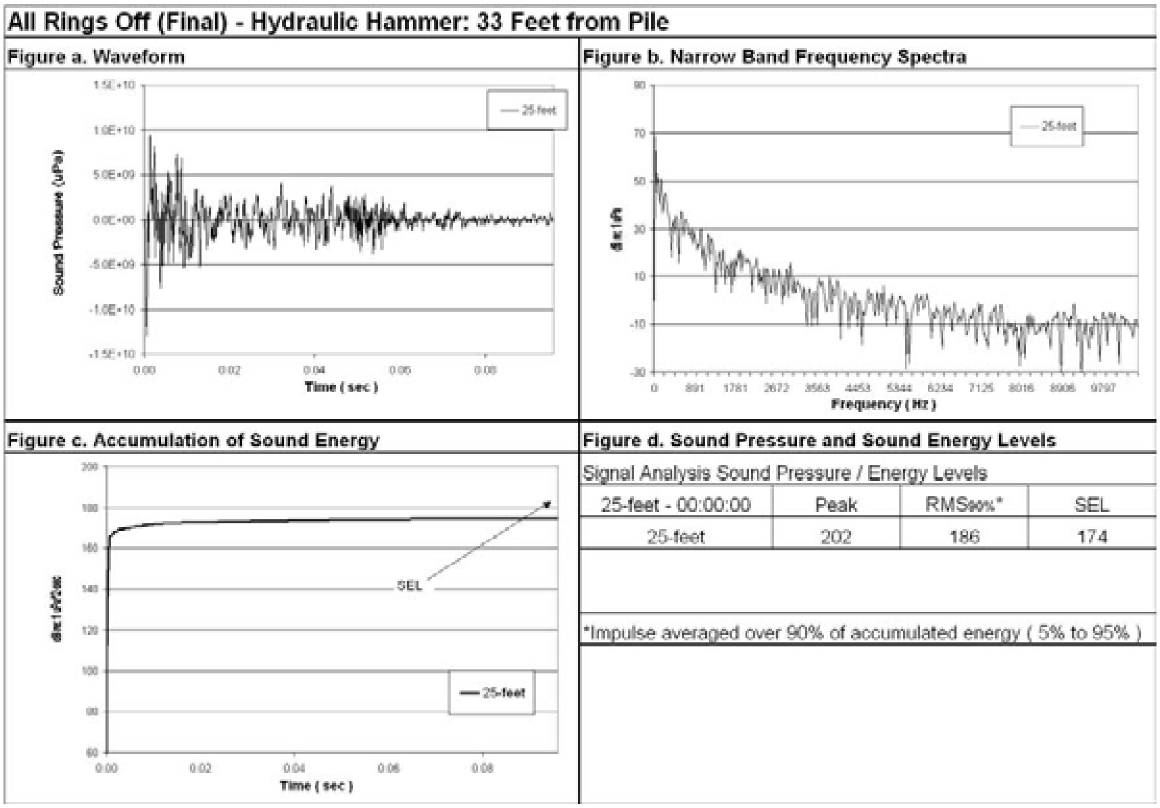


Figure 82 Waveform Analysis for Pile Number 3, 25-feet Deep, 33-Feet from Pile, All Rings Off (Final).

All Rings Off (Final) - Hydraulic Hammer: 33 Feet from Pile

Figure a. Waveform

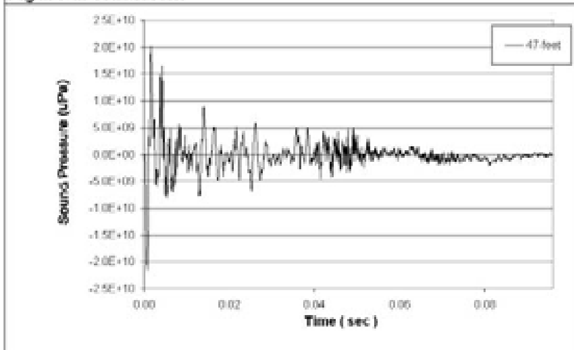


Figure b. Narrow Band Frequency Spectra

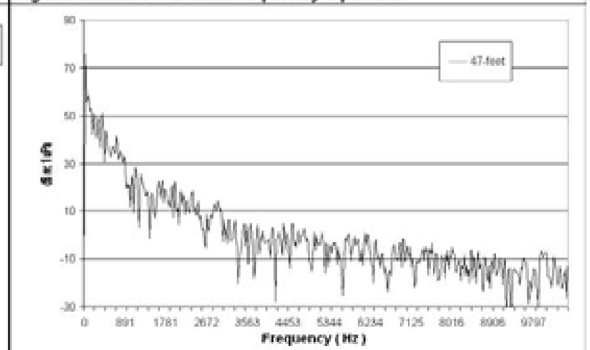


Figure c. Accumulation of Sound Energy

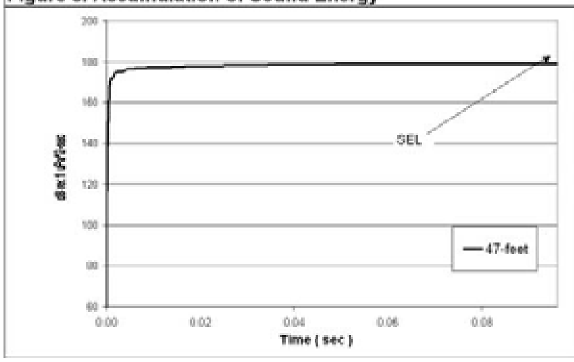


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

47-feet - 00:00:00	Peak	RMS90%*	SEL
47-feet	207	192	179

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

Figure 83 Waveform Analysis for Pile Number 3, 47-feet Deep (Bottom), 33-Feet from Pile, All Rings Off (Final).

PILE 4 – DIESEL HAMMER

BOTTOM RING ON FULL

Pile 4 - Bottom ring on full - Diesel Hammer: 33 Feet from Pile

Figure a. Waveform

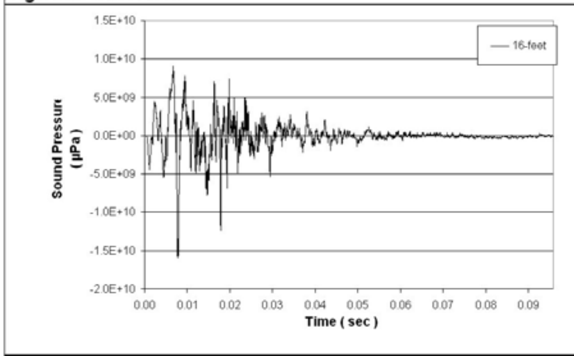


Figure b. Narrow Band Frequency Spectra

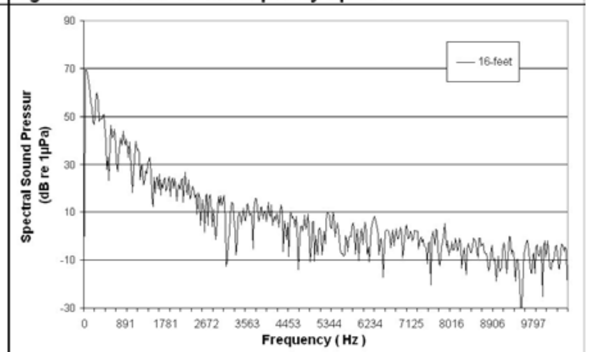


Figure c. Accumulation of Sound Energy

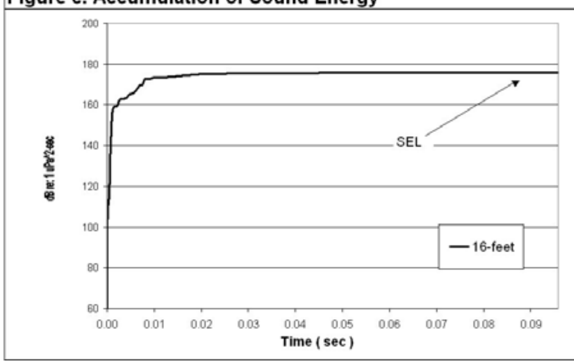


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

16-feet - 00:00:00	Peak	RMS90%*	SEL
16-feet	204	191	176

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

Figure 84: Waveform Analysis for Pile Number 4, 16-Feet Deep, 33-Feet from Pile, Bottom Ring On Full.

Pile 4 - Bottom ring on full - Diesel Hammer: 33 Feet from Pile

Figure a. Waveform

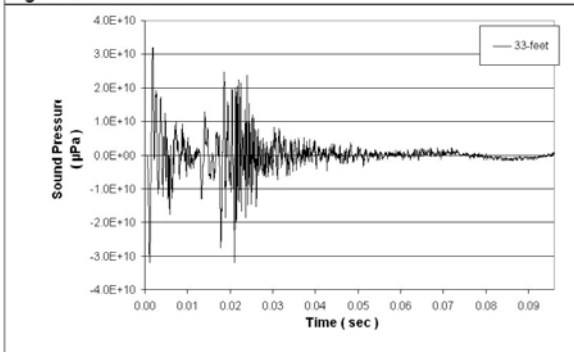


Figure b. Narrow Band Frequency Spectra

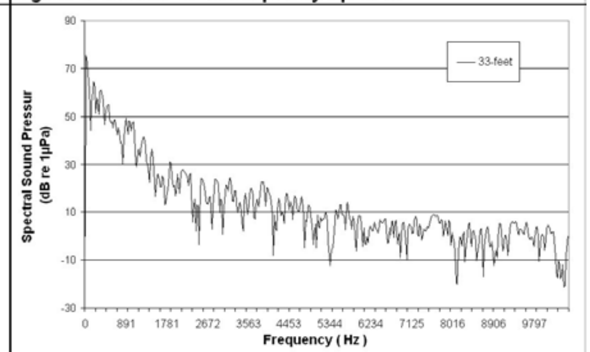


Figure c. Accumulation of Sound Energy

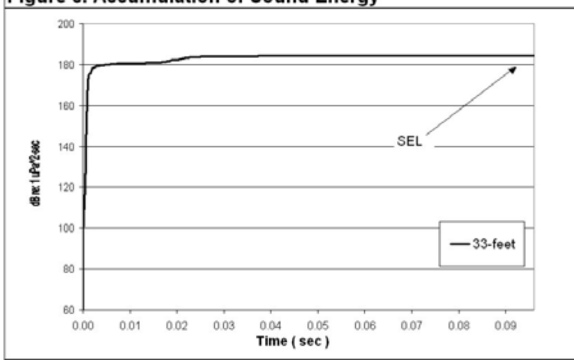


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33-feet - 00:00:00	Peak	RMS90%*	SEL
33-feet	210	199	184

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

Figure 85: Waveform Analysis for Pile Number 4, 33-Feet Deep (Bottom), 33-Feet from Pile, Bottom Ring On Full.

ALL RINGS ON FULL

Pile 4 - All rings on full - Diesel Hammer: 33 Feet from Pile

Figure a. Waveform

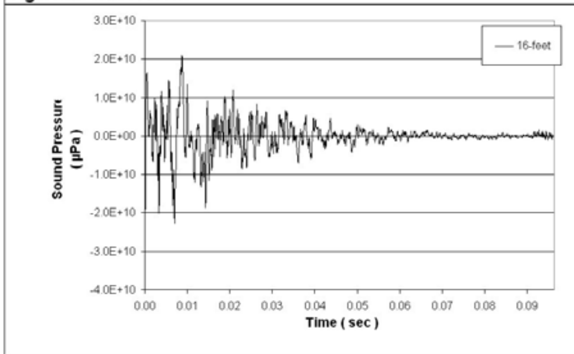


Figure b. Narrow Band Frequency Spectra

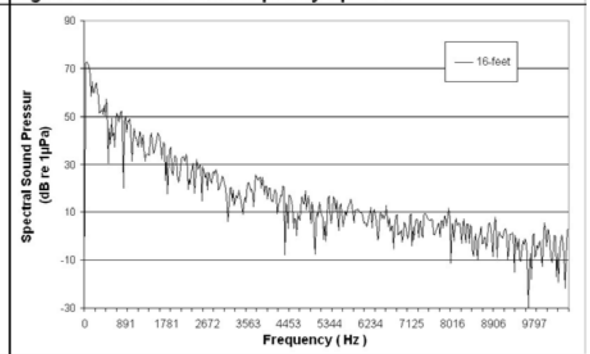


Figure c. Accumulation of Sound Energy

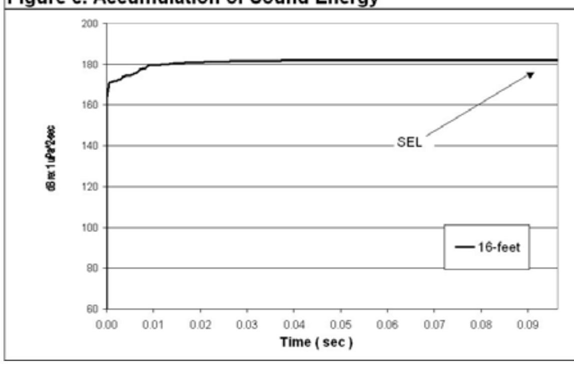


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

16-feet - 00:00:00	Peak	RMS90%*	SEL
16-feet	209	196	182

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

Figure 86: Waveform Analysis for Pile Number 4, 16-Feet Deep, 33-Feet from Pile, All Rings On Full.

Pile 4 - All rings on full - Diesel Hammer: 33 Feet from Pile

Figure a. Waveform

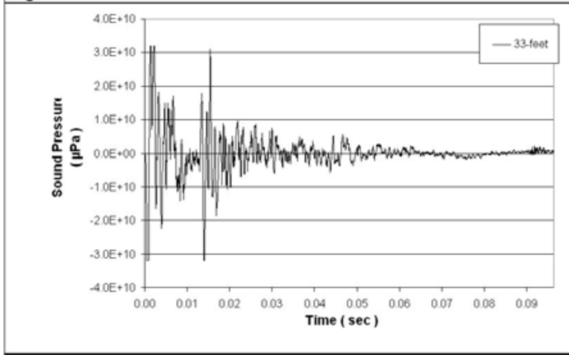


Figure b. Narrow Band Frequency Spectra

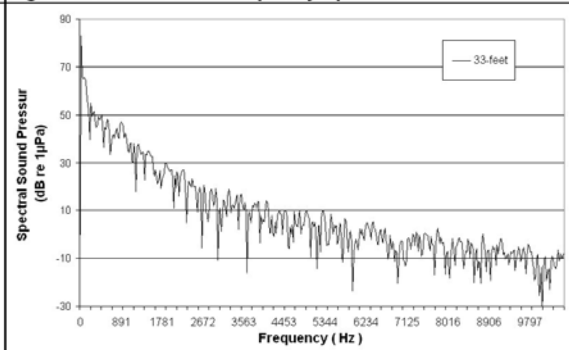


Figure c. Accumulation of Sound Energy

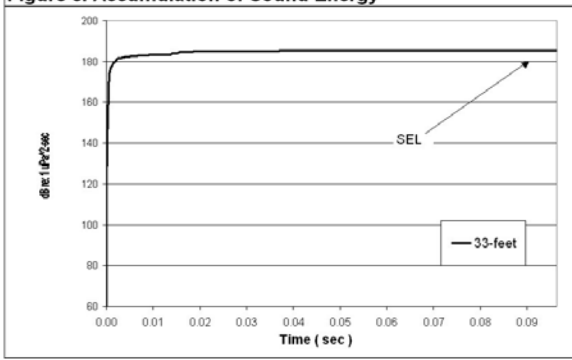


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33-feet - 00:00:00	Peak	RMS90%*	SEL
33-feet	210	200	185

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

Figure 87: Waveform Analysis for Pile Number 4, 33-Feet Deep (Bottom), 33-Feet from Pile, All Rings On Full.

ALL RINGS OFF.

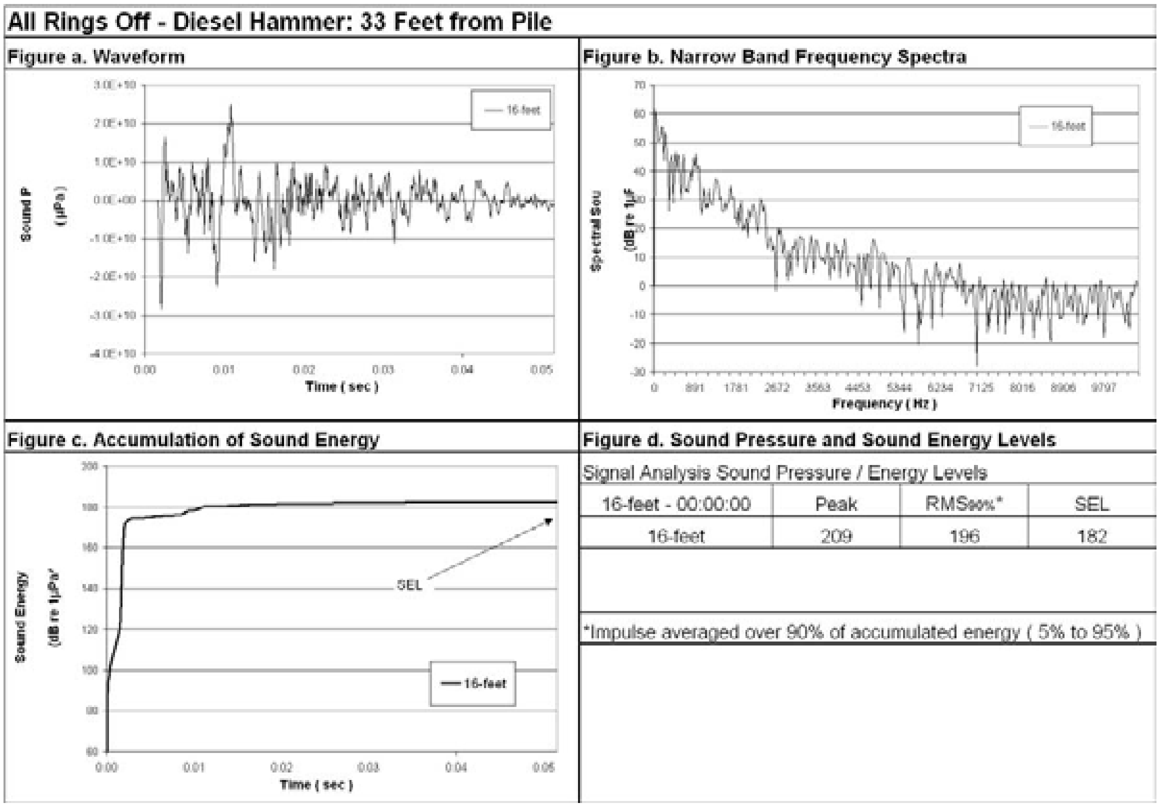


Figure 88: Waveform Analysis for Pile Number 4, 16-Feet Deep, 33-Feet from Pile, All Rings Off.

Pile 4 - All Rings Off - Diesel Hammer: 33 Feet from Pile

Figure a. Waveform

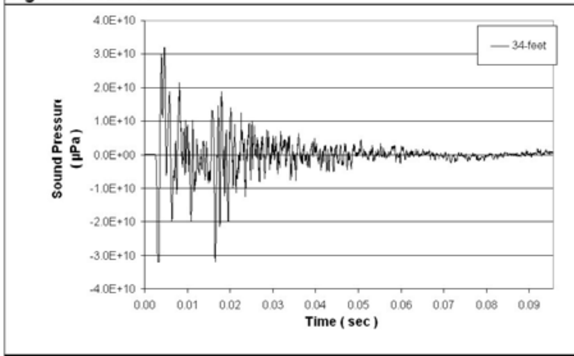


Figure b. Narrow Band Frequency Spectra

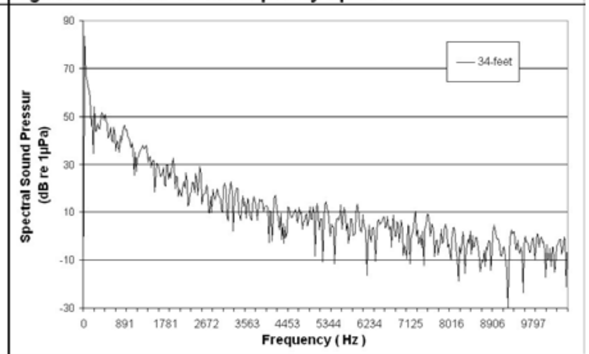


Figure c. Accumulation of Sound Energy

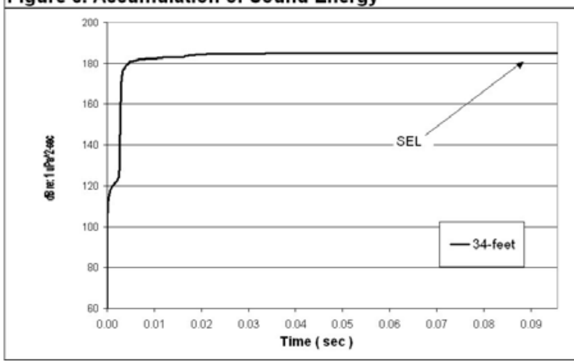


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

34-feet - 00:00:00	Peak	$RMS_{90\%}$*	SEL
34-feet	210	200	185

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

Figure 89: Waveform Analysis for Pile Number 4, 34-Feet Deep (Bottom), 33-Feet from Pile, All Rings Off.

PILE 5 – DIESEL HAMMER

BOTTOM RING ON FULL

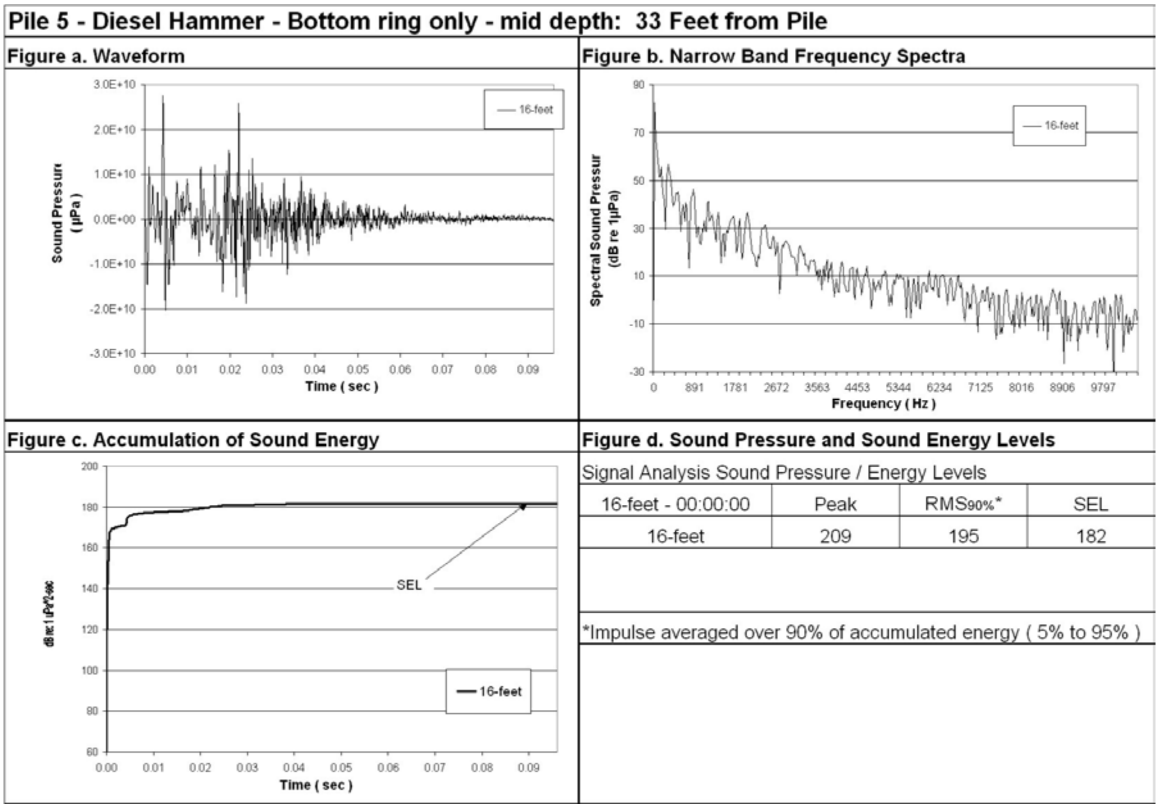


Figure 90: Waveform Analysis for Pile Number 5, 16-feet Deep, 33-Feet from Pile, Bottom Ring On Full.

Pile 5 - Diesel Hammer - Bottom ring only - 1 foot from bottom: 33 Feet from Pile

Figure a. Waveform

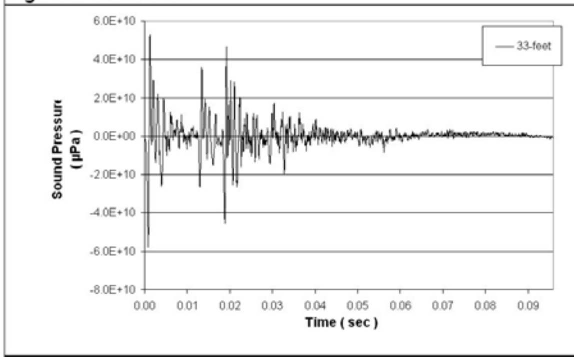


Figure b. Narrow Band Frequency Spectra

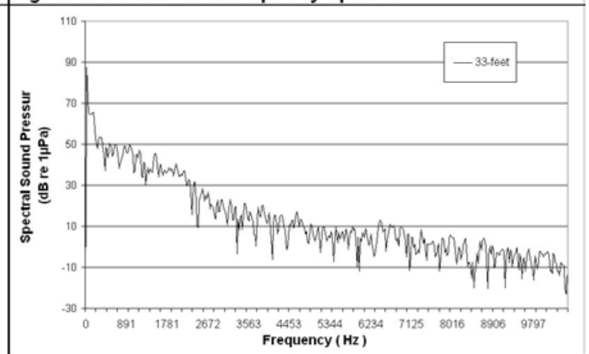


Figure c. Accumulation of Sound Energy

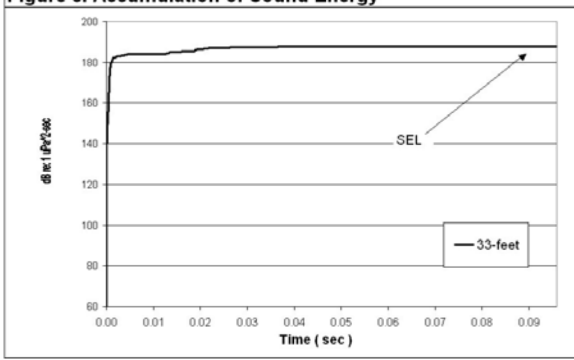


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33-feet - 00:00:00	Peak	RMS90%*	SEL
33-feet	215	202	188

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

Figure 91: Waveform Analysis for Pile Number 5, 33-feet Deep (Bottom), 33-Feet from Pile, Bottom Ring On Full.

ALL RINGS ON FULL

Pile 5 - Diesel Hammer - All rings on full - mid depth: 33 Feet from Pile

Figure a. Waveform

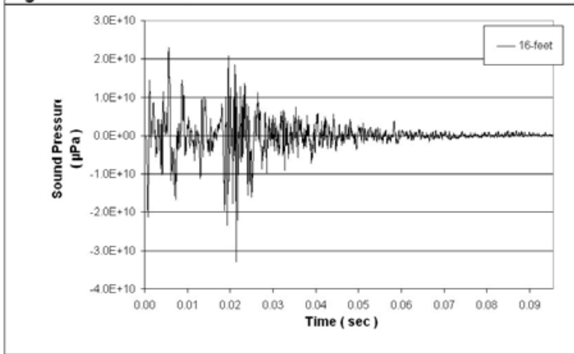


Figure b. Narrow Band Frequency Spectra

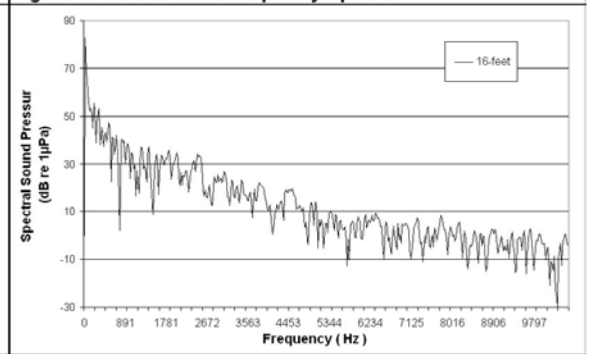


Figure c. Accumulation of Sound Energy

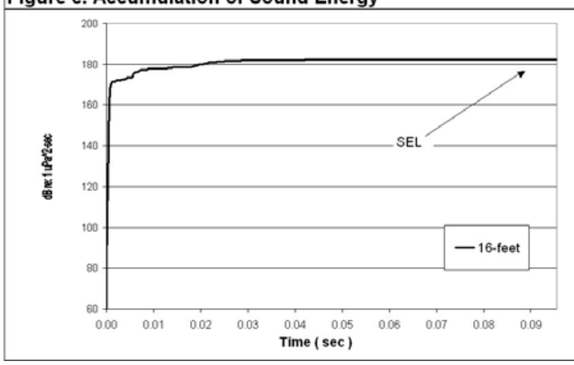


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

16-feet - 00:00:00	Peak	RMS90%*	SEL
16-feet	210	196	182

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

Figure 92: Waveform Analysis for Pile Number 5, 16-Feet Deep, 33-Feet from Pile, All Rings On Full.

Pile 5 - Diesel Hammer - all rings on full - 1 foot from bottom: 33 Feet from Pile

Figure a. Waveform

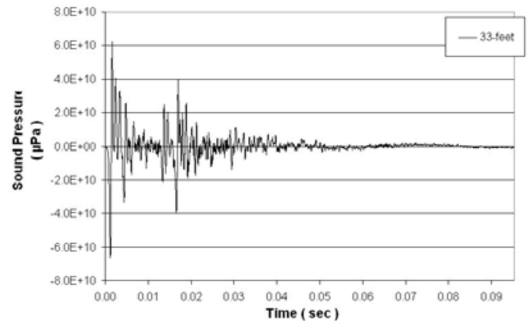


Figure b. Narrow Band Frequency Spectra

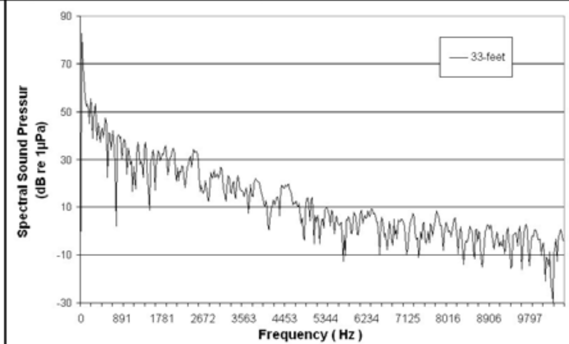


Figure c. Accumulation of Sound Energy

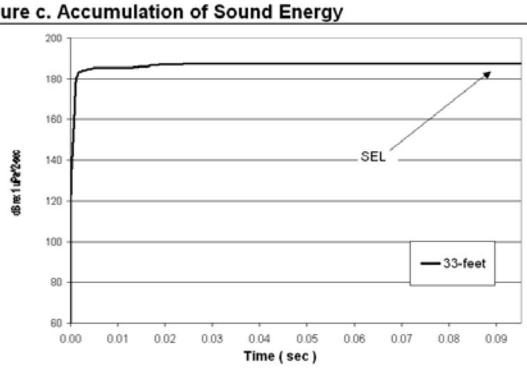


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33-feet - 00:00:00	Peak	RMS90%*	SEL
33-feet	216	203	187

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

Figure 93: Waveform Analysis for Pile Number 5, 33-Feet Deep (Bottom), 33-Feet from Pile, All Rings On Full.

ALL RINGS OFF

Pile 5 - Diesel Hammer - All rings off - mid depth: 33 Feet from Pile

Figure a. Waveform

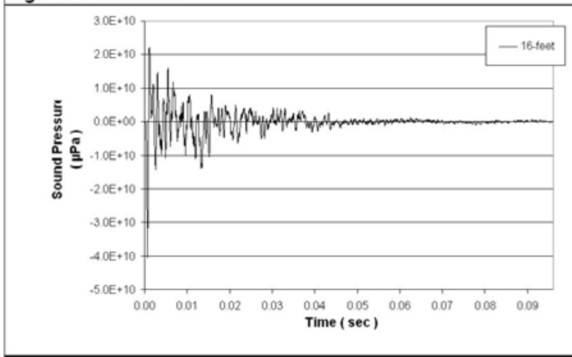


Figure b. Narrow Band Frequency Spectra

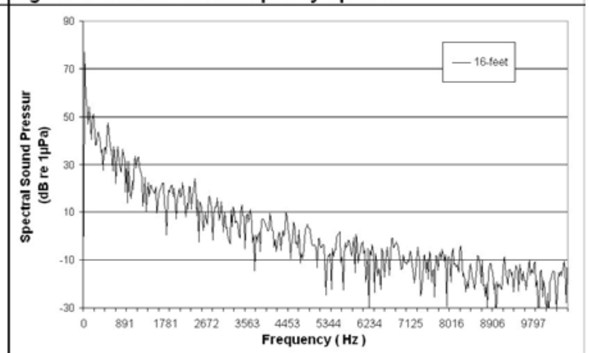


Figure c. Accumulation of Sound Energy

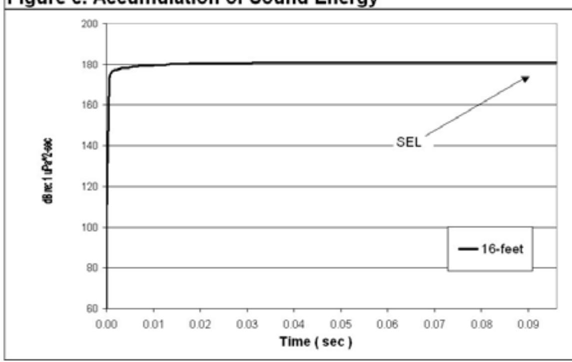


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

16-feet - 00:00:00	Peak	RMS90%*	SEL
16-feet	212	196	181

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

Figure 94: Waveform Analysis for Pile Number 5, 16-Feet Deep (Bottom), 33-Feet from Pile, All Rings Off.

Pile 5 - Diesel Hammer - All rings off - bottom depth: 33 Feet from Pile

Figure a. Waveform

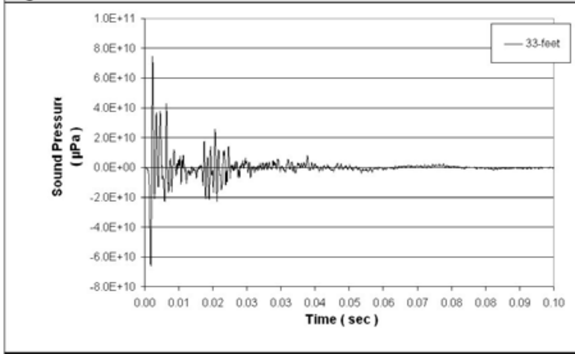


Figure b. Narrow Band Frequency Spectra

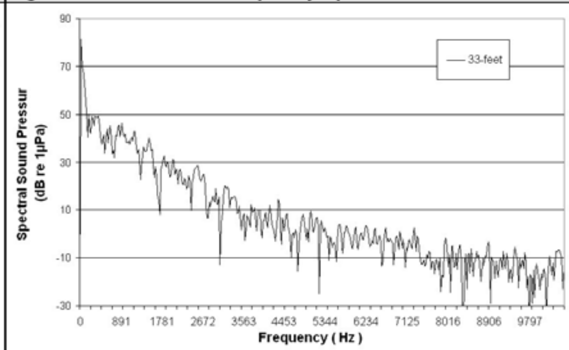


Figure c. Accumulation of Sound Energy

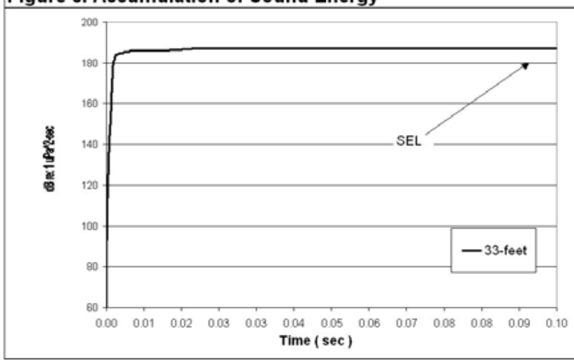


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33-feet - 00:00:00	Peak	RMS90%*	SEL
33-feet	217	204	187

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

Figure 95: Waveform Analysis for Pile Number 5, 33-Feet Deep (Bottom), 33-Feet from Pile, All Rings Off.

PILE 6 – HYDRAULIC HAMMER

BOTTOM RING ON FULL

Pile 6 - Hydraulic Hammer - bottom ring on full - mid depth: 33 Feet from Pile

Figure a. Waveform

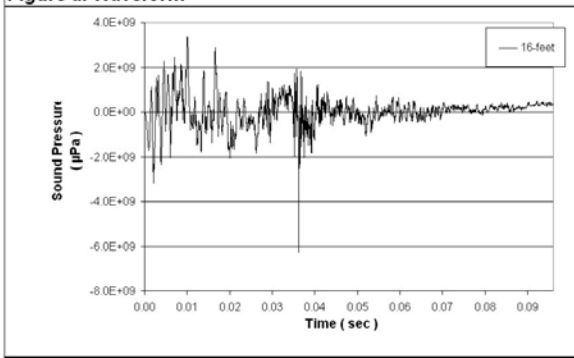


Figure b. Narrow Band Frequency Spectra

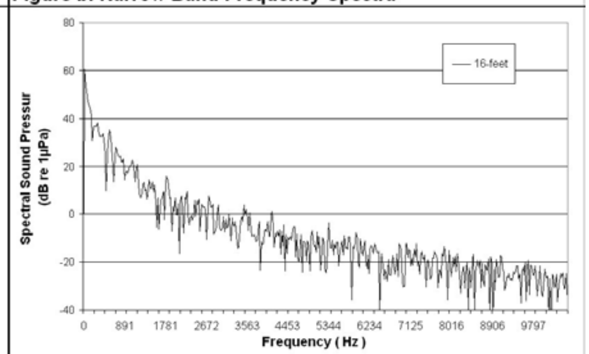


Figure c. Accumulation of Sound Energy

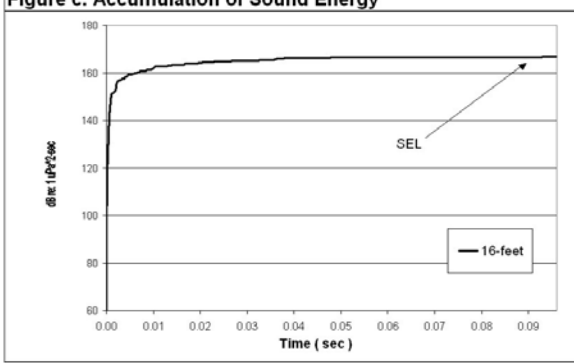


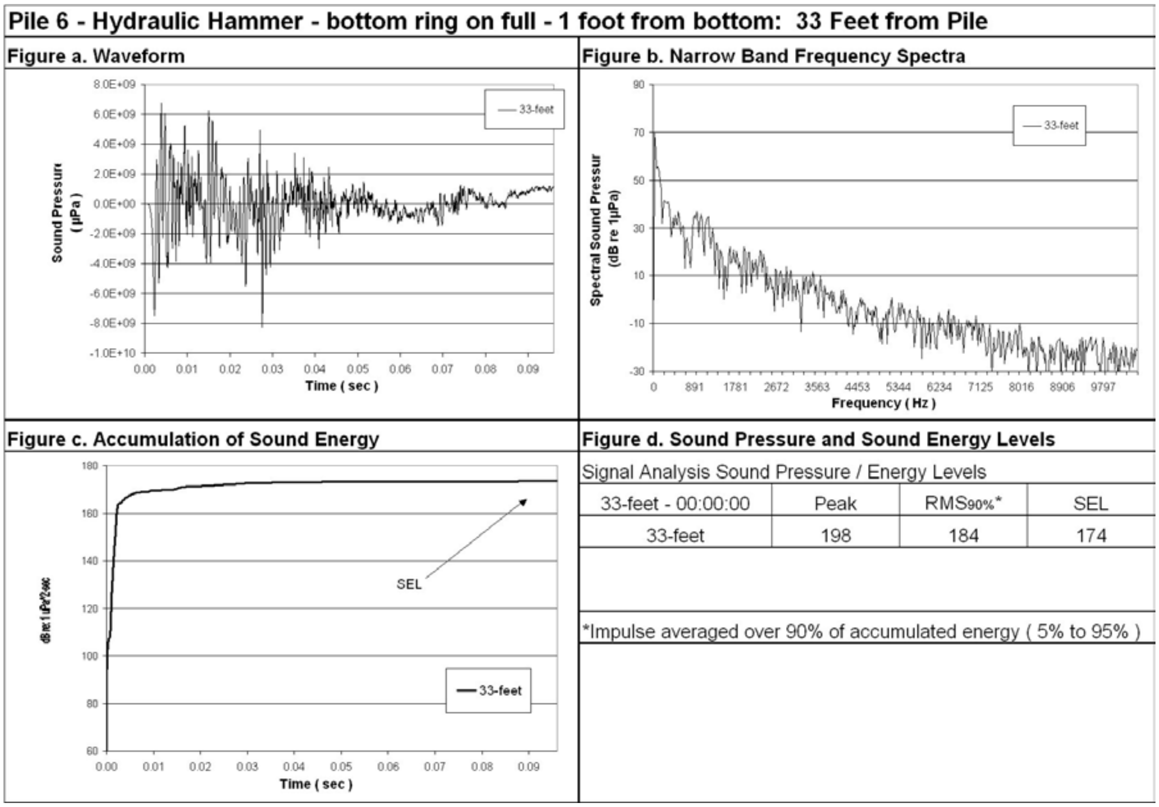
Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

16-feet - 00:00:00	Peak	RMS90%*	SEL
16-feet	196	179	167

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

Figure 96: Waveform Analysis for Pile Number 6, 16-Feet Deep, 33-Feet from Pile, Bottom Ring On Full.



33-feet - 00:00:00	Peak	RMS90%*	SEL
33-feet	198	184	174

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

Figure 97: Waveform Analysis for Pile Number 6, 33-Feet Deep (Bottom), 33-Feet from Pile, Bottom Ring On Full.

ALL RINGS ON FULL

Pile 6 - Hydraulic Hammer - all rings on full - mid depth: 33 Feet from Pile

Figure a. Waveform

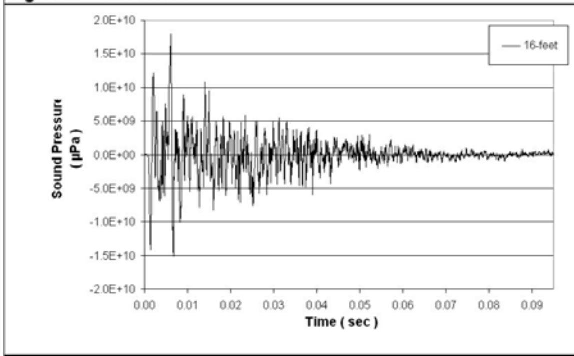


Figure b. Narrow Band Frequency Spectra

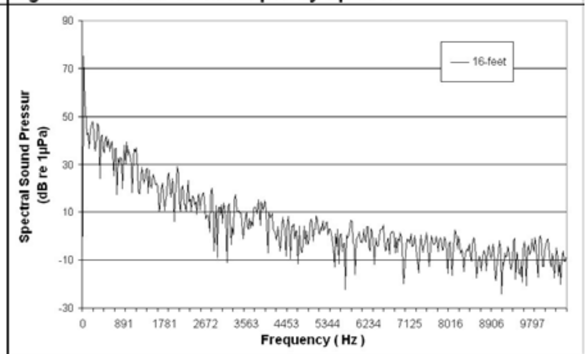


Figure c. Accumulation of Sound Energy

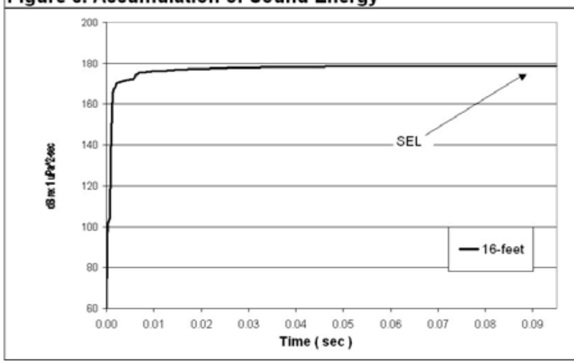


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

16-feet - 00:00:00	Peak	RMS90%*	SEL
16-feet	205	192	178

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

Figure 98: Waveform Analysis for Pile Number 6, 16-Feet Deep, 33-Feet from Pile, All Rings On Full.

Pile 6 - Hydraulic Hammer - all rings on full - 1 foot from bottom: 33 Feet from Pile

Figure a. Waveform

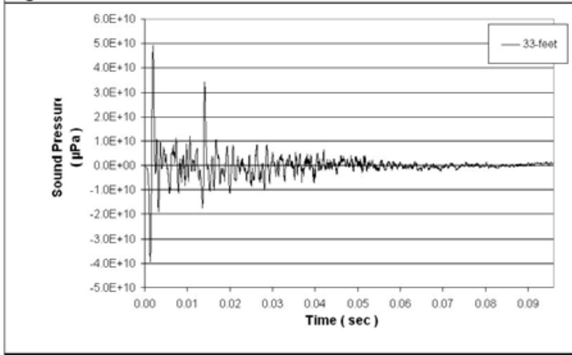


Figure b. Narrow Band Frequency Spectra

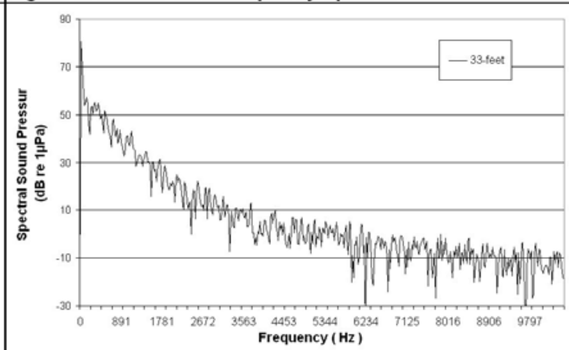


Figure c. Accumulation of Sound Energy

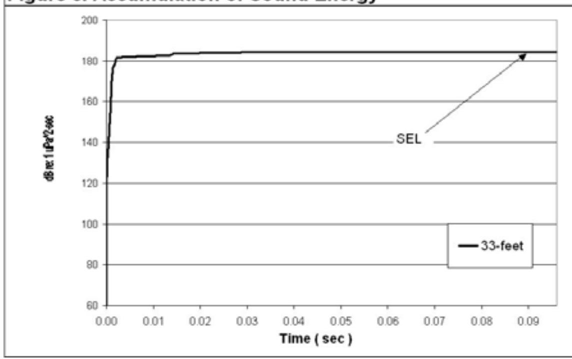


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33-feet - 00:00:00	Peak	RMS90%*	SEL
33-feet	214	199	184

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

Figure 99: Waveform Analysis for Pile Number 6, 33-Feet Deep (Bottom), 33-Feet from Pile, All Rings On Full.

ALL RINGS OFF

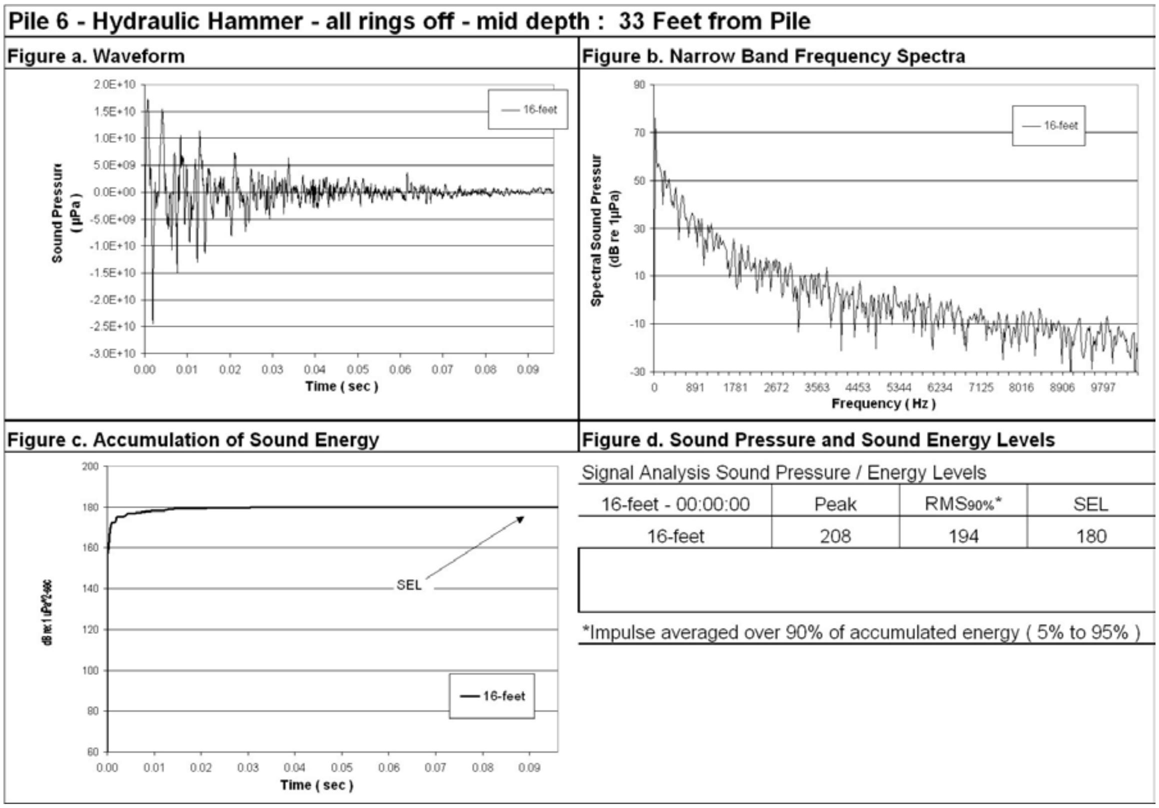


Figure 100: Waveform Analysis for Pile Number 6, 16-Feet Deep, 33-Feet from Pile, All Rings Off.

Pile 6 - Hydraulic Hammer - all rings off - 1 foot from bottom: 33 Feet from Pile

Figure a. Waveform

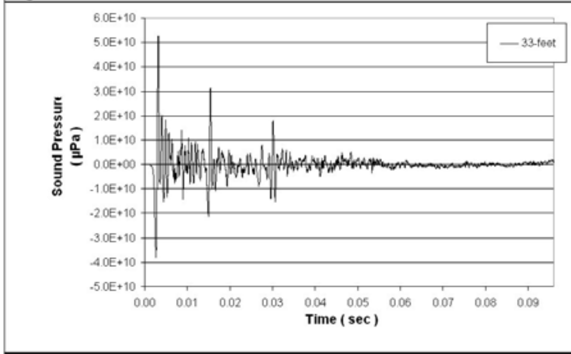


Figure b. Narrow Band Frequency Spectra

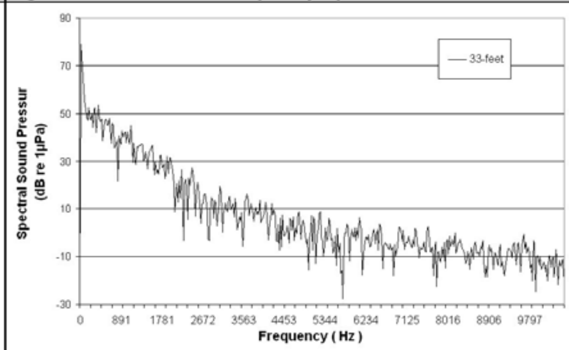


Figure c. Accumulation of Sound Energy

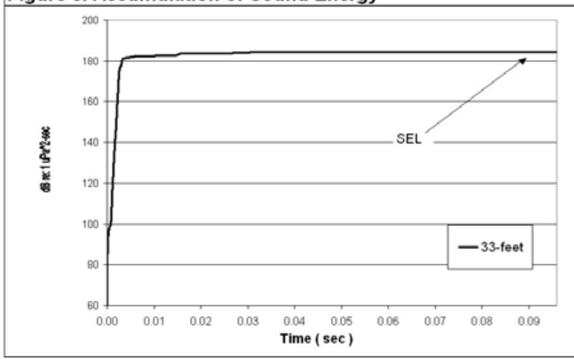


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

33-feet - 00:00:00	Peak	RMS90%*	SEL
33-feet	214	199	184

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

Figure 101: Waveform Analysis for Pile Number 6, 33-Feet Deep (Bottom), 33-Feet from Pile, All Rings Off.

PILE 7 – DIESEL HAMMER

BOTTOM RING ON FULL

Bottom Ring On Full - Diesel Hammer: 33 Feet from Pile

Figure a. Waveform

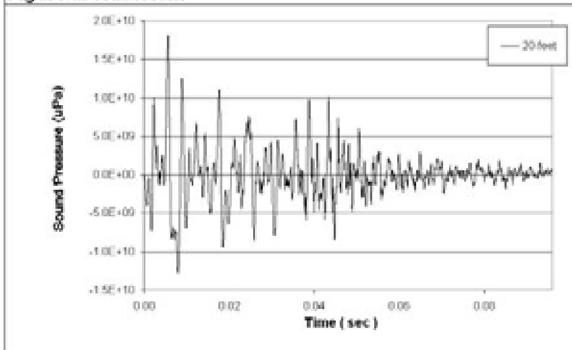


Figure b. Narrow Band Frequency Spectra

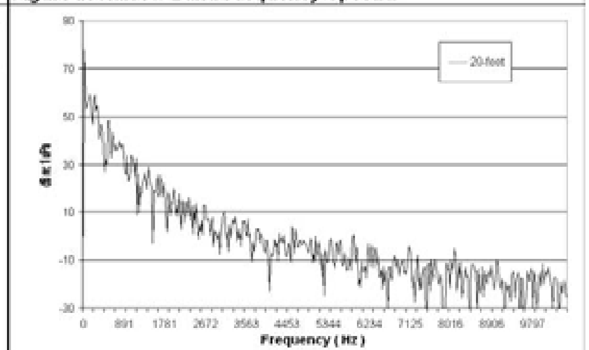


Figure c. Accumulation of Sound Energy

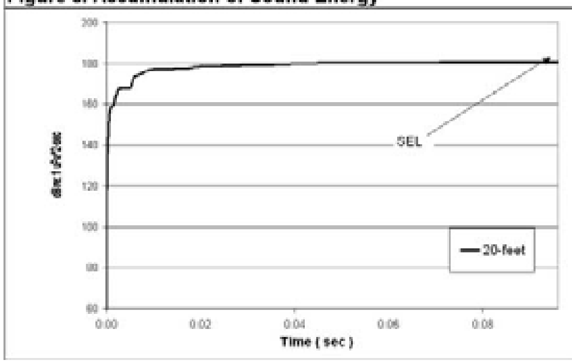


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

20-feet - 00:00:00	Peak	RMS90%*	SEL
20-feet	205	193	180

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

Figure 102: Waveform Analysis for Pile Number 7, 20-Feet Deep, 33-Feet from Pile, Bottom Ring On Full.

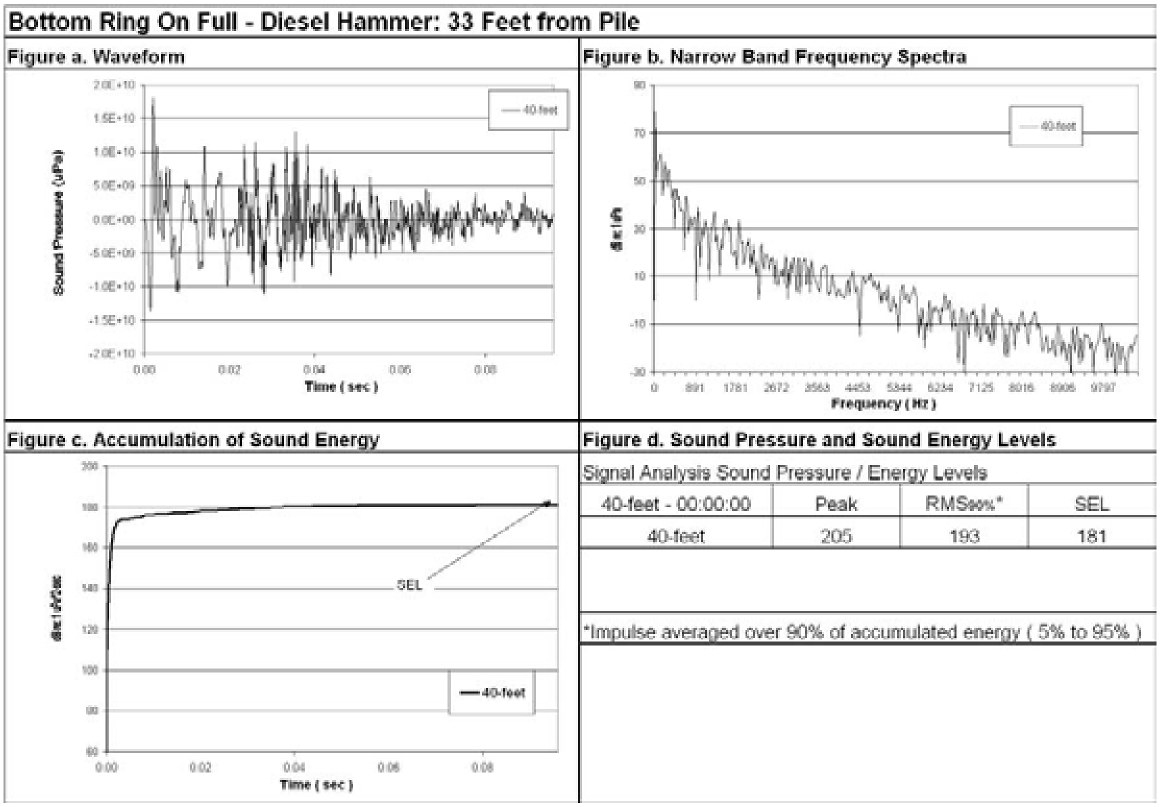


Figure 103: Waveform Analysis for Pile Number 7, 40-Feet Deep (Bottom), 33-Feet from Pile, Bottom Ring On Full.

ALL RINGS ON FULL

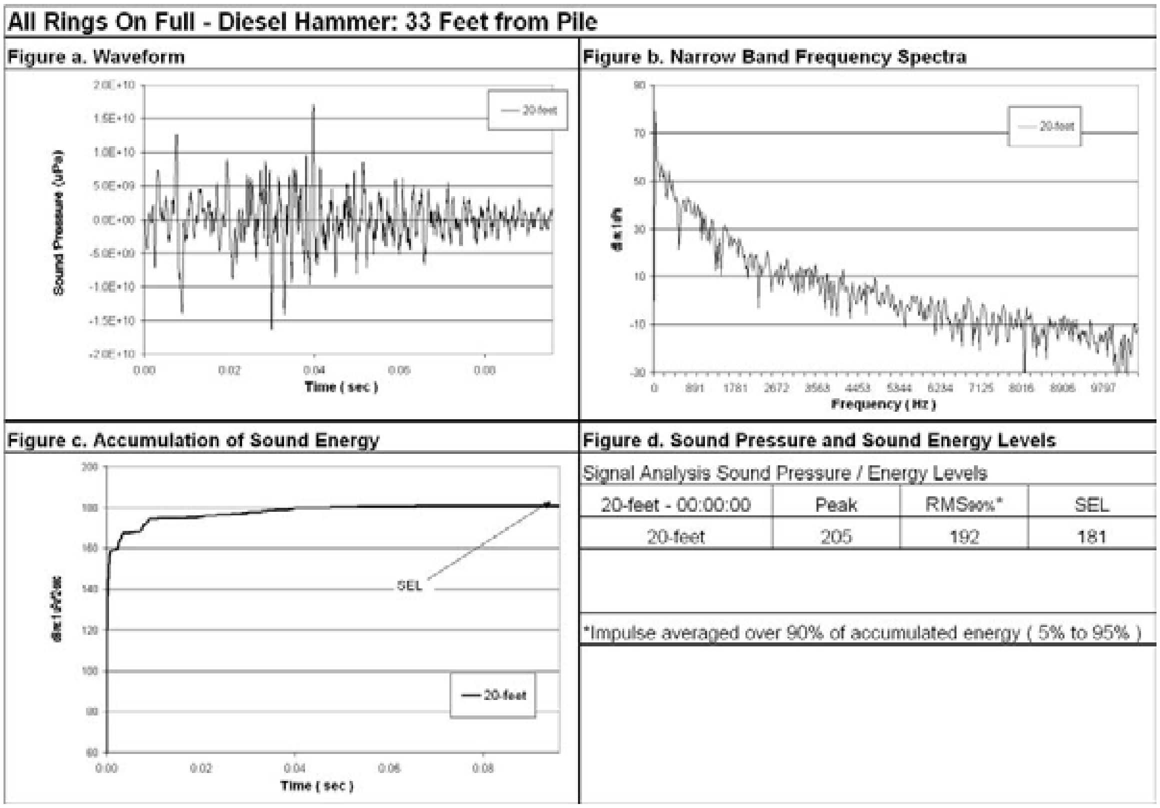


Figure 104: Waveform Analysis for Pile Number 7, 20-Feet Deep, 33-Feet from Pile, All Rings On Full.

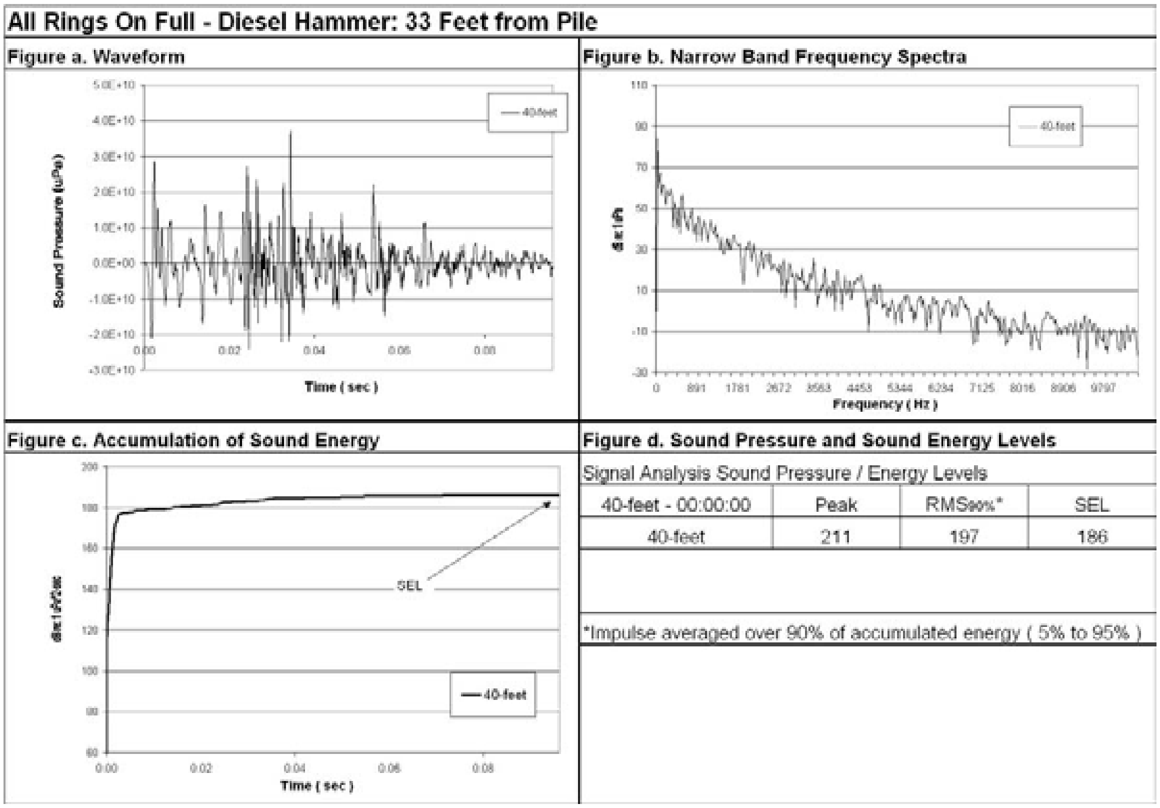


Figure 105: Waveform Analysis for Pile Number 7, 40-Feet Deep (Bottom), 33-Feet from Pile, All Rings On Full.

PILE 8 – DIESEL HAMMER

BOTTOM RING ON FULL

Pile 8 - Diesel Hammer - Bottom ring on full - Mid depth: 33 Feet from Pile

Figure a. Waveform

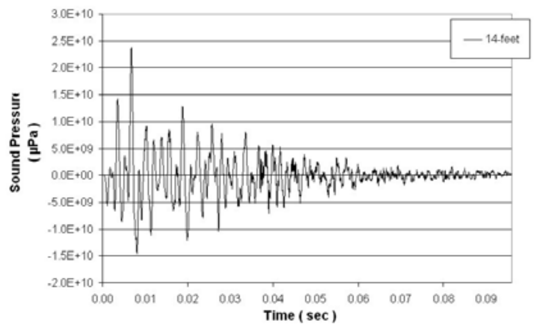


Figure b. Narrow Band Frequency Spectra

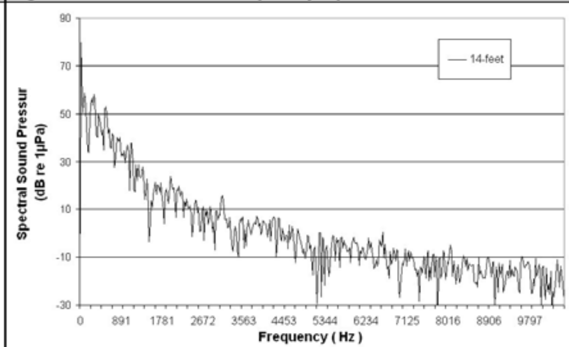


Figure c. Accumulation of Sound Energy

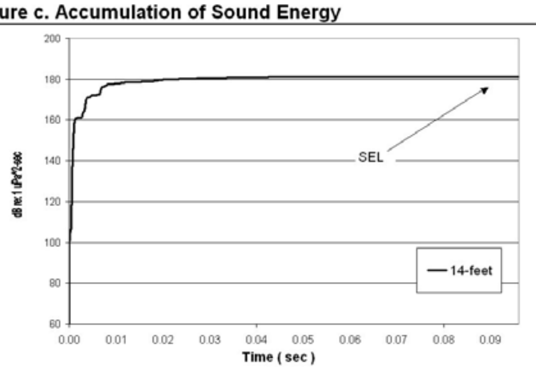


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

14-feet - 00:00:00	Peak	RMS90%*	SEL
14-feet	208	195	181

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

Figure 106: Waveform Analysis for Pile Number 8, 14-Feet Deep, 33-Feet from Pile, Bottom Ring on full.

Pile 8 - Diesel Hammer - Bottom ring on full - One foot from bottom: 33 Feet from Pile

Figure a. Waveform

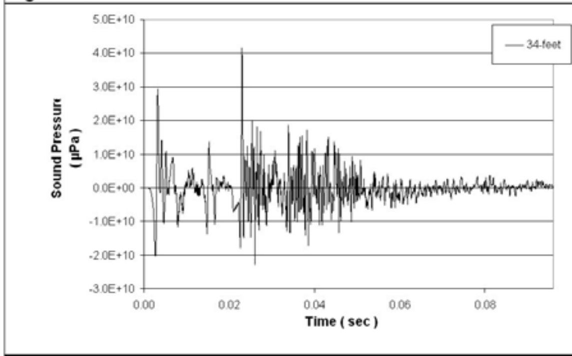


Figure b. Narrow Band Frequency Spectra

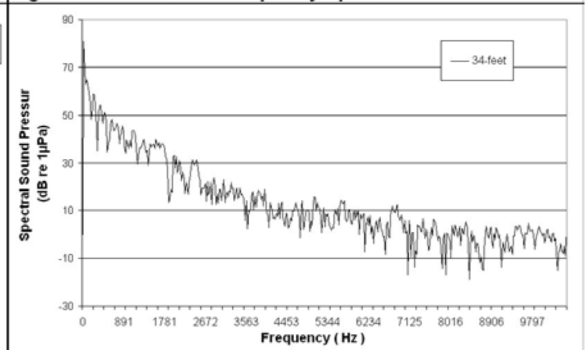


Figure c. Accumulation of Sound Energy

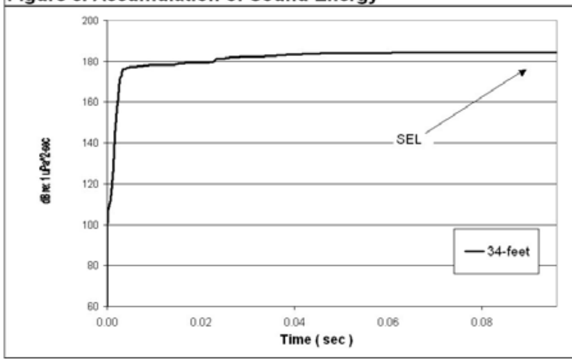


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

34-feet - 00:00:00	Peak	RMS90%*	SEL
34-feet	212	197	184

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

Figure 107: Waveform Analysis for Pile Number 8, 34-Feet Deep (Bottom), 33-Feet from Pile, Bottom Ring on full.

ALL RINGS ON FULL

Pile 8 - Diesel Hammer - All rings on full - Mid depth: 33 Feet from Pile

Figure a. Waveform

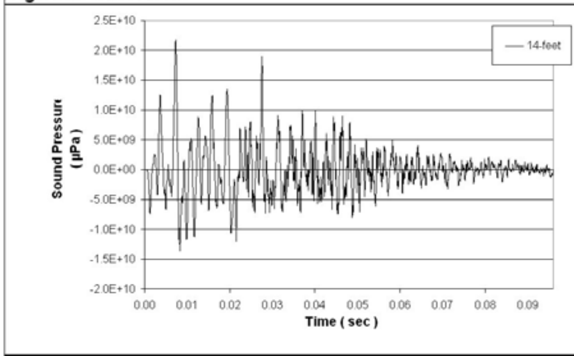


Figure b. Narrow Band Frequency Spectra

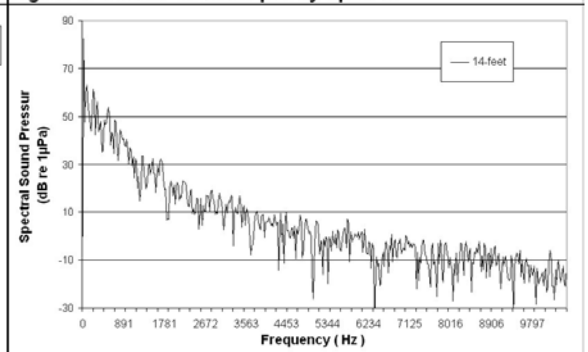


Figure c. Accumulation of Sound Energy

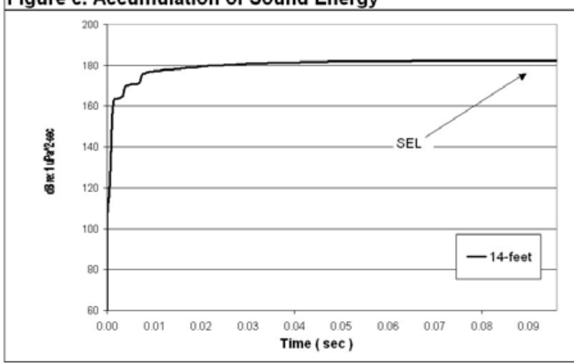


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

14-feet - 00:00:00	Peak	RMS90%*	SEL
14-feet	207	195	182

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

Figure 108: Waveform Analysis for Pile Number 8, 14-Feet Deep, 33-Feet from Pile, All Rings On Full.

Pile 8 - Diesel Hammer - All rings on full - One foot from bottom: 33 Feet from Pile

Figure a. Waveform

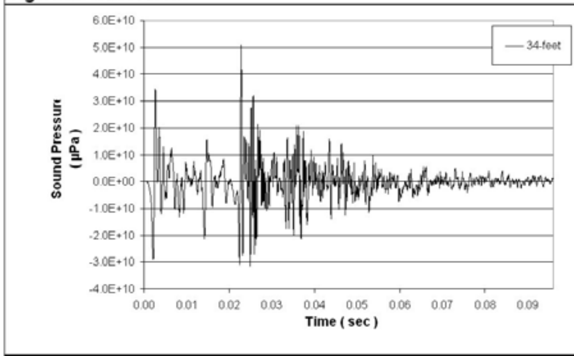


Figure b. Narrow Band Frequency Spectra

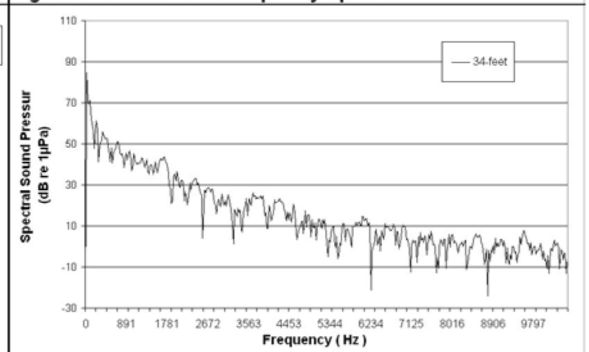


Figure c. Accumulation of Sound Energy

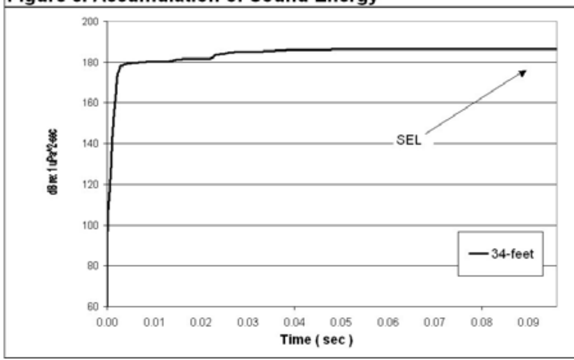


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

34-feet - 00:00:00	Peak	$RMS_{90\%}$*	SEL
34-feet	214	199	186

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

Figure 109: Waveform Analysis for Pile Number 8, 34-Feet Deep (Bottom), 33-Feet from Pile, All Rings On Full.

ALL RINGS OFF

Pile 8 - Diesel Hammer - All rings off - Mid depth: 33 Feet from Pile

Figure a. Waveform

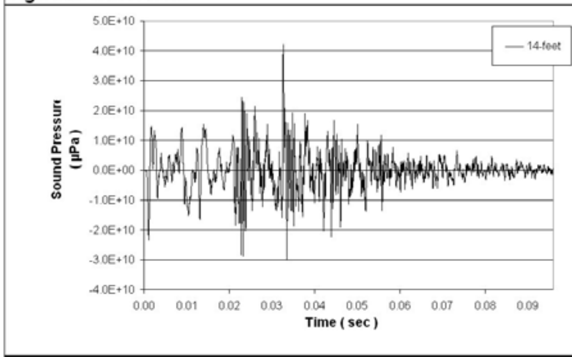


Figure b. Narrow Band Frequency Spectra

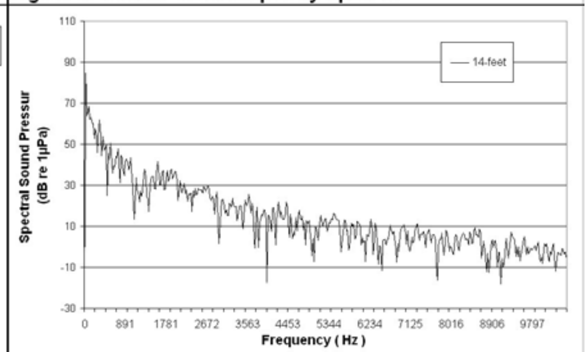


Figure c. Accumulation of Sound Energy

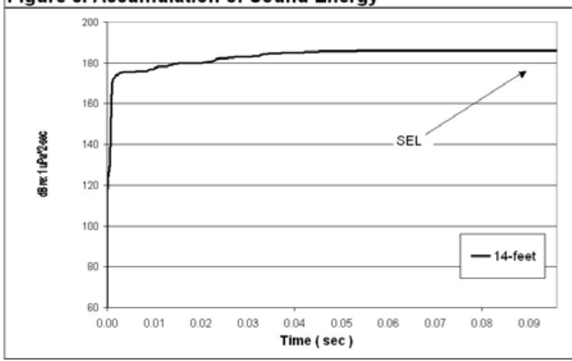


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

14-feet - 00:00:00	Peak	RMS90%*	SEL
14-feet	212	198	186

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

Figure 110: Waveform Analysis for Pile Number 8, 14-Feet Deep, 33-Feet from Pile, All Rings Off.

Pile 8 - Diesel Hammer - All rings off - One foot from bottom: 33 Feet from Pile

Figure a. Waveform

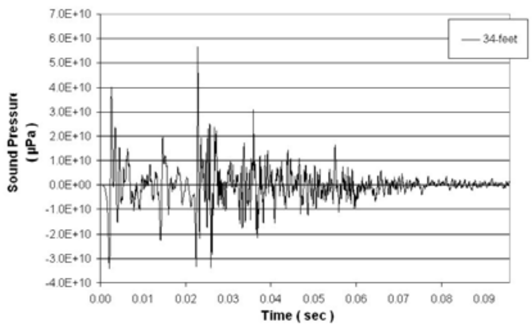


Figure b. Narrow Band Frequency Spectra

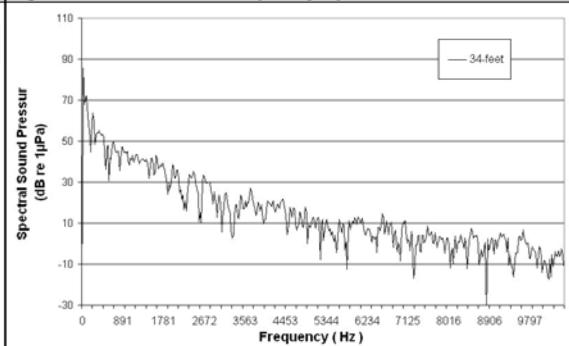


Figure c. Accumulation of Sound Energy

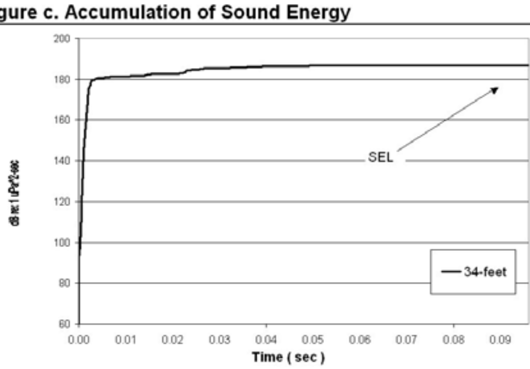


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

34-feet - 00:00:00	Peak	RMS90%*	SEL
34-feet	215	199	187

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

Figure 111: Waveform Analysis for Pile Number 8, 34-Feet Deep (Bottom), 33-Feet from Pile, All Rings Off.