Underwater Sound Levels Associated with Pile Driving during the Anacortes Ferry Terminal Dolphin Replacement Project

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Executive Summary

This technical report describes the data collected during pile driving for the Anacortes Ferry Terminal Dolphin Replacement Project, immediately northwest of the existing Anacortes ferry terminal, in January 2007. Data was collected for seven of the eight steel piles that were part of the replacement of a floating dolphin with a fixed dolphin in Slip 1. Equipment failure prevented collection of date for pile 3. Table 1 summarizes the results for each pile monitored.

- Two standard bubble curtains were used for mitigation. The bubble curtains were tested with the bubbles on and with the bubbles off during the pile driving events.
- Average sound reductions achieved with the bubble curtains ranged from 3 to 11 dB.
- No fish kills were witnessed at any point before, during, or immediately after the pile driving.
- Peak average without the bubble curtain exceeded interim threshold of 208 dB peak.

  Peak average with the bubble curtain did not exceed the 208 dB peak.
- SEL values did not exceed the interim threshold of 187 dB SEL.

Table 1: Summary Table of Monitoring Results.

Pile	Date	Bubble curtain	Number of strikes	Peak RMS (dB)	Avg. peak RMS (dB)	Peak (dB)	Average peak (dB)	Avg. reduction[1] (dB)	SEL (dB)	Avg. SEL reduction[2] (dB)	Cumulative SEL (dB)[3]
1	1/17	off	43	200	166	213	184	11	185	9	203
		on	280	189	157	207	173		175		211
2	1/17	off	51	201	168	214	185	11	186	8	204
		on	299	192	157	207	174		178		212
		off	92	201	166	214	184		186		207
3	1/18	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*
4	1/19	off	36	200	163	213	180	5	185	9	203
		on	305	191	158	205	175		176		212
5	1/19	off	24	199	164	212	181	10	185	9	201
		on	257	192	158	204	174		177		211
		off	52	199	166	212	184		184		204
		on	110	186	156	199	172		173		207
6	1/19	off	12	198	166	211	182	8	183	8	198
		on	151	193	161	205	176		177		209
		off	46	198	165	211	182		183		204
		on	295	188	156	203	173		174		212
7	1/19	off	29	198	163	210	179	3	183	5	202
		on	171	194	161	207	179		179		209
		off	32	199	163	211	179		183		202
		on	299	192	159	204	175		177		212
8	1/19	off	23	201	166	213	182	9	186	9	201
		on	310	190	159	204	176		176		212
		off	48	197	165	210	183		182		204
		on	294	188	157	200	172		174		212

1 - Average reduction is based on the average peak sound levels and the number of pile strikes for the same pile with the bubble curtain on compared to average peak sound levels with the bubble curtain off.
2 - Average reduction is based on the SEL sound levels for the same pile with the bubble curtain on compared to SEL
3 - Cumulative SEL benchmark is 220 dBSEL based on 1995 pile strikes. Formula for calculating cumulative SEL is
NA - Pile 3 was not recorded because of equipment problems.

Introduction

This technical report presents results of underwater sound levels measured during the driving of eight 36-inch diameter steel pipe piles at the Anacortes Ferry Terminal in January 2007. All eight piles had a wall thickness of 5/8-inch.

The eight piles were monitored at mid-water depths, dependent on location and tidal flux. A bubble curtain was tested with on/off cycles during each pile driving event. Equipment failure prevented collection of date for pile 3. Figure 1 shows the project area and Figure 2 shows the locations of monitored piles.

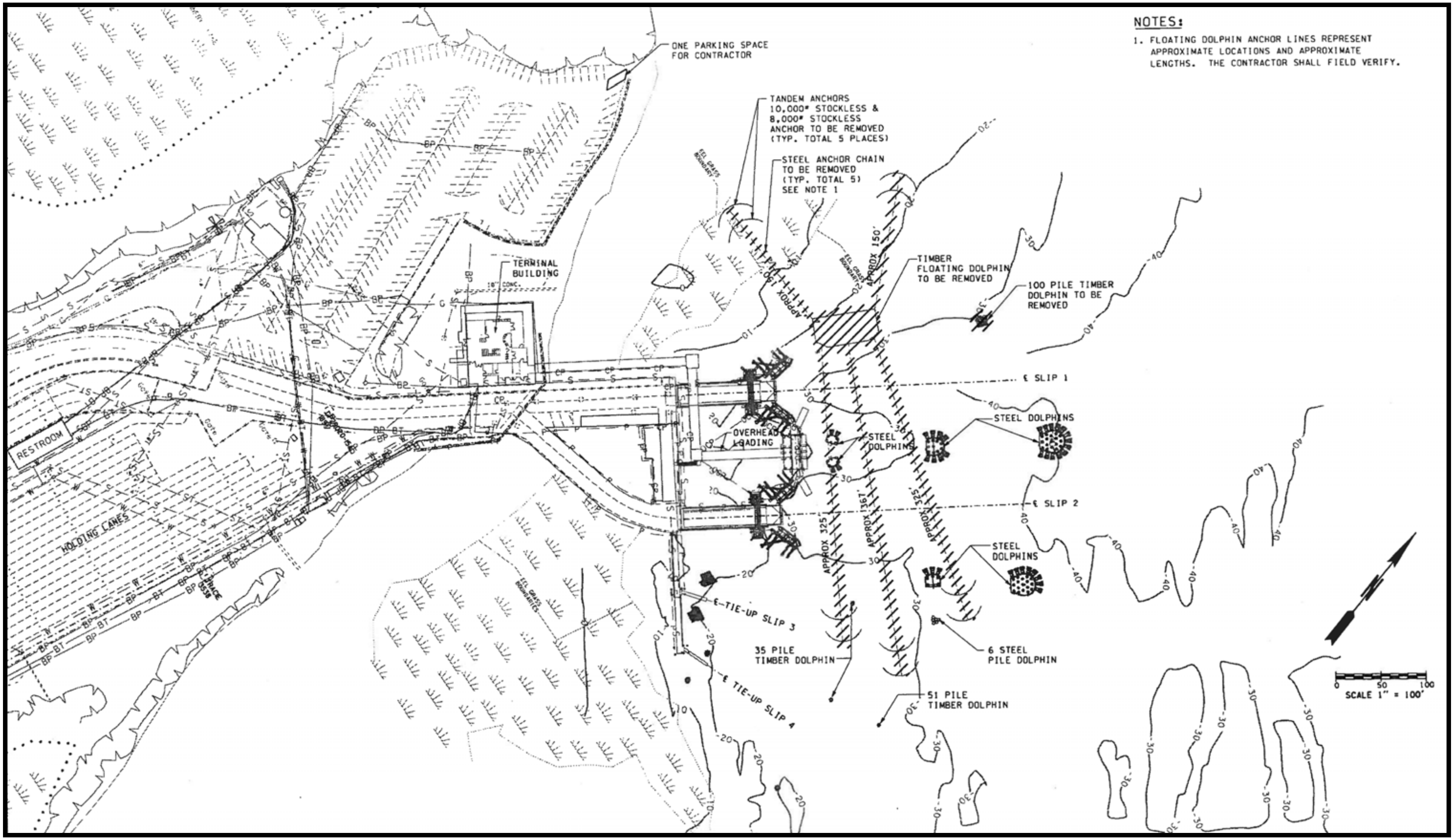
Project Description

In Slip 1, the existing floating dolphin was replaced with an eight-pile fixed dolphin and the existing 100-pile timber dolphin was replaced with a 23-pile fixed dolphin. .A six-pile fixed steel dolphin was installed in Slip 2. To construct the outer fixed dolphin in Slip 1, construction of a temporary dolphin consisting of four piles was needed.

The project location was in the northeast section of the existing Anacortes Ferry Terminal (Figure 1). Piles were driven during slack tide when water depths were approximately 42 feet deep. There was an approximate five-foot tidal flux over a six-hour period. No substantial currents were observed in the area monitored.

Figure 1: Location of dolphin replacement work at the Anacortes Ferry Terminal.

Figure 2: Location of piles relative to the bottom topography. The sediment is a mixture of sand and silt.



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 often referred to as the peak and RMS level respectively.

Peak

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. Sound levels reported in this report are expressed in dB re: 1 µPa, except where otherwise noted.

The equation to calculate the sound pressure level in water is:

Sound Pressure Level (SPL) = 20 log (p/p_{ref}), where p_{ref} is the reference pressure (i.e., 1 µPa for water)

The majority of literature uses peak sound pressures to evaluate barotrauma injuries to fish.

Root mean squared (RMS)

The RMS level is the square root of the energy divided by the impulse duration. This level, presented in dB re: 1 µPa, is the mean square pressure level of the pulse. It has been used by National Marine Fisheries Service (NMFS) in criteria for judging impacts to marine mammals from underwater impulse-type sounds.

Rise Time

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

Sound Exposure Level (SEL)

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 the time over which 90% of the pulse energy occurs. The SEL 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.

SEL is frequently used for human noise exposures and has recently been suggested as a possible metric to quantify impacts to fish (Hastings and Popper 2005). One expert, Dr. Hastings has abandoned her previous 180 dB_{peak} and 150 dB_{rms} thresholds (Hastings, 2002) and adopted the higher thresholds proposed by colleagues Popper et al. In 2006, Popper et al. proposed a threshold of 187 dB_{SEL} and 208 dB_{peak} as the new barotrauma dual criteria for fish.

Popper et al (2006) recommend a dual criterion of 208 dB re: 1 microPa (peak) and 187 dB re: 1 $microPa^2$ as interim guidance to protect fish from physical injury and mortality for a single pile driving impact. One of the reasons we have dual criteria (single peak pressure and SEL) is because the relationship between the SEL and the peak pressure is not consistent between pile strikes or between different types of piles for a given pile driving operation. A dual criteria was recommended to protect fish from barotrauma by limiting the SPL threshold to 208 peak dB, and from physical injury to their hearing by limiting the SEL threshold to 187 dB_{SEL}.

Popper and Carlson (Pers. Comm., 2006) provided the calculations below which, in essence, compare the 187 dB SEL single strike criterion presented in the Popper et al white paper to the 220 dB equivalent SEL that caused a gourami to become unconscious after 10 minutes of exposure (presented in Appendix B of Hastings and Popper 2005.) 220 dB SEL is therefore a reasonable and conservative threshold for injury. The calculations show the number of successive single strikes with an SEL of 187 dB that would be needed to result in a cumulative SEL of 220 dB.

$$\text{Cumulative SEL} = 10 \text{ Log } (\text{\# of strikes}) + \text{Single Strike SEL}$$

$$220 \text{ dB} = 10 \text{ Log } (\text{\# of strikes}) + 187 \text{ dB re: 1 microPa}^2 \bullet s$$

$$\text{\# of strikes} = 10^{(220-187)/10}$$

$$\text{\# of strikes} = 1{,}995$$

The calculations above indicate that 1,995 successive pile strikes, each with an SEL of 187 dB, would be needed to result in a cumulative SEL of 220 dB. WSDOT data indicates that for most of our piles the number of strikes average around 200 strikes per pile, often with breaks during the drive and in-between piles, with a total of approximately 400 strikes per day assuming a maximum of two piles per day.

Pile strike data for The Anacortes Ferry Terminal Dolphin Replacement Project:

- This project averaged 466 strikes per pile for the seven piles.]
- On Jauary 17, 2007, two piles were driven with 765 total pile strikes
- On January 18, 2007, one pile was driven with an unknow total number of pile strikes. It can be assumed that the total number of pile strikes was approximately 466.
- On January 19, 2007, five piles were driven with 2,153 total pile strikes.

Methodology

The hydrophone was positioned at the mid-water level, approximately 21 feet deep and 10 meters (33 feet) from the pile being monitored. The signal conditioner kept the high underwater sound levels within the dynamic range of the signal analyzer (Figure 3). The output was received by the signal spectrum analyzer attached to a 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.

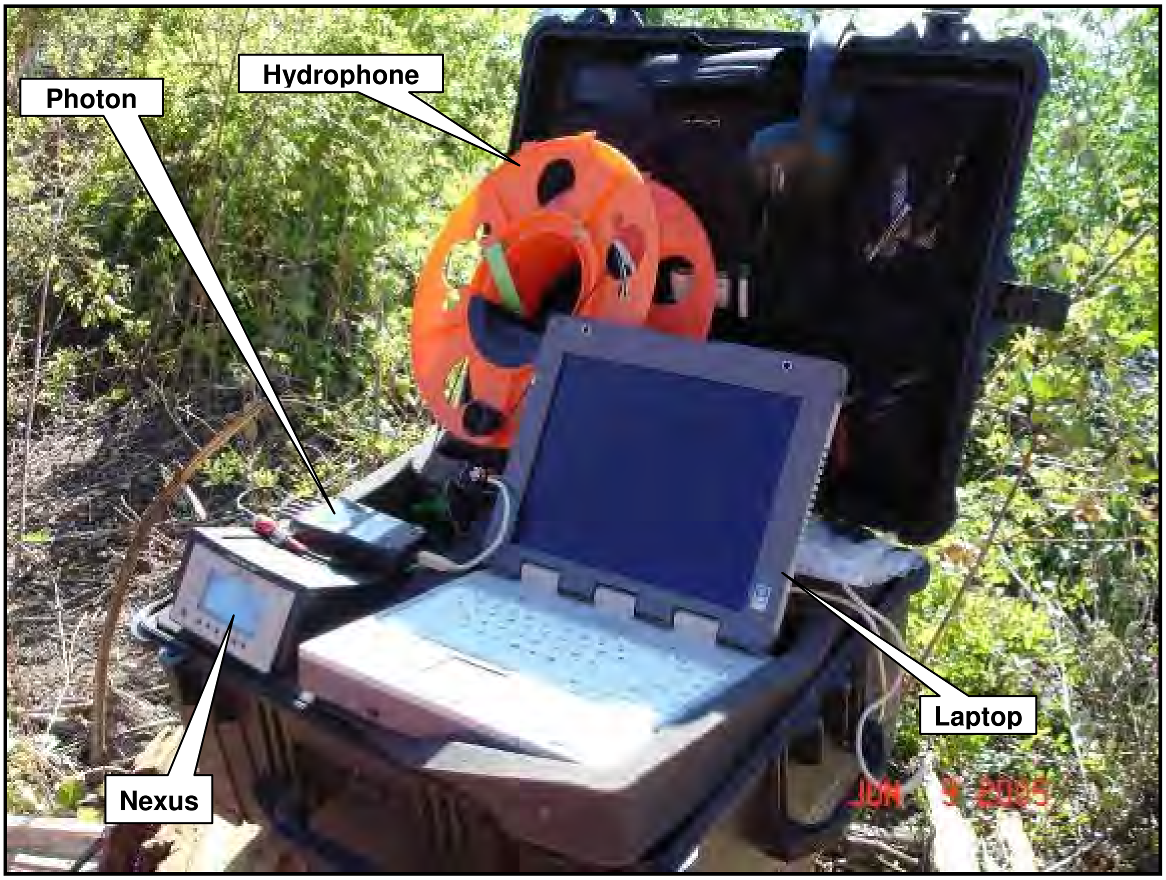
The hydrophone was checked daily by a high-level pistonphone with a hydrophone adaptor. The pistonphone signal was 146 dB at 250 Hz. The pistonphone signal levels were within 1 dB and the operation of the system was judged to be acceptable over the study period. A description of the measurement equipment is included in Table 3 and a photograph of the system and its components are shown in Figure 3 and Table 4.

Table 2: Equipment for underwater sound measurement.

Item	Type	Quantity	Usage
Hydrophone with 200 feet of cable	Reson TC4013	1	Positioned at mid-water to detect underwater sound levels.
Signal Conditioning Amplifier (4-channel)	Brüel & Kjær NEXUS model 2692	1	Reduce high sound levels from hydrophone to levels compatible with recording equipment.
Calibrator	GRAS Type 42AC	1	Daily calibration check of hydrophone in the field.
Portable Dynamic Signal Analyzer (4-channel)	Dactron Photon	1	Analyzes and transfers digital data to laptop hard drive.
Laptop computer	Itronix Go-Book	1	Record digital data on hard drive and signal analysis.
Real time and post-analysis software.	RT-Pro 5.04	1	Monitor real-time signal and post-analysis of sound level signals.
Range finder	Bushnell Yardage Pro		Measured distance between the pile and hydrophone
Weighted nylon line marked in 5-foot increments to attach hydrophone.	-	1	Takes the strain off of the hydrophone cables preventing damage.
Various surface floats.	-	3	To keep the hydrophone at the appropriate depth in relation to the surface.

The above hydrophone, amplifier, and calibrator all have current National Institute of Standards and Technology (NIST) traceable calibration.

Figure 3: Picture of sound level measurement equipment.



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

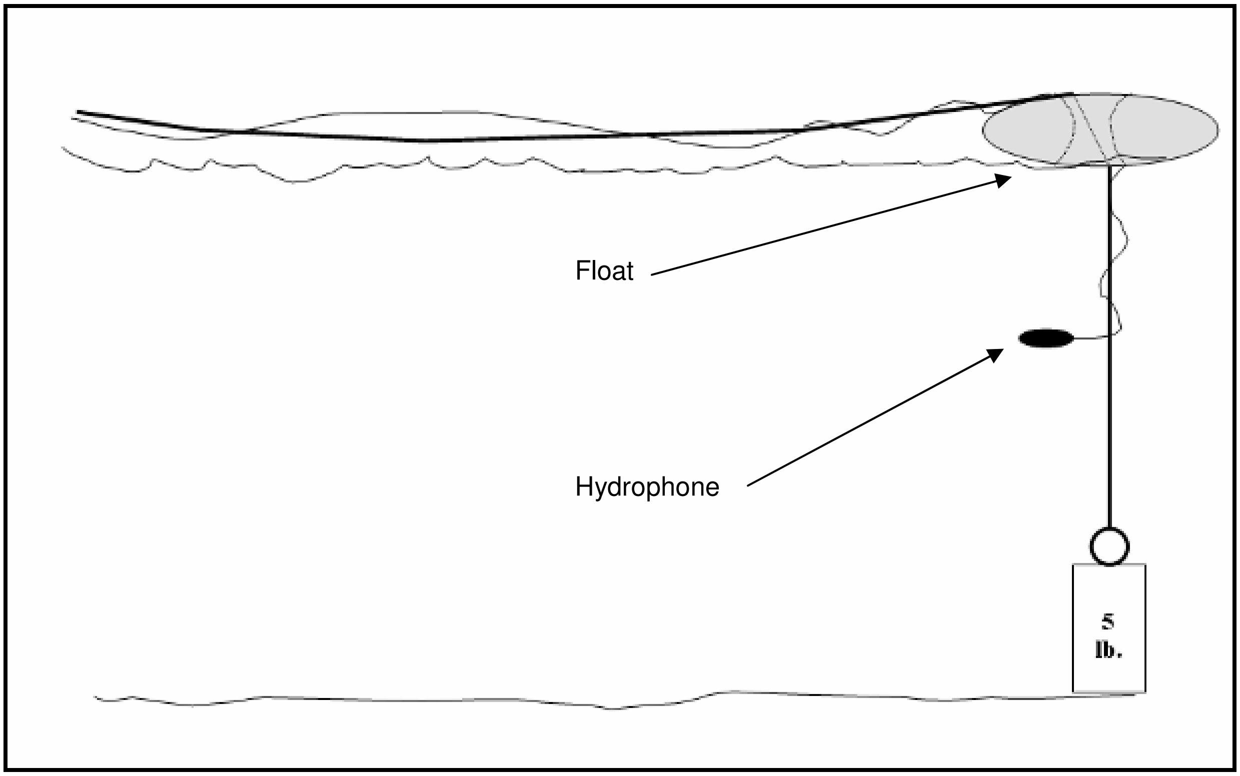
Due to the high degree of variability between the absolute peaks for each pile strike, an average peak, RMS value, and the standard deviation (s.d.) to give an indication of the amount of variation around the average for each pile is calculated.

A vibratory hammer was used to drive the piles initially. Then all of the piles were driven to bearing depth with a diesel hammer. The diesel impact driver was a ICE model 120S-15 single action diesel pile driving hammer rated to a maximum of 165,000 foot pounds. 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 typically 50% to 70% of this maximum energy for most pile installations. This hammer's rated continuous energy is 132,500 foot pounds.

The substrate consisted of a mix of sand and silt. Eight open-ended hollow steel piles, 30-inches in diameter were driven. All measurements were made apprximately 10 meters (33 feet) from the pile, at mid-water depth of approximately 21 feet.

The hydrophone was placed with a clear line of sight to the pile, with no other structures nearby except for the derrick and attached to a weighted nylon cord anchored with a five-pound weight. The cord and hydrophone cables were attached to a surface float at 10 meters (33 feet) from the pile (Figure 4).

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



Bubble Curtain Design

Two bubble curtains were used on the Anacortes Multimodal Terminal Project. The two curtains share a similar design, with one major difference being the weighting system used to keep the curtain flush with the sediment surface. Bubble curtain one was designed by the contractor and used sandbags strapped to the lower curtain ring to keep it settled at the bottom.

Bubble curtain two was the same bubble curtain used on the Mukilteo Test Pile Project (2006) and had weights incorporated into the lower ring. The design is also similar to the bubble curtain used at the Friday Harbor Ferry Terminal Project in 2005. Figure 5 shows the standard bubble curtain design that was used for all three projects.

Bubble curtain specifications are described in Table 3 and Figure 6 shows a photgraph of the bubble curtains.

Figure 5: Diagram of a bubble curtain ring system and the bubble curtain hole spacing pattern.

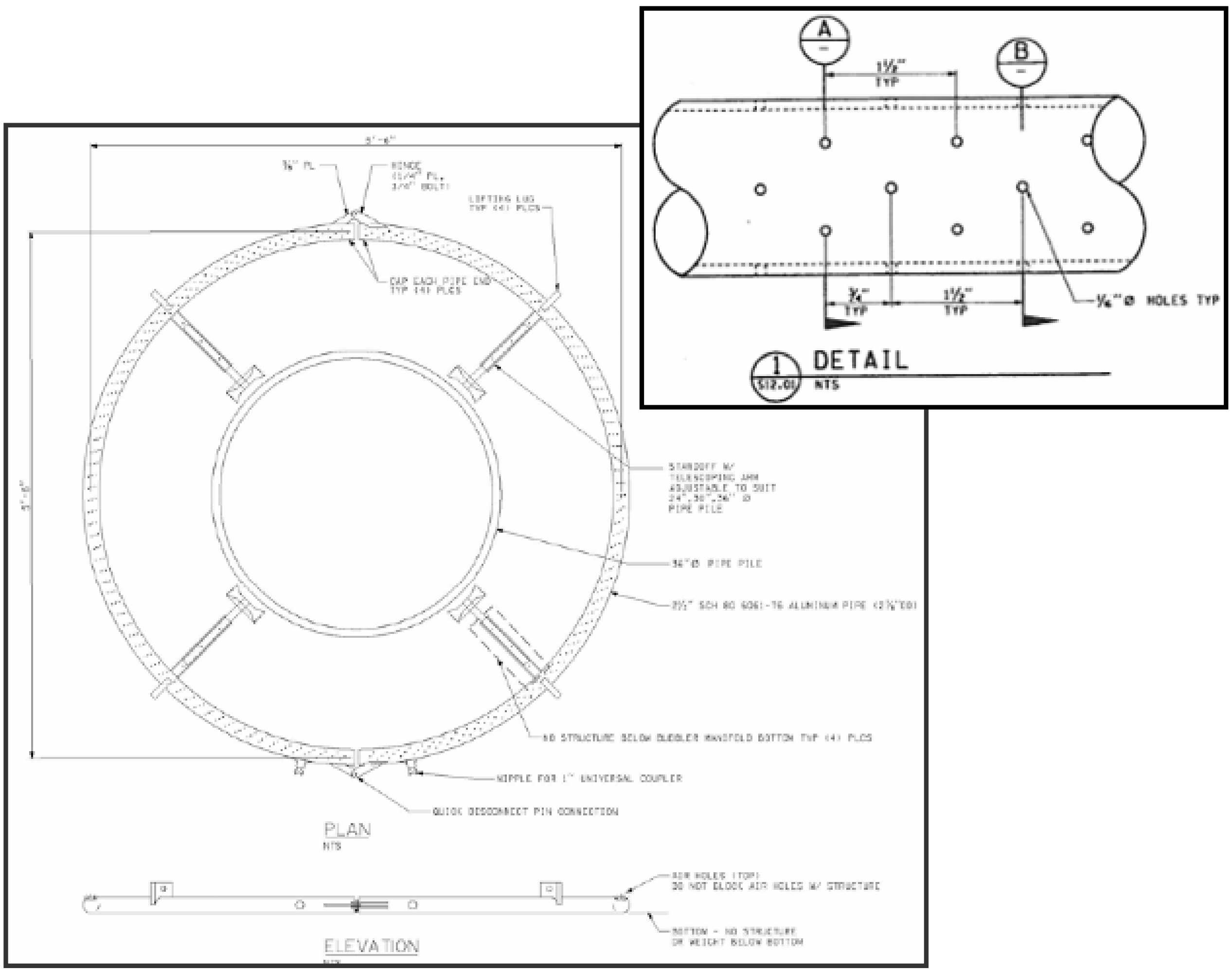
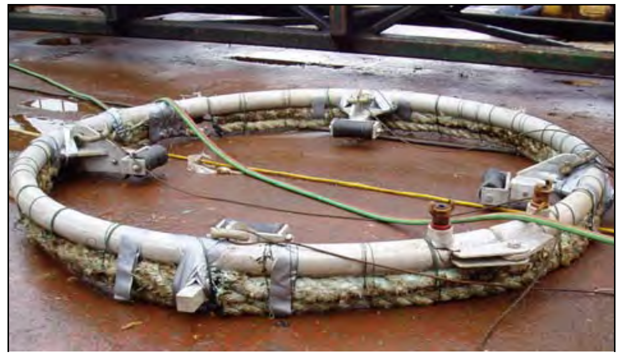
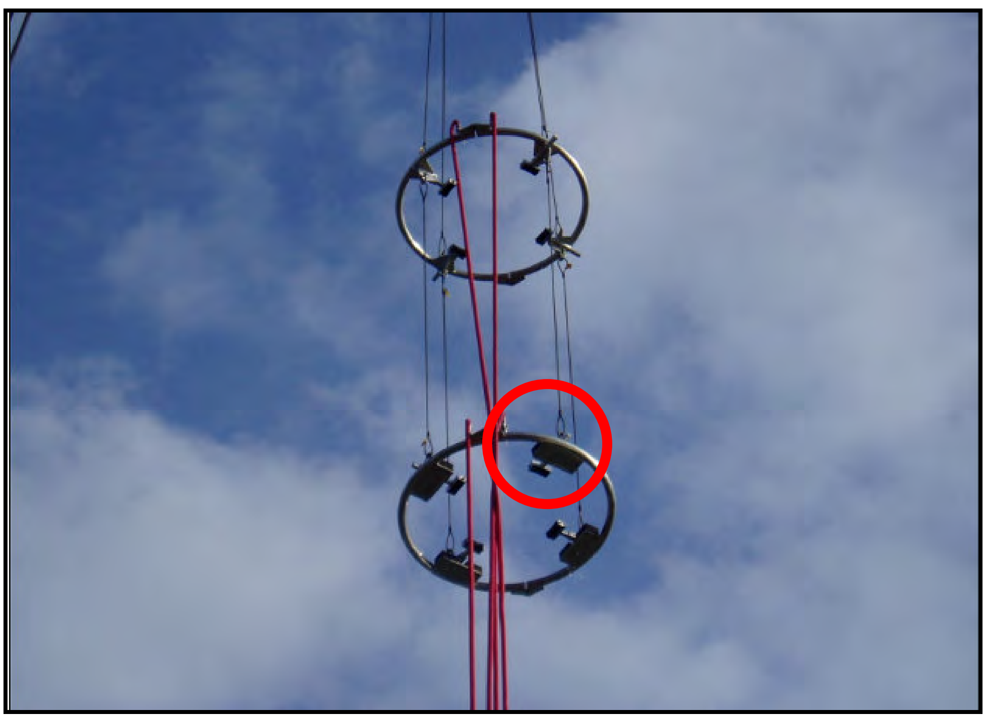


Figure 6: Photographs of the bubble curtains prior to deployment around the pile.



The red circle shows the sandbags strapped on to the metal rings for weight for bubble curtain one. Rope was strapped to the base of the bottom ring to cover the lugs and keep the ring flush with the seafloor bottom.



The red circle shows the weighting system for bubble curtain two.

Table 3: Pile number and bubble curtain specifications.

Pile number	Date (2007)	Bubble curtain	Performance Air flow (scfm)[1]	Pressure (psi)[2]
1	1/17	1	300	75
2	1/18	1	300	75
3	1/19	1	310	80
4	1/19	1	320	80
5	1/19	2	320	80
6	1/19	1	350	110
7	1/19	2	350	110
8	1/19	1	350	110

1- (SCFM) Standard cubic feet per minute

2 - (PSI) Pounds per square inch

Results

A total of 3,259 pile strikes were measured for the seven[1] steel piles driven January 17-19, 2007.

Average Peak and Average Reductions for Peak and RMS

The absolute peak values were pulled directly from the data. Average peaks and average RMS are a simple arithmetic average of the measured peaks for both descriptors.

Average sound level reduction values for the peak and RMS were calculated differently than the average values. Average deductions were calculated using the weighted mean values. The explanation of this process is described in Appendix A.

Waveforms

The waveform tables included in this section all use axes with the same scale, except Pile 2 which requires a larger scale. This will facilitate visual comparisons between piles, and with and without mitigation. There are many interesting attributes of the waveforms of different piles and mitigation types that will become evident.

SEL

SEL was calculated for the single highest absolute peak strike for each pile. None of the SEL values for any of the monitored piles exceeded Popper et al's proposed threshold of 187 dB SEL for a single strike or 220 dB for a single pile (2006). Because decibels are on a logarithmic scale, it would require substantially more energy to exceed the threshold than was measured during this project.

Rise Time

Yelverton (1973) has indicated that rise time was the cause of most injury to fish. 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 times, the higher the likelihood for effects on fish.

In six of the seven monitored piles the rise times were much shorter without mitigation than with the bubble curtain turned on. This could be an indication that the pile was ringing due to the relatively hard substrate or an indication of sound flanking. Sound flanking occurs when the majority of the energy travels up through the sediment in instead of through the water. However, this relationship is not entirely clear.

[1] Pile 3 is not included in the cumulative SEL measurement because it was not measured due to technical problems.

Table 4: Summary of underwater sound levels for the Anacortes Multimodal Terminal Project at mid-water.

Pile	Date	Bubble curtain	Number of strikes	Peak RMS (dB)	Avg. peak RMS (dB)	Average RMS ± s.d.(Pa)	Peak (dB)	Average peak (dB)	Avg. reduction[1] (dB)	Average peak ± s.d.(Pa)	SEL (dB)	Avg. SEL reduction[2] (dB)	Cumulative SEL (dB)[3]	% Strikes exceeding 180 dB	Rise time (millisec)
1	1/17	off	43	200	166	4,118 ± 1,214	213	184	11	32,945 ± 9,712	185	9	203	100%	2.6
		on	280	189	157	1,436 ± 1,24	207	173		9,391 ± 1,900	175		211	100%	6.4
2	1/17	off	51	201	168	5,217 ± 872	214	185	11	35,871 ± 5,543	186	8	204	100%	18.2
		on	299	192	157	1,451 ± 206	207	174		9,648 ± 2,611	178		212	100%	2.0
		off	92	201	166	3,959 ± 481	214	184		33,335 ± 3,524	186		207	100%	6.4
3	1/18	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*
4	1/19	off	36	200	163	2,879 ± 1,244	213	180	5	20,734 ± 9,401	185	9	203	100%	1.6
		on	305	191	158	1,565 ± 211	205	175		11,138 ± 2,768	176		212	99%	5.6
5	1/19	off	24	199	164	3,153 ± 988	212	181	10	22,110 ± 7,324	185	9	201	100%	0.9
		on	257	192	158	1,679 ± 278	204	174		10,243 ± 2,115	177		211	100%	7.0
		off	52	199	166	4,159 ± 844	212	184		31,671 ± 8,342	184		204	98%	17.0
		on	110	186	156	1,291 ± 189	199	172		7,599 ± 812	173		207	100%	8.5
6	1/19	off	12	198	166	3,907 ± 1,310	211	182	8	24,929 ± 8,568	183	8	198	92%	6.9
		on	151	193	161	2,172 ± 242	205	176		13,343 ± 1,645	177		209	99%	21.2
		off	46	198	165	3,542 ± 1,032	211	182		26,011 ± 6,977	183		204	100%	8.2
		on	295	188	156	1,268 ± 157	203	173		8,606 ± 1,596	174		212	100%	16.9
7	1/19	off	29	198	163	2,833 ± 1,144	210	179	3	18,556 ± 9,320	183	5	202	93%	1.1
		on	171	194	161	2,324 ± 239	207	179		17,648 ± 3,013	179		209	99%	7.0
		off	32	199	163	2,710 ± 1,166	211	179		18,259 ± 8,919	183		202	94%	0.8
		on	299	192	159	1,807 ± 181	204	175		11,255 ± 1,486	177		212	100%	7.3
8	1/19	off	23	201	166	3,956 ± 1,497	213	182	9	26,357 ± 12,056	186	9	201	100%	21.0
		on	310	190	159	1,718 ± 297	204	176		12,582 ± 1,968	176		212	100%	6.1
		off	48	197	165	3,535 ± 381	210	183		29,216 ± 2,253	182		204	100%	0.9
		on	294	188	157	1,432 ± 147	200	172		8,263 ± 669	174		212	100%	9.5

1 - Average reduction is based on the average peak sound levels and the number of pile strikes for the same pile with the bubble curtain on compared to average peak sound levels with the bubble curtain off.

2 - Average reduction is based on the SEL sound levels for the same pile with the bubble curtain on compared to SEL sound levels with the bubble curtain off.

3 - Cumulative SEL benchmark is 220 dBSEL based on 1995 pile strikes. Formula for calculating cumulative SEL is 10Log10(#strikes)+187dBSEL.

NA - Pile 3 was not recorded because of equipment problems.

All piles were 36-inch hollow steel piles with 5/8-inch wall thickness.

Pile 1

Pile 1 was driven with a diesel hammer in 42 feet of water using bubble curtain one. The sound levels for Pile 1 in Table 5 indicates an 11 decibel noise reduction with the bubble curtain on compared to driving the pile without a bubble curtain. 11 decibels was the largest decibel reduction measured on this project.

Strike Characteristics

The bubble curtain was turned on after approximately 43 pile strikes without a bubble curtain to assess the effectiveness of the bubble curtain.

Waveform and Frequency Spectral Analysis

In Figure 7 a, b, the peak pile strike waveforms with and without mitigation are represented. When Figure 7b is compared to the peak strike waveform for Pile 1 without a bubble curtain (Figure 7a), there appears to be a decrease in the overall amplitude of the pile strike when the bubble curtain is used.

In Figure 7c, the narrow band frequencies of the peak pile strikes with and without mitigation for Pile 1 are compared. In this spectral analysis there appears to be some suppression of all frequencies which would also correlate to the drop in amplitude of the peak strike seen in Figure 7b.

Monitoring Results

Table 5: Sound level characteristics of Pile 1.

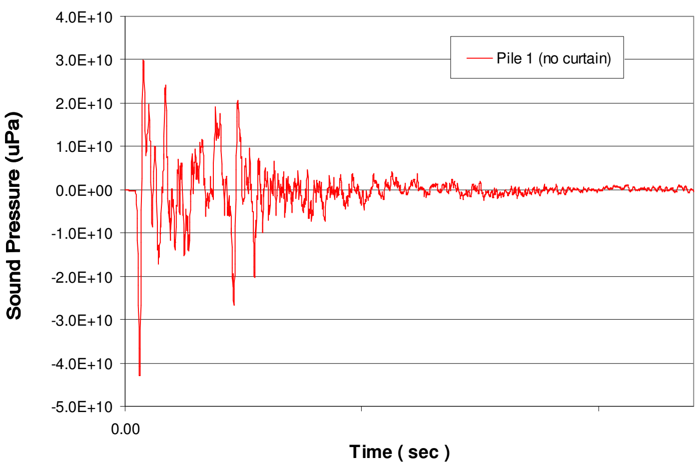
Pile number	**1**	
Bubble Curtain	off	on
Absolute peak	213	207
RMS	200	189
SEL	185	175
Rise Time	2.6	6.4
Cumulative SEL	203	211

Rise time uses the lowest measured value. All other values reflect the highest meausured value.

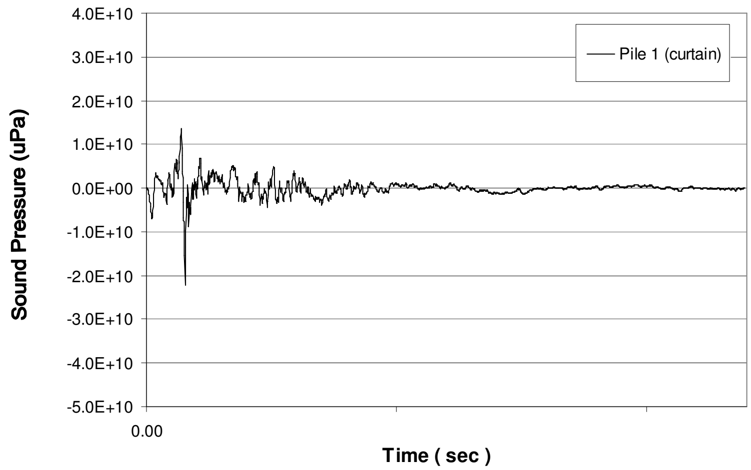
- 100% all of the peak values exceeded both 180 dB_{peak} and 150 dB_{RMS}
- No single strike peak and SEL in Table 2 exceeded the proposed interim dual criteria of 208 dB_{peak} and 187 dB_{SEL} when the bubble curtain was on.

Figure 7: Waveforms and frequency spectral analysis for Pile 1 using bubble curtain one.

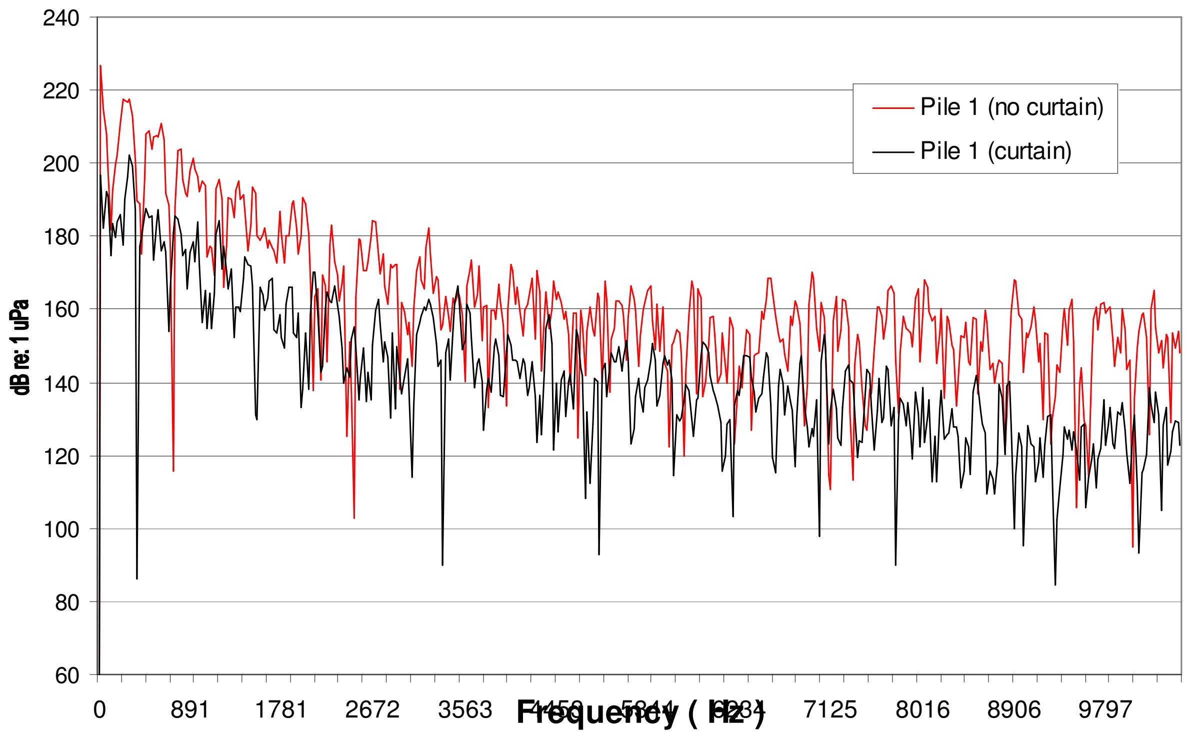
a. Waveform: Pile 1 no bubble curtain.



b. Waveform: Pile 1 with bubble curtain.



c. Frequency spectral analysis of Pile 1.



Pile 2

Pile 2 was driven with a diesel hammer in 42 feet of water using bubble curtain one. The sound levels for Pile 2 in Table 2 indicates an 11 decibel noise reduction with the bubble curtain compared to driving the pile without a bubble curtain. 11 decibels was the greatest reduction measured on this project.

Strike Characteristics

The bubble curtain was turned on after approximately 51pile strikes without a bubble curtain pile strikes to assess the effectiveness of mitigation. The curtain was then turned off again before the end of the drive in an attempt to compare the sound levels without a bubble curtain early in the driving to those at the end.

Waveform and Frequency Spectral Analysis

In Figures 8a, b and c, the peak pile strike waveforms with and without the bubble curtain are represented. When compared to the peak strike waveform for Pile 2 without mitigation (Figure 8a,c) there appears to be a decrease in the overall amplitude of the pile strike when the bubble curtain is used (Figure 10b).

In Figure 8 d, the narrow band frequencies of the peak pile strikes with and without mitigation for Pile 2 are compared. In this spectral analysis there appears to be some suppression of all the frequencies with the bubble curtain, which would also correlate to the drop in amplitude of the peak strike seen in Figure 8b.

Monitoring Results

Table 6: Sound level characteristics of Pile 2.

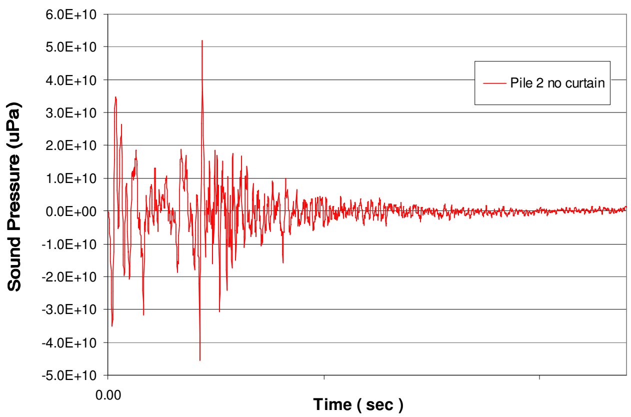
Pile number	**2**	
Bubble Curtain	off	on
Absolute peak	214	207
RMS	201	192
SEL	186	175
Rise Time	6.4	2.0
Cumulative SEL	212	207

Rise time uses the lowest measured value. All other values reflect the highest meausured value.

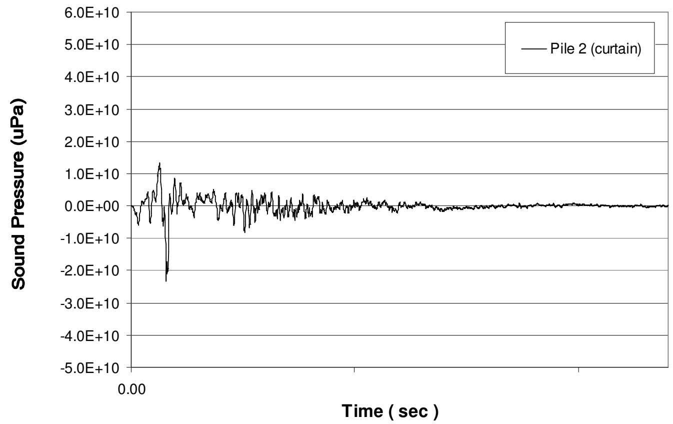
- 100% all of the peak values exceeded both 180 dB_{peak} and 150 dB_{RMS}.
- No single strike peak and SEL in Table 2 exceeded the proposed interim dual criteria of 208 dB_{peak} and 187 dB_{SEL} when the bubble curtain was on.

Figure 8: Waveforms and frequency spectral analysis for Pile 2 using bubble curtain one.

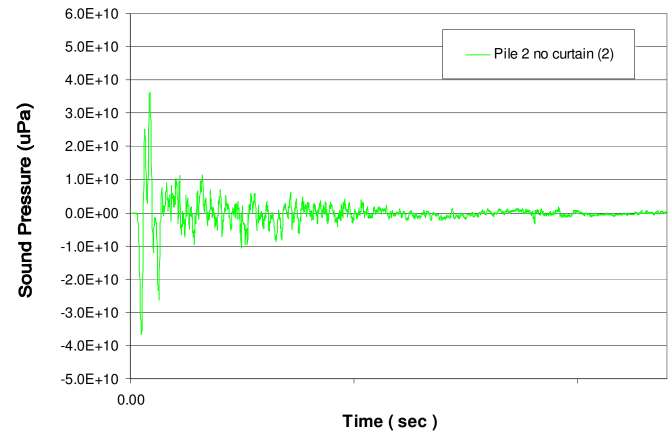
a. Waveform: Pile 2 no bubble curtain



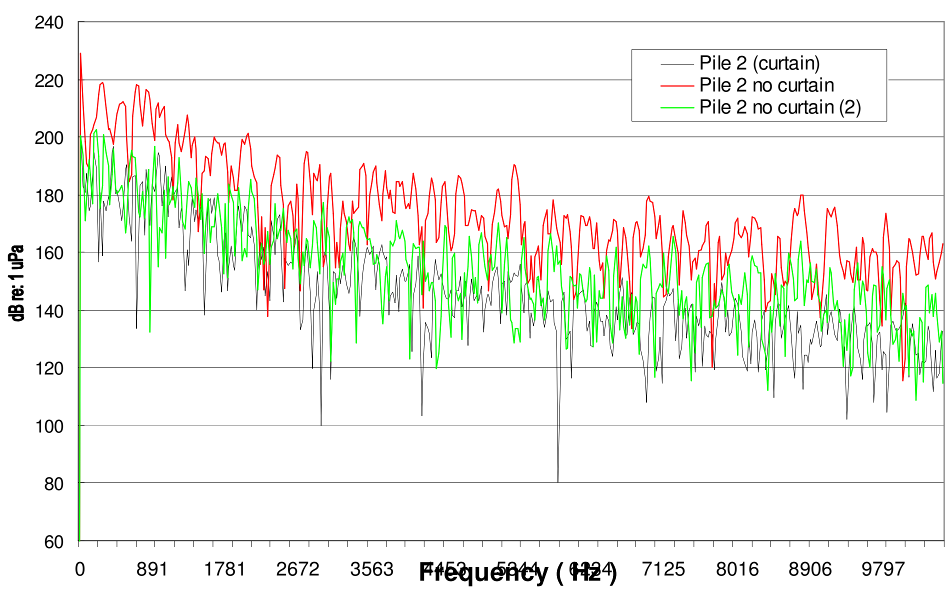
b. Waveform: Pile 2 with bubble curtain



c. Waveform: Pile 2 no bubble curtain (2)



d. Frequency Spectral Analysis of Pile 2.



Pile 3

Pile 3 was driven with a diesel hammer in 42 feet of water using bubble curtain one. The sound levels for Pile 3 in Table 2 are listed as “na” for not available. The sound analyst had a problem with the equipment and the strikes were not recorded accurately. Therefore, Pile 3 data is not considered reliable or sufficient to include in this report.

Pile 4

Pile 4 was driven with a diesel hammer in 42 feet of water using bubble curtain one. The sound levels for Pile 4 in Table 2 indicates a five decibel noise reduction with the bubble curtain compared to driving the pile without a bubble curtain.

Strike Characteristics

The bubble curtain was turned on after approximately 36 pile strikes without a bubble curtain pile strikes to assess the effectiveness of the bubble curtain.

Waveform and Frequency Spectral Analysis

In Figures 9a, b, the peak pile strike waveforms with and without the bubble curtain are represented. When compared to the peak strike waveform for Pile 4 without the bubble curtain (Figure 9a) there appears to be a decrease in the overall amplitude of the pile strike when the bubble curtain is used (Figure 9b).

In Figure 9c, d, the narrow band frequencies of the peak pile strikes with and without the bubble curtain for Pile 4 are compared. In this spectral analysis there appears to be some suppression of all the frequencies, which would also correlate to the drop in amplitude of the peak strike seen in Figure 9b.

Monitoring Results

Table 7: Sound level characteristics of Pile 4.

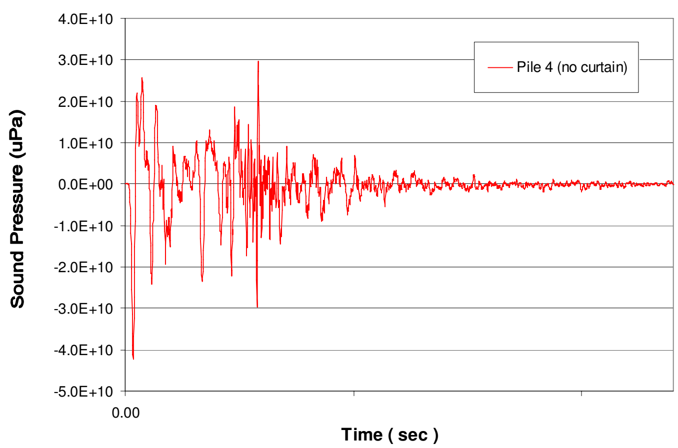
Pile number	**4**	
Bubble Curtain	off	on
Absolute peak	213	205
RMS	200	191
SEL	185	176
Rise Time	1.6	5.6
Cumulative SEL	203	212

Rise time uses the lowest measured value. All other values reflect the highest meausured value.

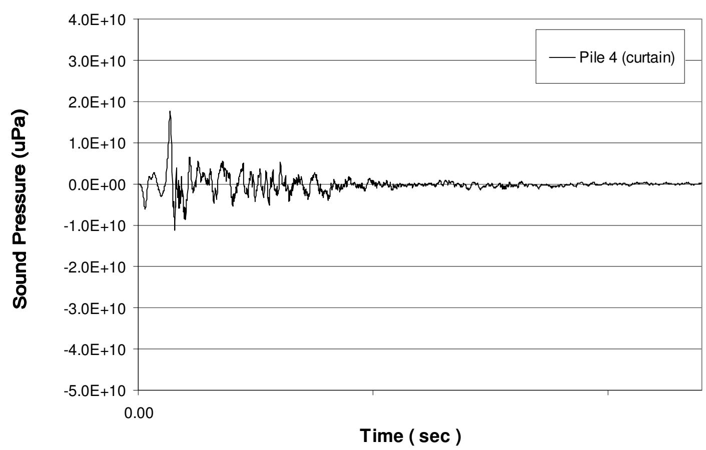
- 99% all of the peak values exceeded 180 dB_{peak} and 100% exceeded 150 dB_{RMS}.
- No single strike peak and SEL in Table 2 exceeded the proposed interim dual criteria of 208 dB_{peak} and 187 dB_{SEL} when the bubble curtain was on.

Figure 9: Waveforms and frequency spectral analysis for Pile 4 using bubble curtain one.

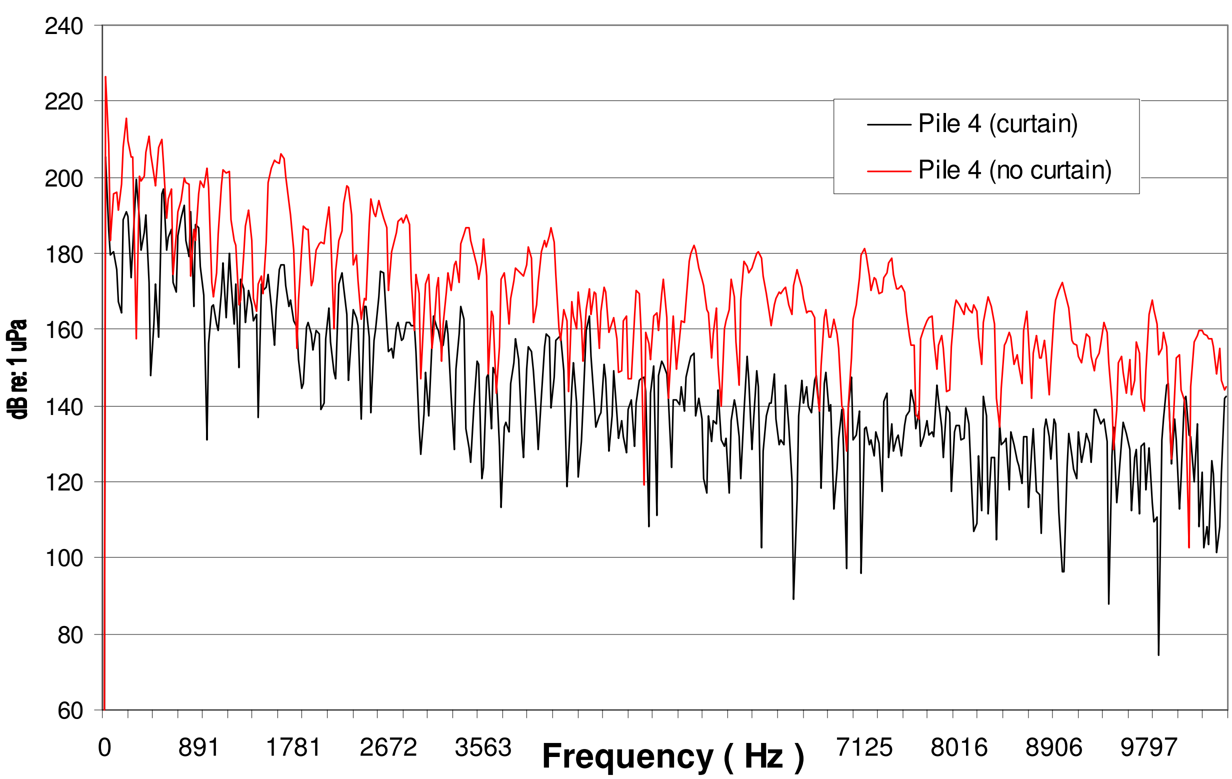
a. Waveform: Pile 4 with bubble curtain



b. Waveform: Pile 4 with bubble curtain



c. Frequency spectral analysis of Pile 4.



Pile 5

Pile five was driven with a diesel hammer in 42 feet of water using bubble curtain two. The sound levels for pile five in Table 2 indicates a 10 decibel noise reduction with the bubble curtain compared to driving the pile without a bubble curtain.

Strike Characteristics

The bubble curtain was turned on and off as follows to assess the effectiveness of the bubble curtain.

- Off – 24 strikes
- On – 257 strikes
- Off – 52 strikes
- On – 110 strikes

Waveform and Frequency Spectral Analysis

In Figures 10a-d, the peak pile strike waveforms are represented with and without a bubble curtain. When compared to the peak strike waveform for Pile 5 without mitigation (Figure 10a, c) there appears to be a decrease in the overall amplitude of the pile strike when the bubble curtain is used (Figure 10b,d).

In Figure 10e, the narrow band frequencies of the peak pile strikes with and without mitigation for Pile 5 are compared. In this spectral analysis there appears to be some suppression of the higher frequencies which would also correlate to the drop in amplitude of the peak strike seen in Figure 10b and 10d.

Monitoring Results

Table 8: Sound level characteristics of Pile 5.

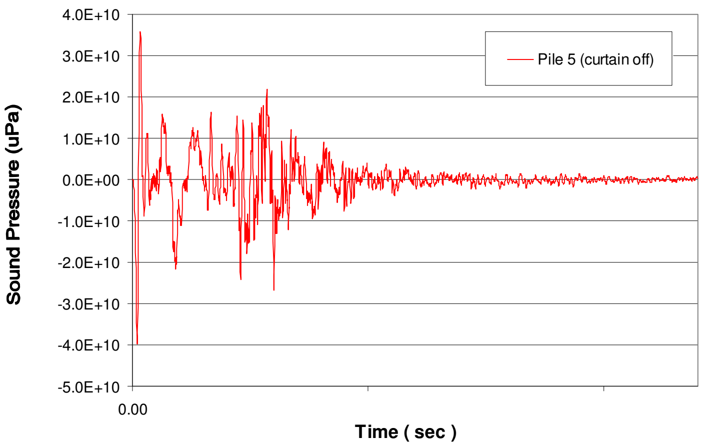
Pile number	**5**	
Bubble Curtain	off	on
Absolute peak	212	204
RMS	199	192
SEL	185	177
Rise Time	0.9	7.0
Cumulative SEL	204	211

Rise time uses the lowest measured value. All other values reflect the highest meausured value.

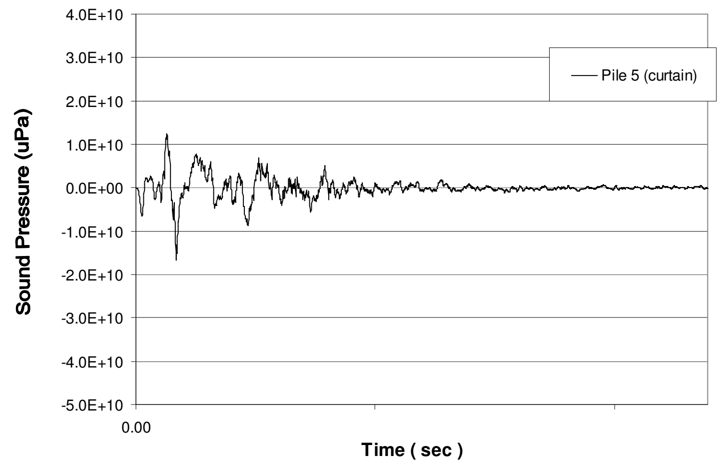
- 98% all of the peak values exceeded 180 dB_{peak} and 100% exceeded 150 dB_{RMS}.
- No single strike peak and SEL in Table 2 exceeded the proposed interim dual criteria of 208 dB_{peak} and 187 dB_{SEL} when the bubble curtain was on.

Figure 10: Waveforms and frequency spectral analysis for Pile 5 using bubble curtain one.

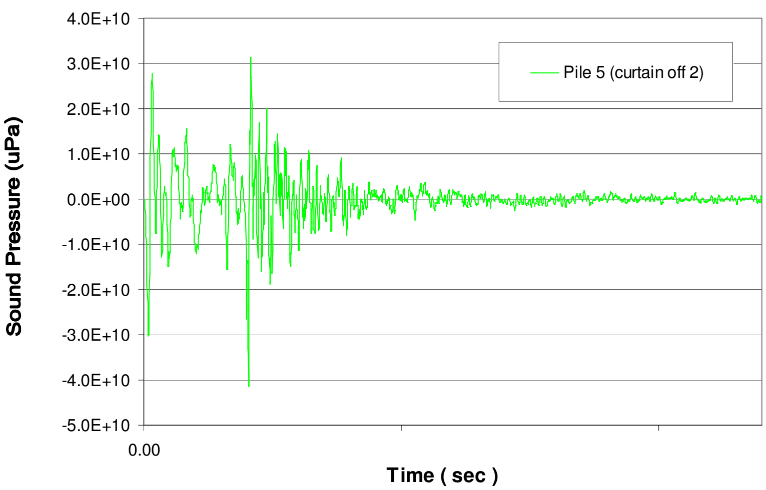
a. Waveform: Pile 5 no bubble curtain



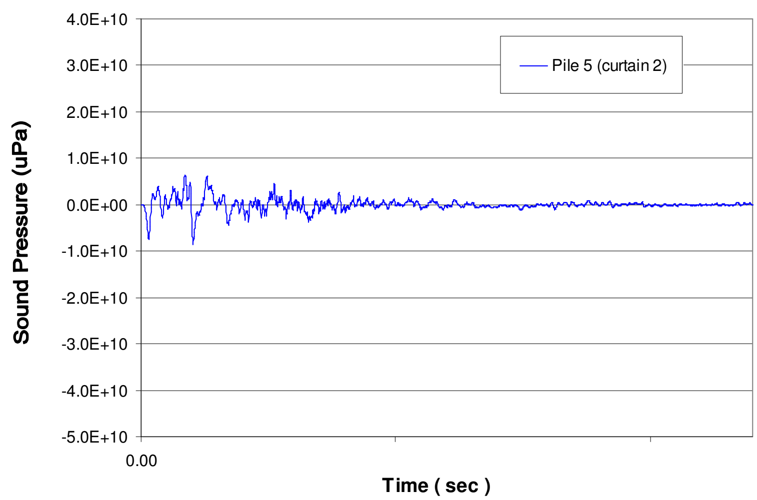
b. Waveform: Pile 5 with bubble curtain



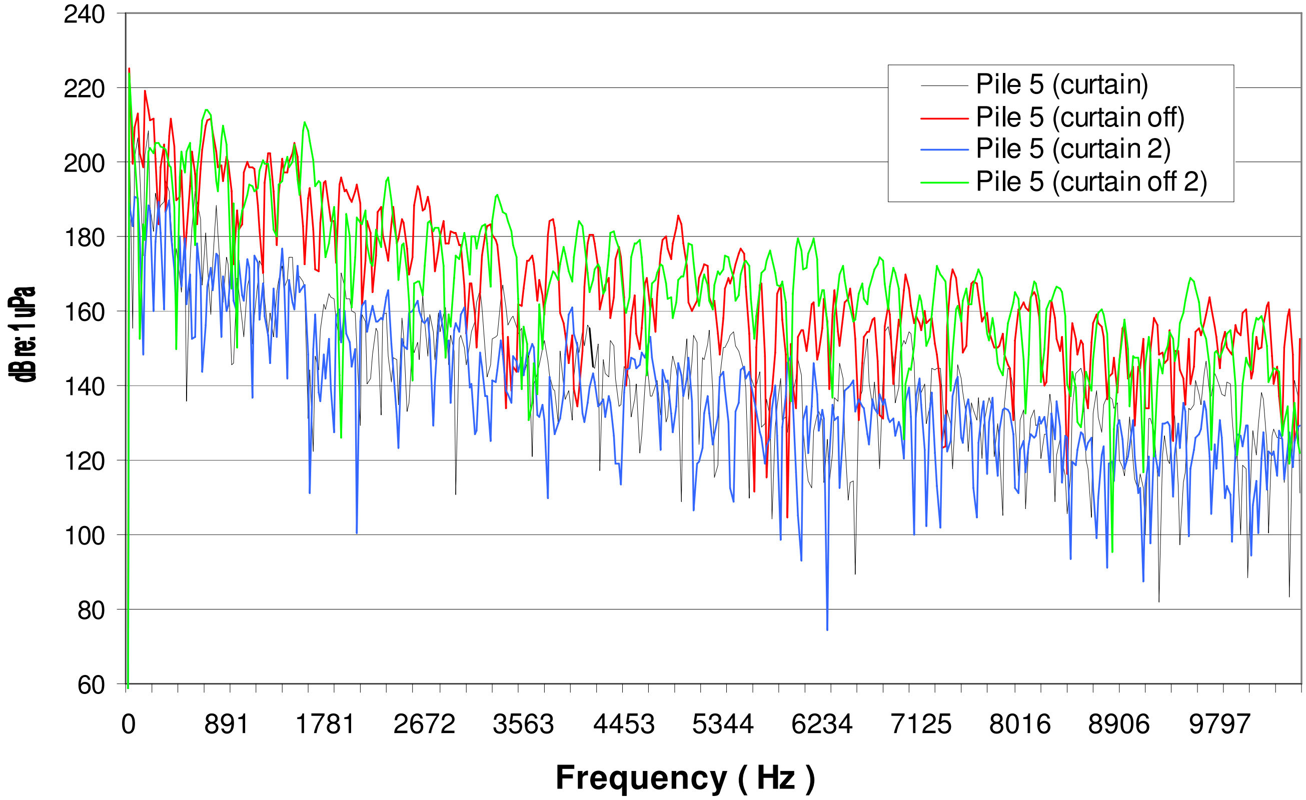
c. Waveform: Pile 5 no bubble curtain (2)



d. Waveform: Pile 5 with bubble curtain (2)



e. Frequency spectral analysis of Pile 5.



Pile 6

Pile 6 was driven with a diesel hammer in 42 feet of water using bubble curtain one. The sound levels for Pile 6 in Table 2 show a eight decibel noise reduction with the bubble curtain compared to driving the pile without a bubble curtain.

Strike Characteristics

The bubble curtain was turned on and off as follows to assess the effectiveness of the bubble curtain.

- Off – 12 strikes
- On – 151 strikes
- Off – 46 strikes
- On – 295 strikes

Waveform and Frequency Spectral Analysis

In Figures 11a-d, the peak pile strike waveforms with and without mitigation are represented. When compared to the peak strike waveform for Pile 6 without the bubble curtain (Figure 11a,c) there appears to be a decrease in the overall amplitude of the pile strike when the bubble curtain is used (Figure 11b,d).

In Figure 11 e, the narrow band frequencies of the peak pile strikes with and without the bubble curtain for Pile 6 are compared. In this spectral analysis there appears to be some suppression of all the frequencies, which would also correlate to the drop in amplitude of the peak strike seen in Figure 11b and 11d.

Monitoring Results

Table 9: Sound level characteristics of Pile 6.

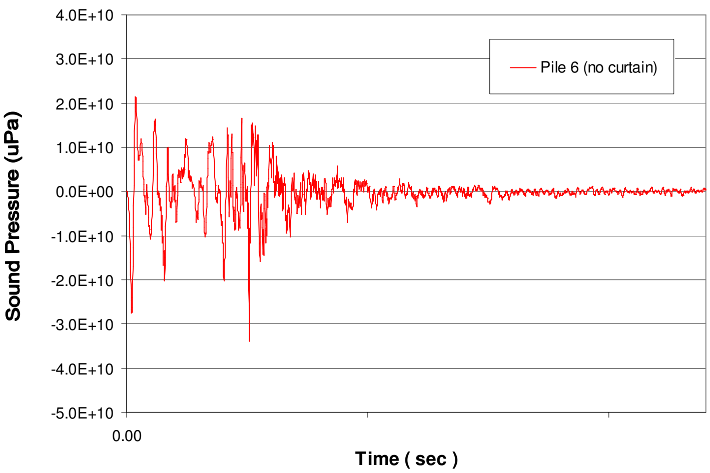
Pile number	**6**	
Bubble Curtain	off	on
Absolute peak	211	205
RMS	198	193
SEL	183	177
Rise Time	6.9	16.9
Cumulative SEL	204	212

Rise time uses the lowest measured value. All other values reflect the highest meausured value.

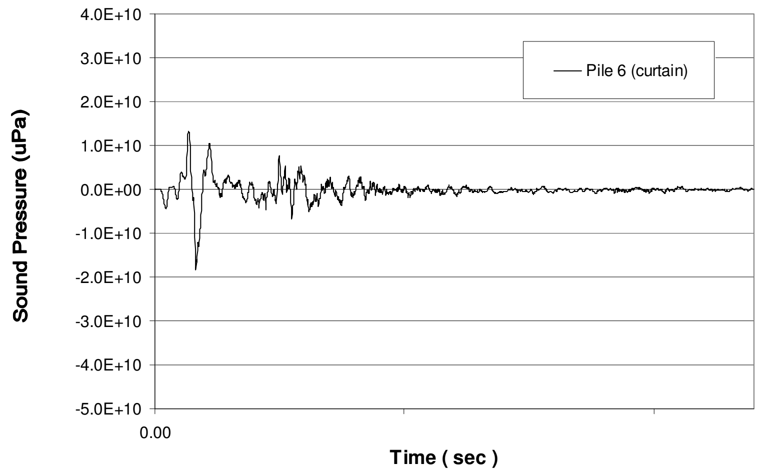
- 99% all of the peak values exceeded 180 dB_{peak} and 100% exceeded 150 dB_{RMS}.
- No single strike peak and SEL in Table 2 exceeded the proposed interim dual criteria of 208 dB_{peak} and 187 dB_{SEL} when the bubble curtain was on.

Figure 11: Waveforms and frequency spectral analysis for Pile 6 using bubble curtain one.

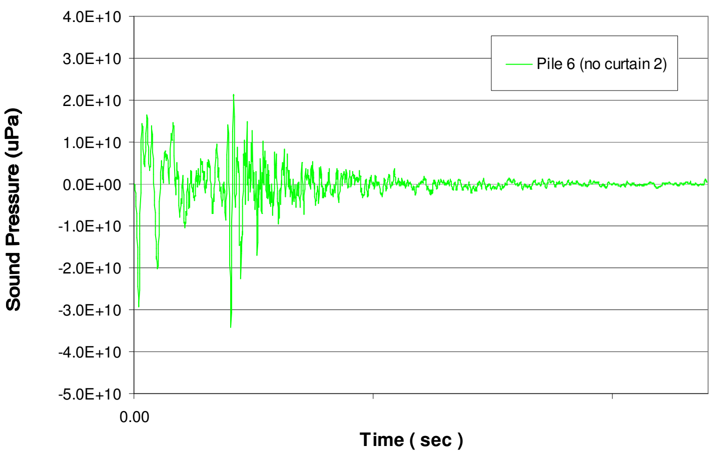
a. Waveform: Pile 6 no bubble curtain



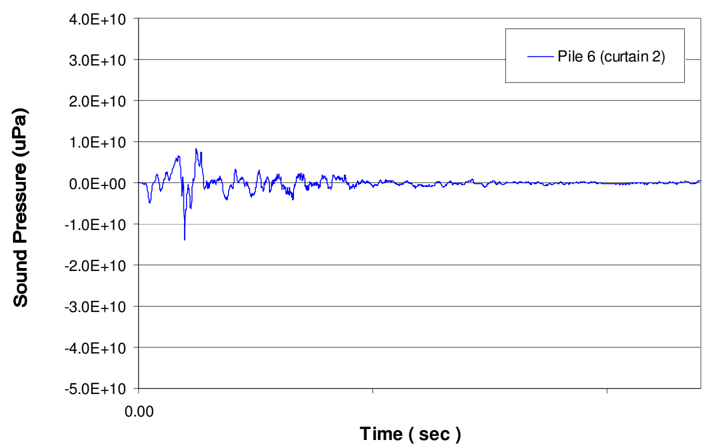
b. Waveform: Pile 6 with bubble curtain



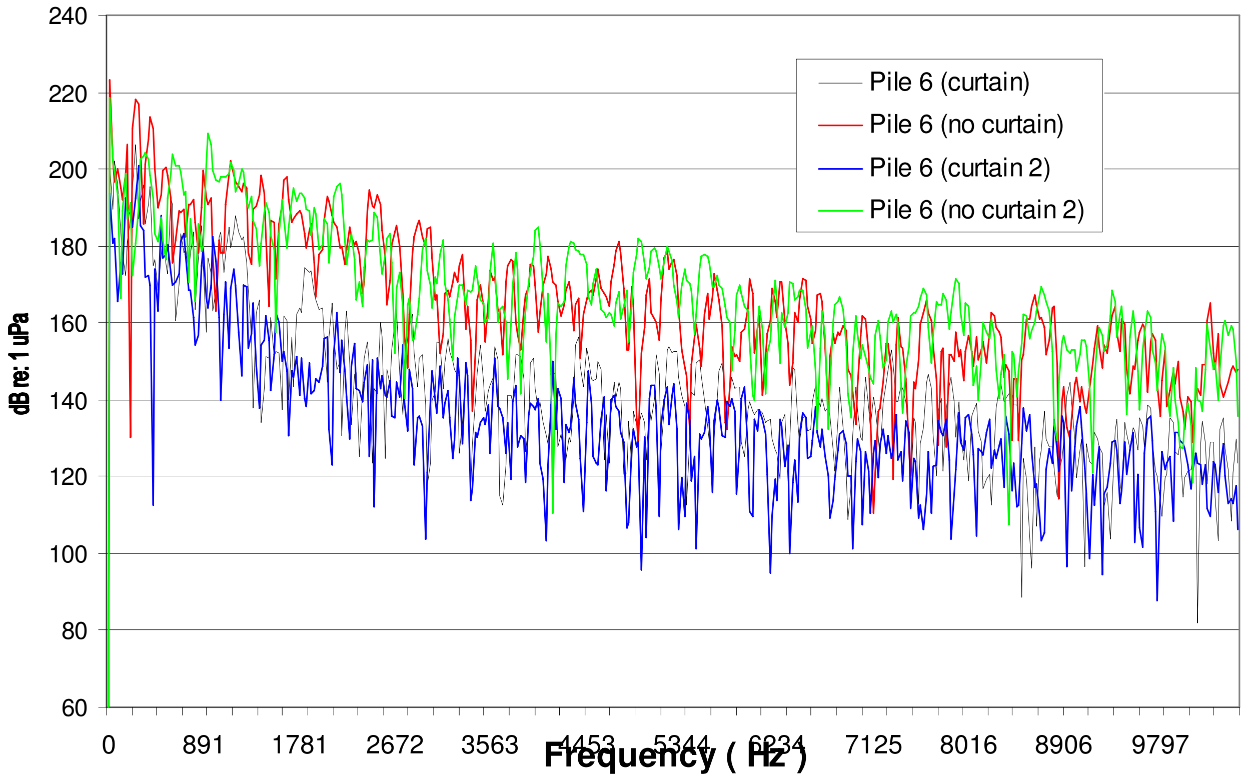
c. Waveform: Pile 6 no bubble curtain (2)



Waveform: Pile 6 with bubble curtain (2)



d. Frequency spectral analysis of Pile 6.



Pile 7

Pile 7 was driven with a diesel hammer in 42 feet of water using bubble curtain two. The sound levels for Pile 7 in Table 2 indicates a three decibel noise reduction with the bubble curtain compared to driving the pile without the bubble curtain. This was the least amount of sound reduction measured on the project.

Strike Characteristics

The bubble curtain was turned on and off as follows to assess the effectiveness of the bubble curtain.

- Off – 29 strikes
- On – 171 strikes
- Off – 32 strikes
- On – 299 strikes

Waveform and Frequency Spectral Analysis

In Figures 12a-d, the peak pile strike waveforms with and without a bubble curtain are represented. When compared to the peak strike waveform for Pile 7 without the bubble curtain (Figure 12a, c) there appears to be a decrease in the overall amplitude of the pile strike when the bubble curtain is used (Figure 12b, d).

In Figure 12c, d, the narrow band frequencies of the peak pile strikes with and without mitigation for Pile 7 are compared. In this spectral analysis, there appears to be some suppression (the least of all the measured piles) of all the frequencies, which would also correlate to the drop in amplitude of the peak strike seen in Figure 12b and 12d.

Monitoring Results

Table 10: Sound level characteristics of Pile 7.

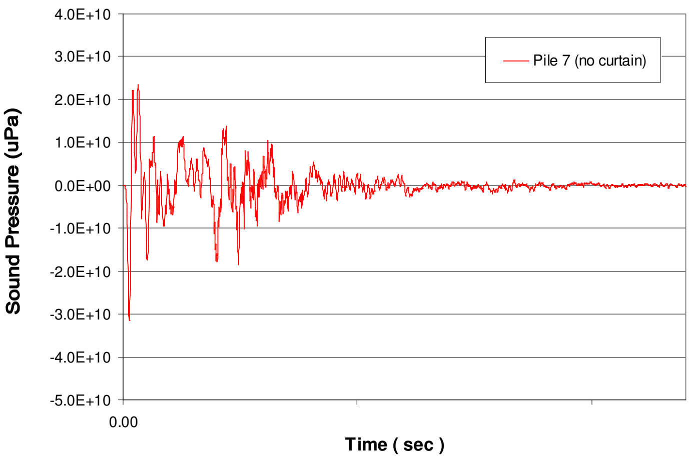
Pile number	**7**	
Bubble Curtain	off	on
Absolute peak	211	207
RMS	199	194
SEL	183	179
Rise Time	0.8	7.0
Cumulative SEL	212	212

Rise time uses the lowest measured value. All other values reflect the highest meausured value.

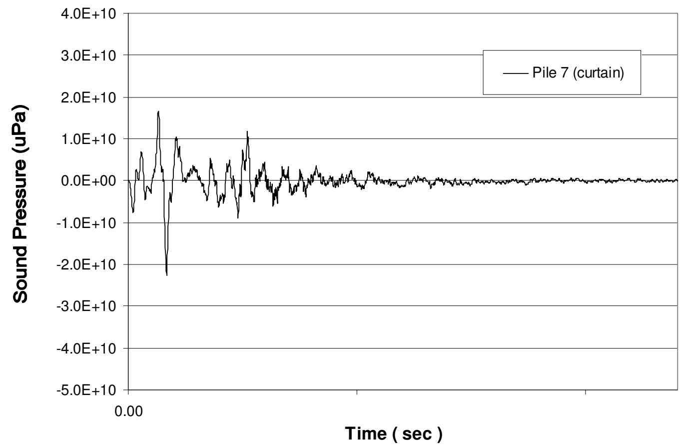
- 100% all of the peak values exceeded 180 dB_{peak} and 100% exceeded 150 dB_{RMS}.
- No single strike peak or SEL in Table 2 exceeded the proposed interim dual criteria of 208 dB_{peak} and 187 dB_{SEL} when the bubble curtain was on.

Figure 12: Waveforms and frequency spectral analysis for Pile 7 using bubble curtain two.

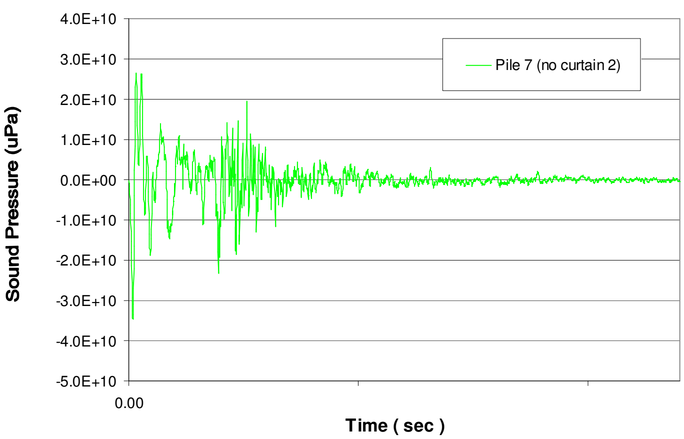
a. Waveform: Pile 7 no bubble curtain



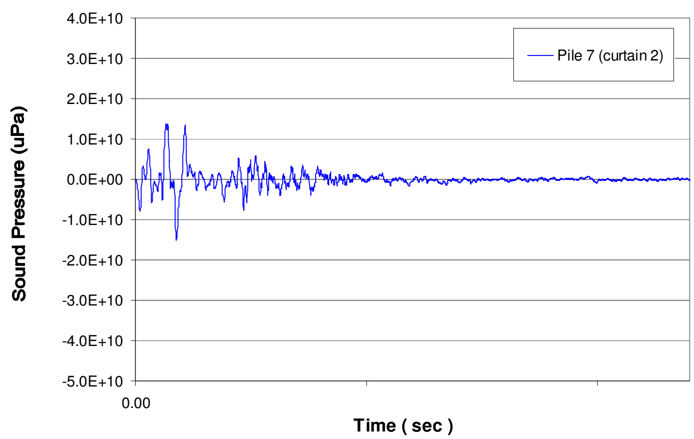
b. Waveform: Pile 7 with bubble curtain



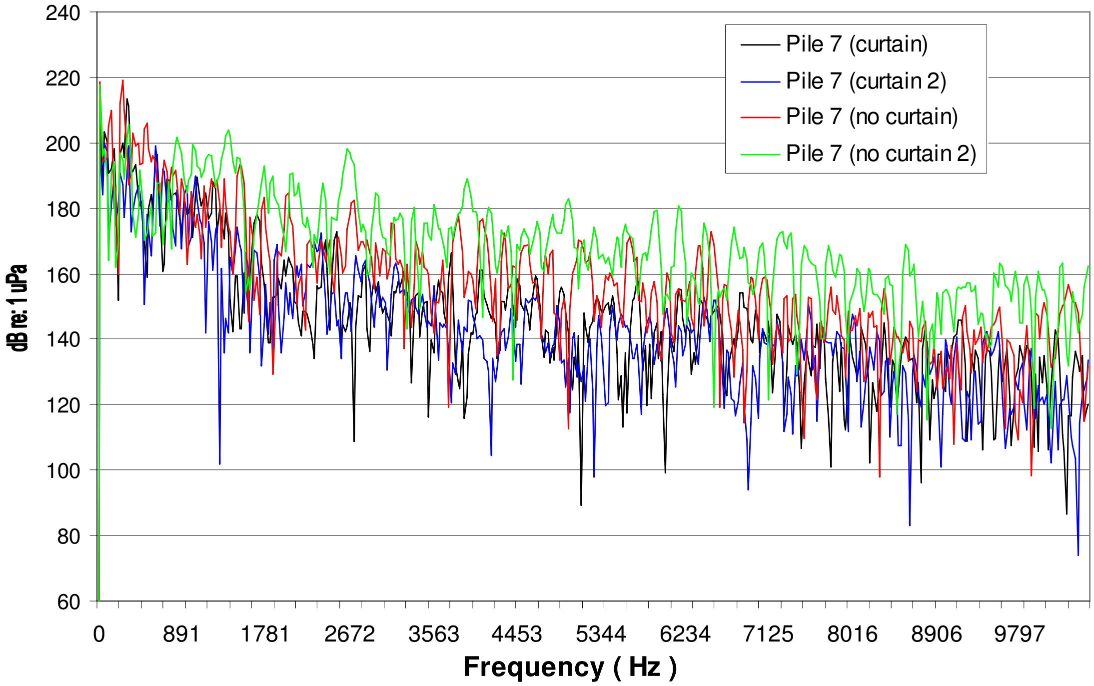
c. Waveform: Pile 7 no bubble curtain (2)



Waveform: Pile 7 with bubble curtain (2)



e. Frequency spectral analysis of Pile 7.



Pile 8

Pile 8 was driven with a diesel hammer in 42 feet of water using bubble curtain one. The sound levels for Pile 8 in Table 2 show a nine decibel noise reduction with the bubble curtain compared to driving the pile without a bubble curtain.

Strike Characteristics

The bubble curtain was turned on and off as follows to assess the effectiveness of the bubble curtain.

- Off – 23 strikes
- On – 310 strikes
- Off – 48 strikes
- On – 294 strikes

Waveform and Frequency Spectral Analysis

In Figures 13a-d, the peak pile strike waveforms with and without a bubble curtain are represented. When compared to the peak strike waveform for Pile 8 without the bubble curtain (Figure 13a, c) there appears to be a decrease in the overall amplitude of the pile strike when the bubble curtain is used (Figure 13b, d).

In Figure 13e, the narrow band frequencies of the peak pile strikes with and without the bubble curtain for Pile 8 are compared. In this spectral analysis there appears to be some suppression of the higher frequencies, which would also correlate to the drop in amplitude of the peak strike seen in Figure 13b and 13 d.

Monitoring Results

Table 11: Sound level characteristics of Pile 8.

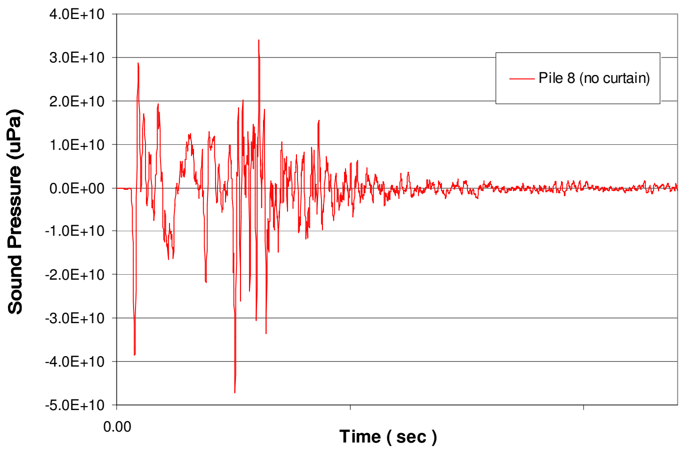
Pile number	**8**	
Bubble Curtain	off	on
Absolute peak	213	204
RMS	201	190
SEL	186	176
Rise Time	0.9	6.1
Cumulative SEL	204	212

Rise time uses the lowest measured value. All other values reflect the highest meausured value.

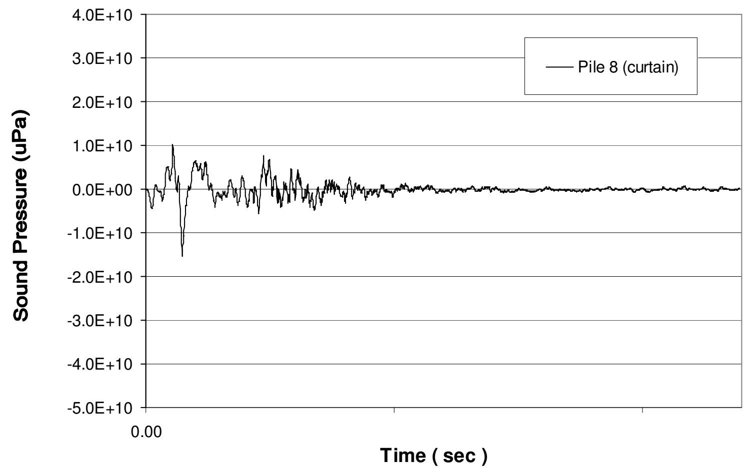
- 100% all of the peak values exceeded 180 dB_{peak} and 100% exceeded 150 dB_{RMS}.
- No single strike peak and SEL in Table 2 exceeded the proposed interim dual criteria of 208 dB_{peak} and 187 dB_{SEL} when the bubble curtain was on.

Figure 13: Waveforms and frequency spectral analysis for pile eight using bubble curtain one.

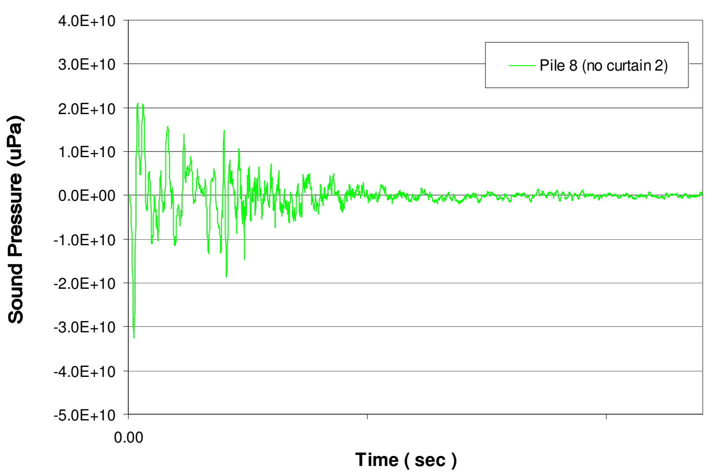
a. Waveform: Pile 8 no bubble curtain



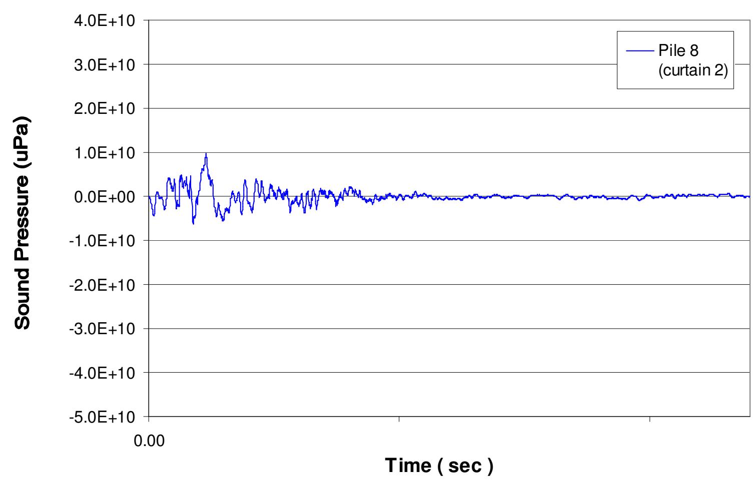
b. Waveform: Pile 8 with bubble curtain



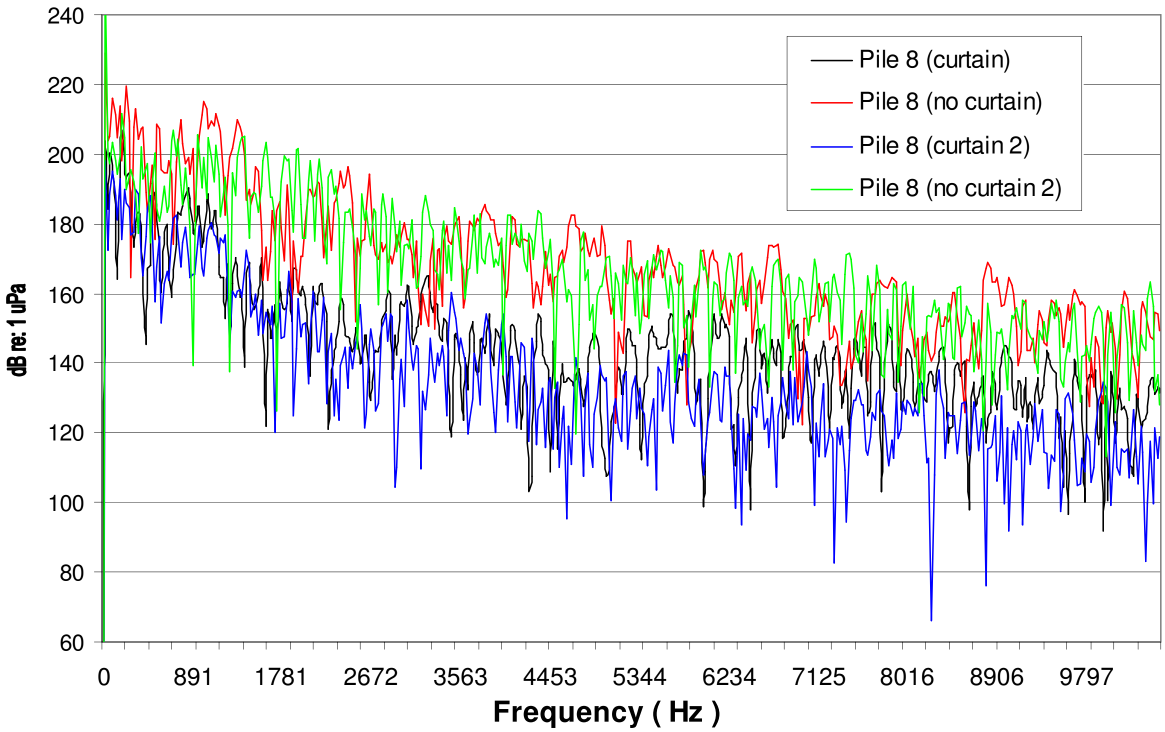
c. Waveform: Pile 8 no bubble curtain (2)



Waveform: Pile 8 with bubble curtain (2)



d. Frequency spectral analysis of Pile 8.



Biological Observations

WSDOT biologists and consultant biologists were present for the driving of the eight piles measured for underwater sound levels. The water surface and surrounding air was visually observed by eye and binoculars from the barge and from a survey boat during pile driving. After a pile was completed, a boat was used to aid surveying the water within 1000 feet of the construction site.

Birds within 1000 feet on the water tended to flush and depart the area when pile driving commenced. Several returned to sit on the water within six minutes during construction breaks. Birds, particularly cormorants and gulls, would fly by within a few hundred feet during pile driving. One murrelet was observed swimming on the surface within 20 meters of the pile-driving platform and exhibited abnormal behavior following the pile driving on January 27, 2009. Sound levels were not measured on this day.

No fish or mammals appeared to be injured or behave in a way that suggested having been injured. In order to help prevent injuries to fish during unattenuated baseline readings, the contractor turned the bubble curtain on before pile driving began to scare away any fish that might be in the immediate area of the piles. Then the bubble curtain was turned off and pile driving started. Besides the murrelet, no other animals were seen on or came to the water surface within 200 feet during any of the initial pile blows. The harbor seal departed the work area when human activity increased, before pile driving began. A bald eagle perched on a tree ~2000 west of the project but departed during pile driving.

Wildlife observed during the pile driving include:

Mammals

- Harbor seal within construction area
- Harbor porpoise at least 3000 feet away from construction
- Otter species within construction area

Birds

- Hooded merganser
- American robin
- Bufflehead
- American widgeon
- Mallard
- Double-crested cormorant
- Pelagic cormorant
- Great blue heron
- Fox sparrow
- Gadwall
- Pigeon guillemot
- Red-breasted merganser
- Barrow’s goldeneye
- Western grebe
- Herring gull
- Surf scoter
- Northwest crow
- Mew gull
- Common merganser
- Belted kingfisher
- Brant’s cormorant
- Bald eagle
- Brown-headed cowbird
- Red-winged blackbird
- Winter wren
- Killdeer
- Marbled Murrelet
- Bufflehead
- Canada Geese
- Common Goldeneye
- Pacific loon

Conclusions

No thresholds were exceeded when the bubble curtain was turned on, nor were any fish kills observed throughout the duration of the pile driving that was measured for underwater sound levels. One murrelet was observed on the water surface near the pile driving, and was possibly stressed by the airbourne sound levels. However, no noise measurements were being conducted that day, so no conclusions about noise impacts on the bird can be drawn.

The seven measured piles exhibited a wide range of noise reductions with a bubble curtain compared to sound levels when the bubble curtain was turned off. Peak reductions using the bubble curtain ranged from three to 11 decibel peaks. These sound level reductions were less than the sound level reductions of 19 to 24 decibel peaks measured at the Mukilteo Multimodal Ferry Terminal Test Project in December, 2006.

None of the single strike SEL values calculated on the absolute peak pile strike exceeded the proposed threshold of 187 dB SEL for a single strike or the calculated cumulative SEL value of 220 dB for one entire pile (Popper et al., 2006).

Table 12: Cumulative and single strike SEL totals for all piles.

Pile number	Max single strike SEL (dB)	Cumulative SEL (dB)
1	185	211
2	186	212
3	*na*	*na*
4	185	212
5	185	211
6	183	212
7	183	212
8	186	212

Proposed single strike threshold: 187 dB SEL
Cumulative benchmark vaule: 220 dB SEL

No significant relationship was seen between increased air flow and air pressure, and/or the introduction of a different bubble curtain and underwater sound level reductions (Table 13). Therefore, the sound reductions could be related to one of the variables not included in this report. For example, changes in the hammer's performance and sediment characteristics were not studied.

Table 13: Pile hammer characteristics and sound level reductions.

Pile number	Date (2007)	Bubble curtain	Performance Air flow (scfm)[1]	Performance Pressure (psi)[2]	Avg. peak reduction (dB)	Avg. reduction[3](dB)
1	1/17	1	300	75	11	9
2	1/18	1	300	75	11	8
3	1/19	1	310	80	*na*	na
4	1/19	1	320	80	5	9
5	1/19	2	320	80	10	9
6	1/19	1	350	110	8	8
7	1/19	2	350	110	3	5
8	1/19	1	350	110	9	9

1- (SCFM) Standard cubic feet per minute

2 - (PSI) Pounds per square inch

3 - (dB) Decibels

References

Bland, Martin J. and Sally M. Kerry (1998). "Weighted comparison of means." British Medical Journal, 316: 129.

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

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

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Appendix A – Explanation of Average Reduction Calculations

Average peak and average RMS reductions were calculated using both periods when the bubble curtain was turned on and both periods when the bubble curtain was turned off[2]. The effort was an attempt to quantify the average reduction received with a bubble curtain for each pile throughout the duration of the driving. Throughout the driving of a single pile, sound levels are commonly higher at the end of the driving, when the pile is deeper in the sediment, than early in the driving.

Pile 5 is a good example of these sound level changes (Table 7). If the measured reductions were taken from early in the pile driving, the measured reduction would have been 7 dB. In contrast, measured reductions later in the driving were 12 dB.

Weighted Mean

The weighted mean was used to address the measured sound level changes, such as those seen in Pile 5. I calculated the weighted mean using the number of pile strikes for weighting. This allowed me to combine the two multiple periods when the bubble curtain was off and compare it to the multiple periods when the bubble curtain was turned on, based on the number of strikes during each period. This comparison was used as the average reduction.

I acknowledge that the number of strikes during each on/off cycle is highly variable. However, this is true for all pile strike measurements and the weighted mean only an attempt to accurately collect the *measured* average sound level reduction.

Table 14: Example of average reduction calculations using Pile 5 average reduction as an example

Pile	Date	Bubble curtain	Number of strikes	Avg. peak (dB)	Avg. reduction[1] (dB)
5	1/19	off	24	181	10
		on	257	174	
		off	52	184	
		on	110	172	

The weighted mean was calculated in three steps.

1. The average peak was determined for each “on” (x 2) and “off” (x 2) cycle for each pile.
2. The averages of the “on” and “off” cycles were weighted proportionally for each pile based on the number of pile strikes occurring with each cycle. This is an attempt to normalize the changes in sound levels based on the extent of the pile beneath the sediment’s surface.
3. The average “off” peak was subtracted from the average “on” peak for the entire pile.

[2] The following calculations were done for Piles 5-8. The two “off” peak/RMS averages were compared with the one “on” cycle for Pile 2.

Figure 14 Weighted mean calculation, Pile 5

[(# of strikes x avg. peak) + (# of strikes x avg. peak)] / total number of strikes

on: [(24 x 181) + (52 x 184)] / (24 + 52)
4,344 + 9,568
13,912 / 76
183

off: [(257 x 174) + (110 x 172)] / (257 + 110)
44,718 + 18,920
63,638 / 367
173

Avg. reduction: 183 - 173 = **10**