WSF COLMAN DOCK TEST PILE PROJECT

Underwater Sound Level Report: Colman Dock Test Pile Project 2016

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ACRONYMS AND ABBREVIATIONS

dB	decibel
Hz	hertz
NIST	National Institute of Standards and Technology
Pa	Pascal
RMS	root mean squared
s.d.	standard deviation
SEL	Sound Exposure Level
SPL	sound pressure level
WSF	Washington State Ferries
WSDOT	Washington State Department of Transportation

EXECUTIVE SUMMARY

This technical report describes the data collected during impact pile driving for the Washington State Ferries (WSF) Colman Dock – Test Pile Project from January 28, 2016 through February 8, 2016. Hydroacoustic data was collected for a total of nine piles: two 24-inch steel control piles, two 36-inch steel test piles, three 36-inch hollow concrete test piles with a 24-inch diameter steel stinger, and two 18-inch solid octagonal concrete test piles with a 12-inch diameter steel stinger. Six of the nine piles monitored were located on the northwest side of the existing Colman Dock Ferry Terminal and the remaining three piles were located on the south side of Colman Dock. A confined bubble curtain was deployed during impact driving of all steel piles. All measurements were collected at midwater depth between 10-24 meters from the pile. Measurements from a range of 3H, where H is the water depth at the pile were only collected for the 24-inch steel control Pile 1 due to a malfunction of the 3H hydrophone which prevented further measurements from being recorded. Table 1 summarizes the results for each pile monitored.

The 36-inch steel piles were observed to be 25 dB louder than the 24-inch steel control piles with Peak levels of 199 dB_{peak} and 205 dB_{peak} for the 36-inch piles and 174 dB_{peak} and 180 dB_{peak} for the 24-inch piles primarily due to differing substrate conditions. The difference between the sound levels of the 36-inch hollow concrete piles and the 36-inch steel piles was 8 dB_{peak}, 5 $dB_{RMS90\%}$, and 4 $dB_{SEL90\%}$. The difference between the 18-inch octagonal concrete pile and the 36-inch steel pile was 15 dB_{peak}, 14 $dB_{RMS90\%}$, and 12 $dB_{SEL90\%}$.

Narrow Band Frequency comparisons between the different pile types showed that the 36-inch steel piles were significantly louder than the 24-inch control piles. This is likely due to the uncharacteristically soft substrate that the control piles were driven into. The 36-inch hollow concrete piles were found to be similar to the 36-inch steel piles at lower frequencies, but were 10-20 dB louder at frequencies higher than 3000 Hz. The 18-inch solid octagonal concrete piles were also found to be similar to the 36-inch steel piles at lower frequencies, but were 10-20 dB louder at frequencies higher than 3000 Hz.

Table 1: Summary of Control and Test Piles Underwater Sound Levels.

Pile #	Date	Pile Diameter (in.)	Pile Type	Range (m)	Total # Strikes	Peak (dB)	Peak L_{50}	RMS (dB)	RMS L_{50}	SEL (dB)	SEL L_{50}	Cumulative SEL (dB)	Daily Cumulative SEL (dB)
1*	1/28/2016	24	Steel (control)	12	54	174	170	157	158	149	147	171	176**
2*	1/28/2016	24	Steel (control)	15	64	180	-	165**	-	155**	-	173**	
3	2/2/2016	36	Steel	14	529	205	200	189	185	176	172	193	201
4	2/2/2016	36	Steel	24	328	199	194	184	182	172	169	195	
5	2/3/2016	36	Hollow Concrete	12	383	190	188	180	179	168	166	192	192
6	2/4/2016	36	Hollow Concrete	19	394	186	183	174	173	162	160	186	186
7	2/5/2016	36	Hollow Concrete	10	193	197	194	184	183	172	170	192	195
8	2/5/2016	18	Octagonal Concrete	10	835	190	187	175	174	164	162	191	
9	2/8/2016	18	Octagonal Concrete	10	795	189	184	173	173	163	162	191	191

*Pile driven to tip depth through very soft substrate with very little resistance and less energy going into pile resulting in lower than normal sound levels.
**RMS is estimated by subtracting 15 dB from the peak level, SEL estimated by subtracting 25 dB from the peak level and cSEL estimated by adding SEL to 10*LOG(total number of strikes)
- L_{50} statistics could not be estimated or calculated due to corrupted data

INTRODUCTION

This technical report presents results of underwater sound levels measured during the driving of two 24-inch steel control piles, two 36-inch steel test piles, three 36-inch hollow concrete test piles with a 24-inch diameter stinger, and two 18-inch solid octagonal concrete test piles with a 12-inch diameter stinger at the Colman Dock Test Pile Project in January and February of 2016.

The piles were monitored at a variable water depth of 32-17 feet with the hydrophone placed at midwater depth (9-18 feet) and a range of 33 to 78 feet (10-24 meters) from the piles. A confined bubble curtain was used during the impact driving of all steel piles. Figure 1 shows the project area and Figure 2 shows the locations of monitored piles.

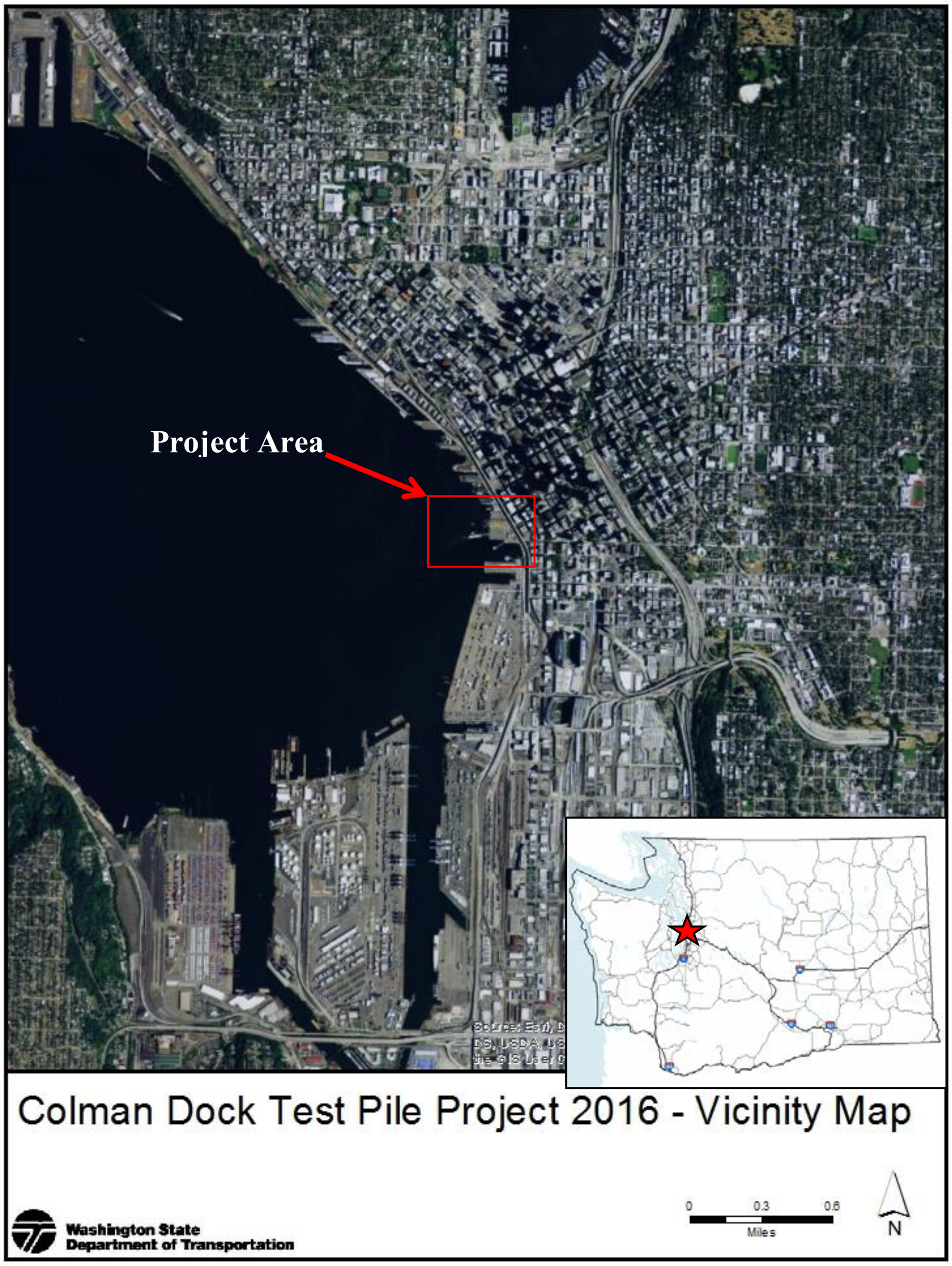
Project Description

The control pile, used as part of the pile driving template for the test piles, and test piles were driven to assess alternative pile designs. The Test Pile Project addresses the potential for using concrete piles with steel stingers in ferry terminal design. The traditional 24-inch steel control piles serve as the control piles with the 36-inch steel piles, 36-inch hollow concrete piles with a 24-inch diameter steel stinger, and 18-inch solid octagonal concrete piles with a 12-inch diameter steel stinger. The concrete piles had a smaller diameter steel pile attached to the bottom of the pile which facilitated easier driving through stiffer substrates and provided more structural rigidity. The combination of the wood pile cap at the top of the concrete pile absorbing energy from the impact hammer and transference of energy across different media (concrete to steel and steel to concrete) results in less sound energy entering the water and substrate. The project location is on the northwest corner and the south side of the existing Colman Dock Ferry Terminal.

PROJECT AREA

The Colman Dock Ferry Terminal is located on the west edge of downtown Seattle in King County, Washington. The terminal is located within Sections 6, Township 24 North, Range 4 East (USGS 1981).

Figure 1: Colman Dock Test Pile Project Area



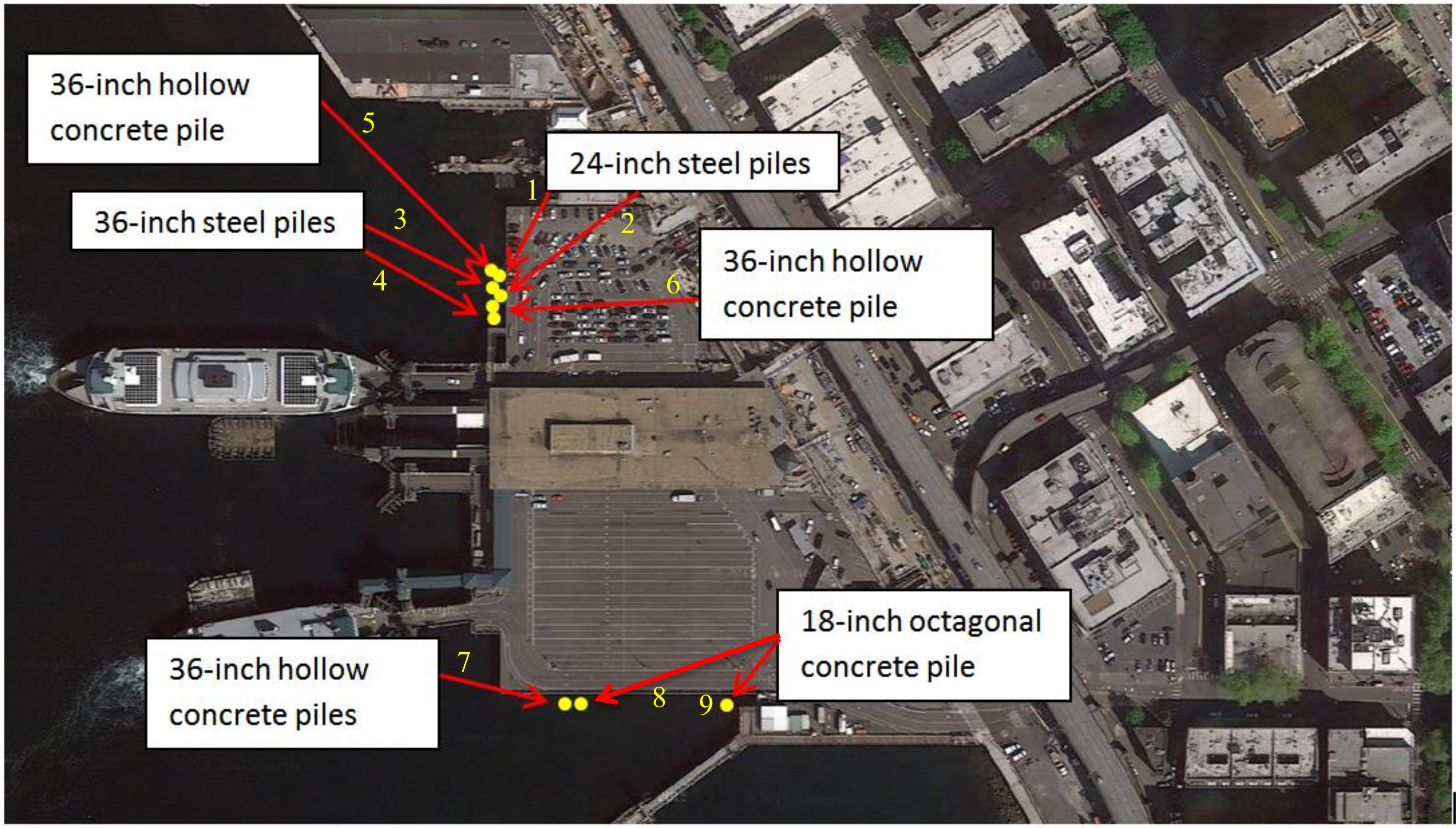
PILE INSTALLATION LOCATION

A total of nine piles were installed and monitored on the northwest and south side of the Colman Dock Ferry Terminal. Figure 2 indicates the approximate location of the two control piles and the seven test piles.

Hydroacoustic monitoring of pile driving included:

- Measurement of noise levels between 10 and 24 meters from the pile due to logistical and safety issues.
- Hydrophones placed at midwater depth.
- Each pile has a clear acoustic line-of-sight between the pile and the hydrophone.

Figure 2: The locations of the nine monitored piles at the Colman Dock Ferry Terminal. Numbers represent pile number.



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. The peak SPL 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 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 majority of literature uses peak sound pressures to evaluate barotrauma injury to fish. Except where otherwise noted, sound levels reported in this report are expressed in dB re: 1 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)

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 the National Marine Fisheries Service (NMFS) in criteria for judging effects to marine mammals from underwater impulse-type sounds.

The L_{50} or 50^{th} percentile is a statistical measure of the median value over the measurement period where 50 percent of the measured values are above the L_{50} and 50 percent are below.

One-third octave band analysis offers a more convenient way to look at the composition of the sound and is an improvement over previous techniques. One-third octave bands are frequency bands whose upper limit in hertz is $2^{1/3}$ (1.26) times the lower limit. The width of a given band is 23% of its center frequency. For example, the 1/3-octave band centered at 100 Hz extends from 89 to 112 Hz, whereas the band centered at 1000 Hz extends from 890 to 1120 Hz. The 1/3-octave band level is calculated by integrating the spectral densities between the band frequency limits. Conversion to decibels is:

$$dB = 10*LOG\text{ (sum of squared pressures in the band)} \qquad \text{(eq. 1)}$$

Sound levels are often presented for 1/3-octave bands because the effective filter bandwidth of mammalian hearing systems is roughly proportional to frequency and often about 1/3-octave. In other words, a mammal's perception of a sound at a given frequency will be strongly affected by other sounds within a 1/3-octave band around that frequency. The overall level (acoustically summing the pressure level at all frequencies) of a broadband (20 Hz to 20 kHz) sound exceeds the level in any single 1/3-octave band.

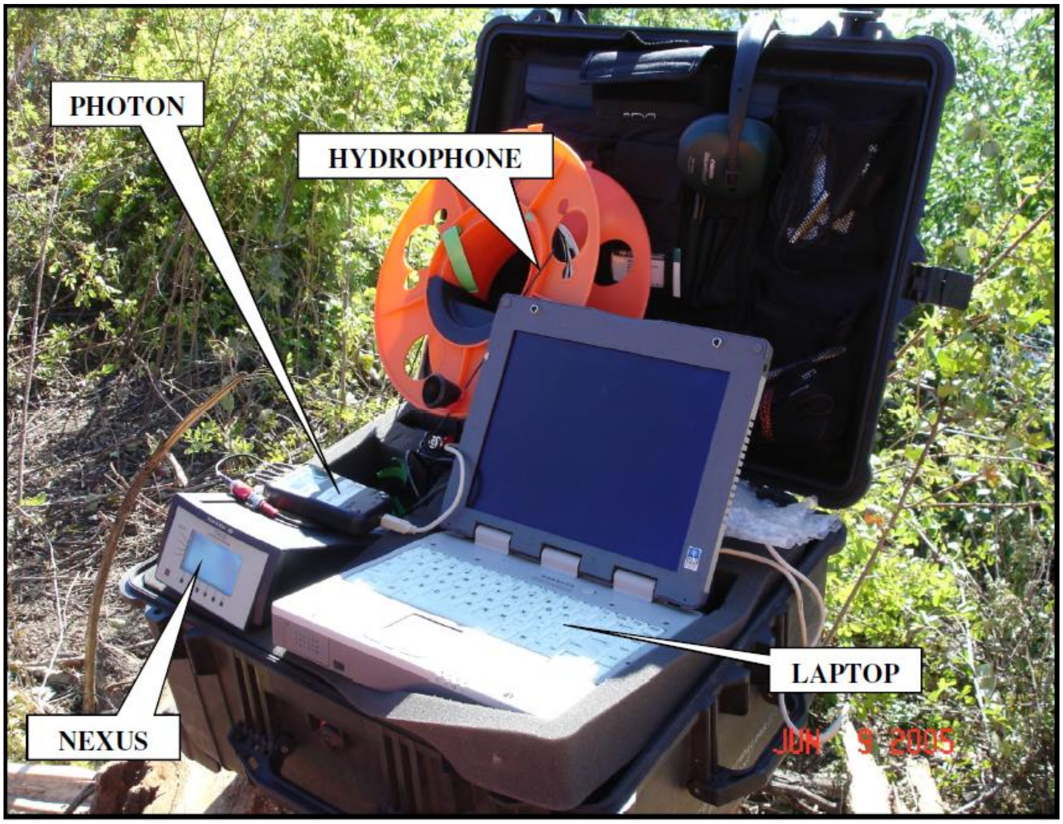
METHODOLOGY

Typical Equipment Deployment

The hydrophone was deployed from the Colman Dock near the piles. The monitoring equipment is outlined below and shown in Figure 3. The hydrophone was stationed and fixed with an anchor and a surface float at a nominal distance of 10 to 24 meters from the pile.

A confined bubble curtain was deployed for all steel piles.

Figure 3: Near Field Acoustical Monitoring Equipment



Underwater sound levels were measured near the piles using a Reson TC 4013 hydrophone deployed on a weighted nylon cord from the monitoring location. The hydrophone was positioned at a distance of 10 to 24 meters and at mid-water depth. 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, shown in Figure 3. The output of the Nexus signal conditioner is received by a Brüel and Kjær Photon 4-channel signal spectrum analyzer that is attached to a Dell ATG laptop computer similar to the one shown in Figure 3.

The equipment captures underwater sound levels from the pile driving operations in the format of an RTPro signal file for processing later. The WSDOT has the system and software calibration checked annually against NIST traceable standard.

Signal analysis software provided with the Photon was set at a sampling rate of one sample every 20.8 μs (18,750 Hz). This sampling rate provides sufficient resolution to catch the peaks and other relevant data. The anti-aliasing filter included in the Photon also allows the capture of the true peak.

Due to the variability between the absolute peaks for each pile impact strike, an average peak and RMS value is computed along with the standard deviation (s.d.) to give an indication of the amount of variation around the average for each pile. Additionally, the L_{50}, which is a more accurate statistical measure of the median of all values for a given measurement period, was calculated for each pile and each of the Peak, $RMS_{90\%}$ and $SEL_{90\%}$ metrics.

The $RMS_{90\%}$ was calculated for each individual impact strike. Except where otherwise noted the $SEL_{90\%}$ was calculated for each individual impact strike using the following equation:

$$SEL_{90\%} = RMS_{90\%} + 10\ LOG\ (\tau) \qquad \text{(eq. 2)}$$

Where τ is the 90% time interval over which the $RMS_{90\%}$ value is calculated for each impact strike. Then the cumulative SEL (cSEL) is calculated by accumulating each of these values for each pile and each day.

For the second control pile where it was not possible to calculate the $SEL_{90\%}$ for each pile strike the cumulative SEL was calculated using the following equation.

$$cSEL = SEL_{90\%} + 10\ LOG\ (\text{total number of pile strikes}) \qquad \text{(eq. 3)}$$

Test Pile Design

Three test piles were evaluated as a part of this test pile project. The first pile tested is a 36-inch steel pile, shown in Figure 4. The 36-inch steel pile functions similarly to the 24-inch steel control pile. The only notable difference is the diameter of the steel piles. The second test pile is a 36-inch hollow concrete pile with a 24-inch diameter steel stinger, which helps in driving the pile through the substrate, shown in Figure 5. The third test pile is an 18-inch solid octagonal concrete pile with a 12-inch steel stinger which helps drive the pile through the substrate, shown in Figure 6.

Figure 4: 36-inch Steel Pile

Figure 5: 36-inch Hollow Concrete Pile with a 24-inch steel stinger

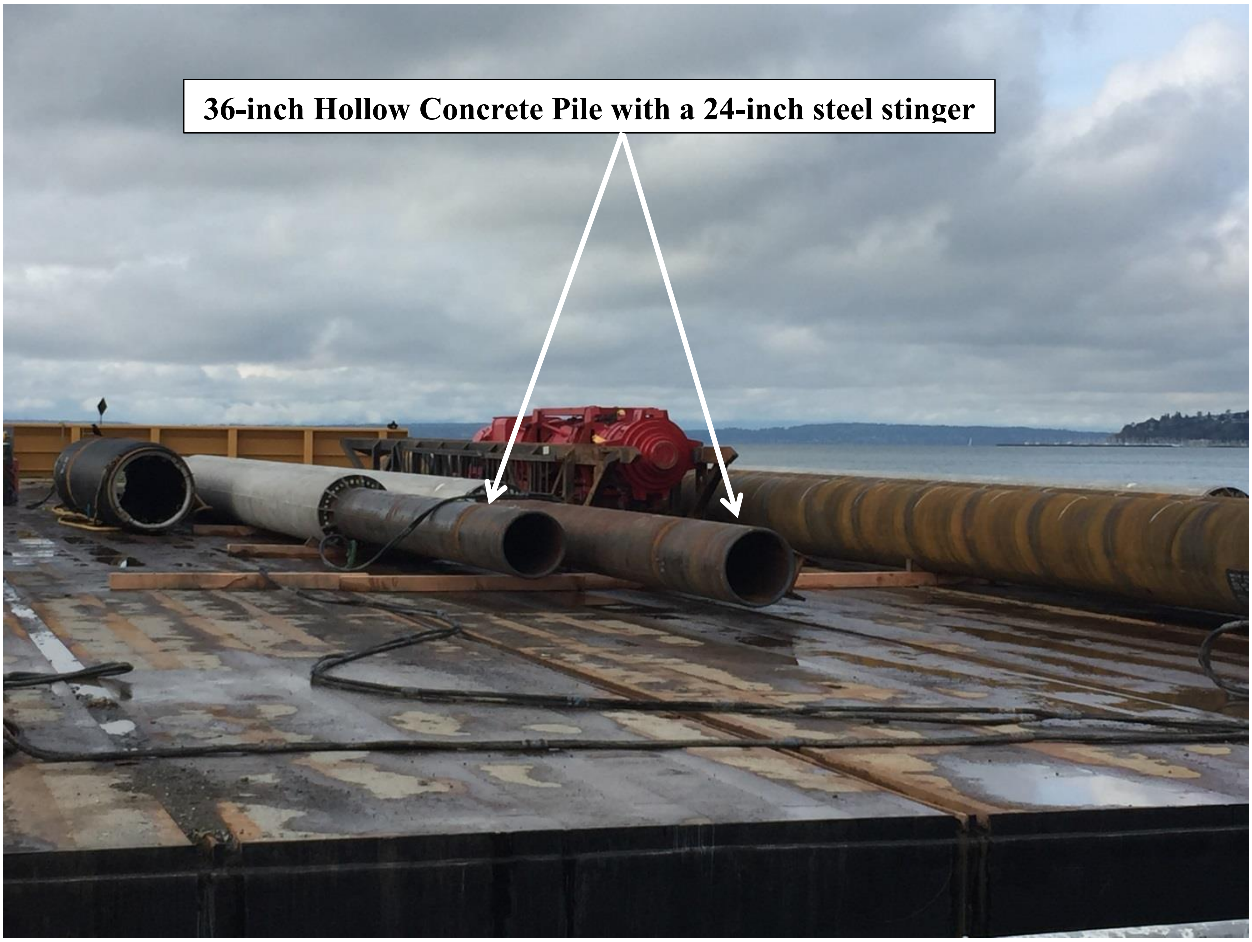


Figure 6: 18-inch Solid Octagonal Concrete Pile with a 12-inch steel stinger

RESULTS

Underwater Sound Levels

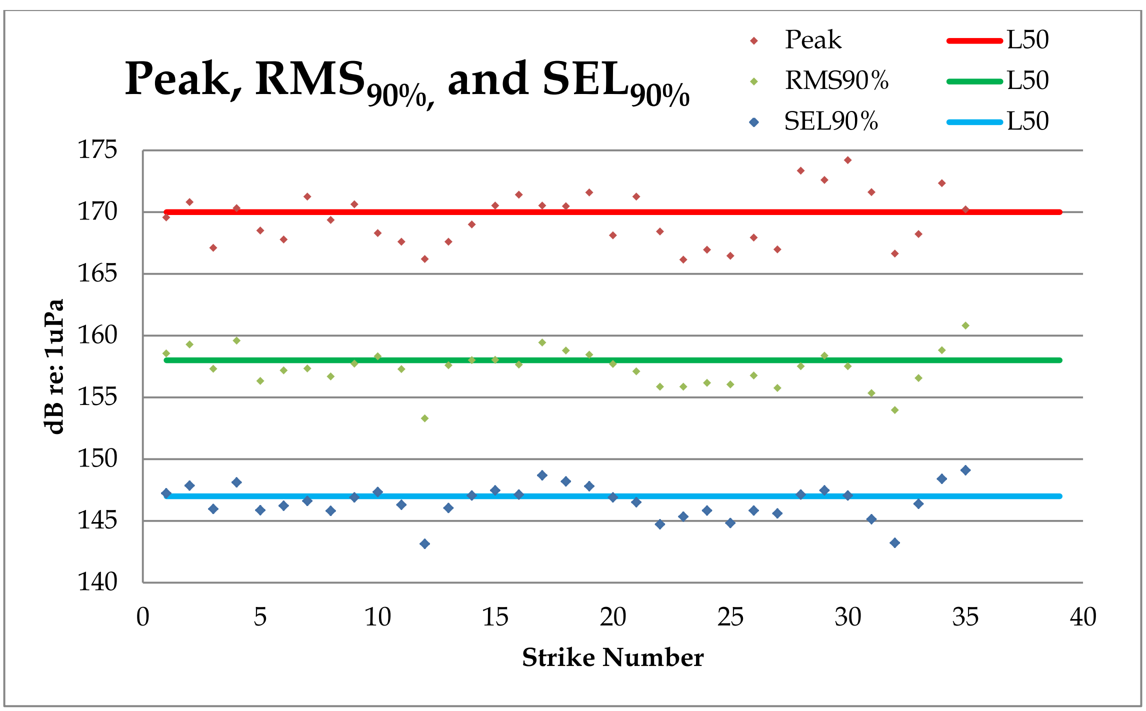
WSDOT monitored a total of nine piles for underwater noise, two 24-inch steel control piles, two 36-inch steel test piles, three 36-inch hollow concrete test piles with a 24-inch steel stinger, and two 18-inch solid octagonal concrete test piles with a 12-inch steel stinger. Data from all piles are analyzed in the paragraphs below and summarized in Table 2.

Pile 1

Pile 1 is located approximately 50 feet west of the Seattle waterfront (Figure 2). The pile was a traditional 24-inch steel control pile and had an absolute peak value of 174 dB_{peak} at 12 meters, an $RMS_{90\%}$ of 157 $dB_{RMS90\%}$ and a $SEL_{90\%}$ of 149 $dB_{SEL90\%}$. The cumulative SEL (cSEL) for Pile 1 was 177 dB_{cSEL} calculated based on the accumulation of the single strike $SEL_{90\%}$ for each pile strike (Table 2).

The dB_{peak}, $RMS_{90\%}$, $dB_{SEL90\%}$ for each pile strike are plotted in Figure 7. This plot is a typical scatterplot for steel pipe piles being impact driven over time with some degree of variability amongst the individual pile strikes represented by the diamond shapes. The solid horizontal lines in these figures represent the L_{50} of 170 for dB_{peak}, 158 for $RMS_{90\%}$, and 147 for $SEL_{90\%}$. The steep decrease in sound levels beginning around the 5^{th} pile strike is likely due to driving the pile through an unusually soft substrate which provides less resistance to the pile resulting in a relatively low sound level.

Figure 7: 24-inch Steel Control Pile 1, dB_{peak}, $RMS_{90\%}$, and $dB_{SEL90\%}$ levels for each pile strike with the L_{50}



Pile 2

Pile 2 is located approximately 50 feet west of the Seattle waterfront and is adjacent to Pile 1 (Figure 2). The pile was a 24-inch steel control pile and had an absolute peak value of 180 dB_{peak} at 15 meters, an estimated $RMS_{90\%}$ of 165 $dB_{RMS90\%}$ and an estimated $SEL_{90\%}$ of 155 $dB_{SEL90\%}$. The $RMS_{90\%}$ and $SEL_{90\%}$ are estimated values due to the corruption of the recorded data during monitoring of the pile. The conservative rule of thumb for estimating these values is that the $RMS_{90\%}$ is 15 dB less than the peak value and the $SEL_{90\%}$ is 25 dB less than the peak value. The cumulative SEL (cSEL) for Pile 2 is 173 dB_{cSEL} and calculated based on the $SEL_{90\%}$ and the total number of pile strikes (Table 2).

Pile 3

Pile 3 is located approximately 50 feet West of the Seattle Waterfront and adjacent to Pile 2 (Figure 2). The pile is a 36 inch steel pile. This pile had an absolute peak value of 205 dB_{peak} at 14 meters, an $RMS_{90\%}$ of 189 $dB_{RMS90\%}$ and a $SEL_{90\%}$ of 176 dB $_{SEL90\%}$. The cumulative SEL (cSEL) is 200 dB_{cSEL} and was calculated based on the accumulation of the single strike $SEL_{90\%}$ for each pile strike (Table 2).

The dB_{peak}, $dB_{RMS90\%}$, $dB_{SEL90\%}$ for each pile strike are shown in Figure 8. This plot shows a relatively typical plot over time with a gradual rise at the beginning of the drive and fairly consistent sound levels afterwards and some degree of variability amongst the individual pile strikes represented by the diamond shapes. The solid horizontal lines in these figures represent the L_{50} of 200 for dB_{peak}, 185 for $RMS_{90\%}$, and 172 for $SEL_{90\%}$. This pile was driven multiple times, and the abrupt change in sound levels observed around strike 35, 350, and 500 is due to restarting pile driving operations or differences in the substrate which the pile is being driven through.

Figure 8: 36-inch Steel Pile 3, dB_{peak}, $dB_{RMS90\%}$, and $dB_{SEL90\%}$ levels for each pile strike with the L_{50}

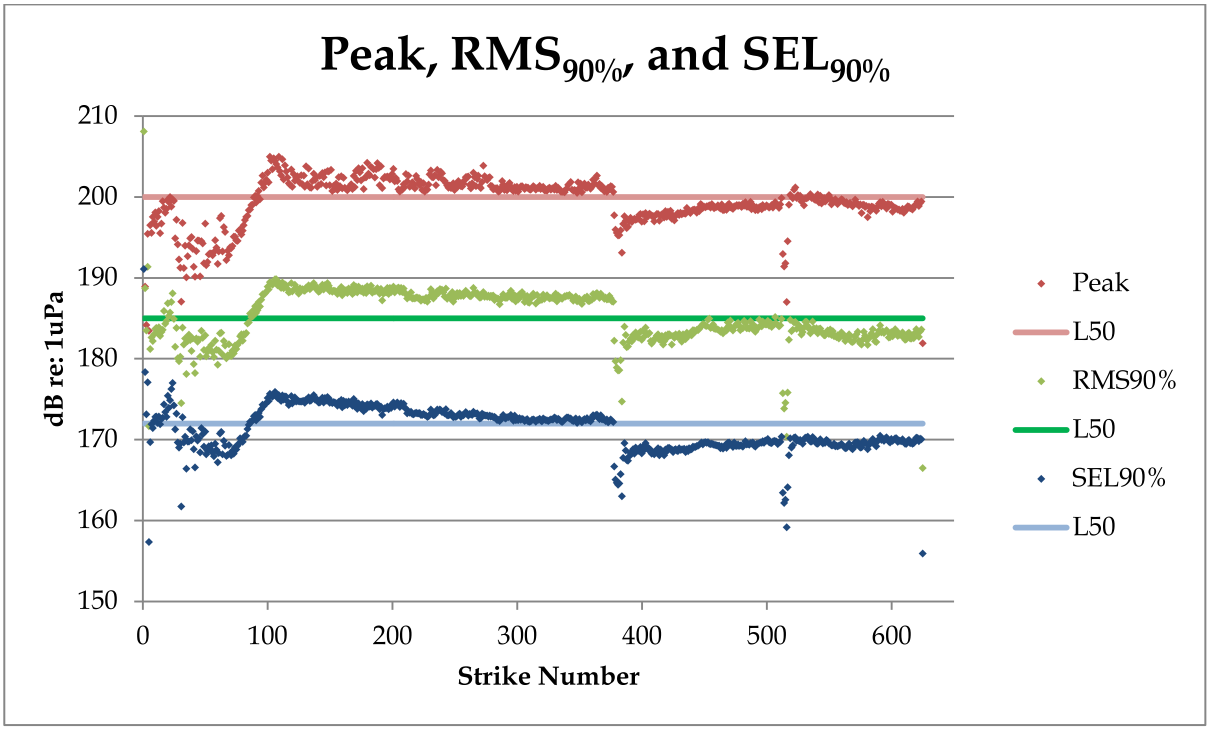
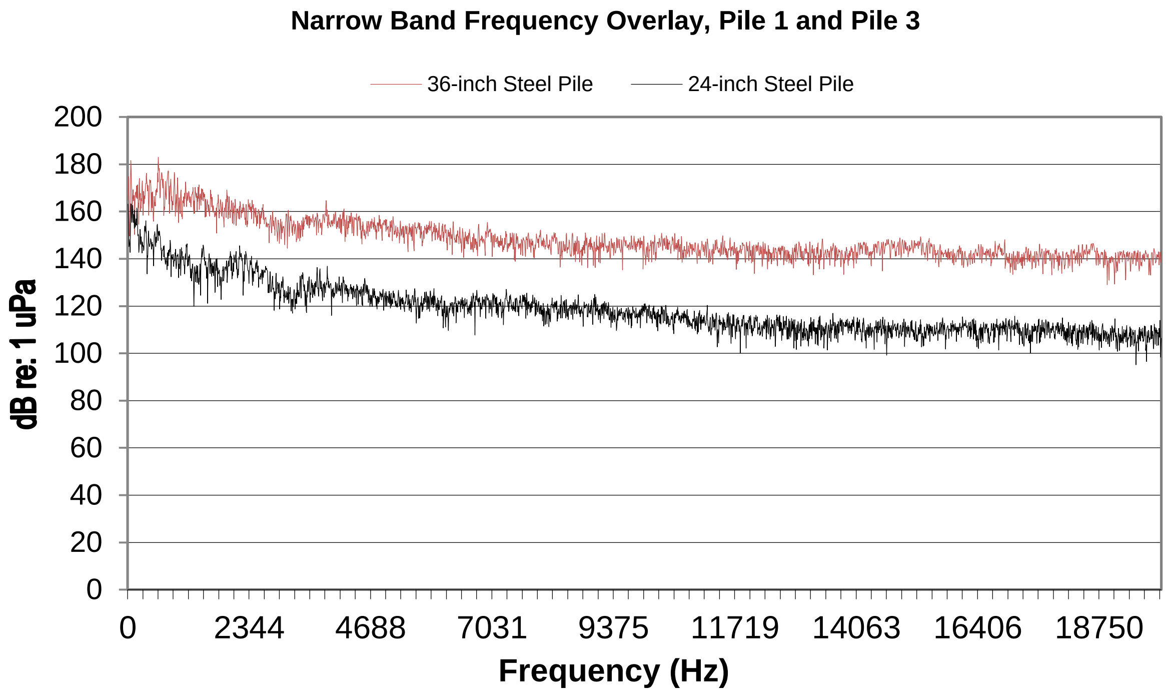


Figure 9 shows an overlay plot of the Narrow Band Frequency Spectra for the 24-inch steel control pile and the 36-inch steel Pile 3. This figure shows the differences in the dB levels for an average of three consecutive pile strikes recorded at various frequencies. This graph suggests that the 24-inch steel pile is notably quieter than the 36-inch steel pile at almost all frequencies. There were significant differences in the driving conditions and substrates between the 24-inch steel pile and the 36-inch steel pile which could explain some of the differences in the Narrow Band Frequency.

Figure 9: Narrow Band Frequency Spectra overlay for 24-inch steel pile 1 and 36-inch steel Pile 3



The single strike waveform for the 24-inch steel pile 1 was significantly quieter than the waveform for the 36-inch steel pile 3. This difference in energy levels is likely due to differences in the substrate at the location of the 24-inch pile where the substrate was very soft and there was very little resistance during driving of the pile to tip depth. The lower energy levels exhibited by the 24-inch pile make waveform comparisons difficult. Instead, the single strike waveform charts of other test piles will be compared to the 36-inch steel piles and not the 24-inch steel piles.

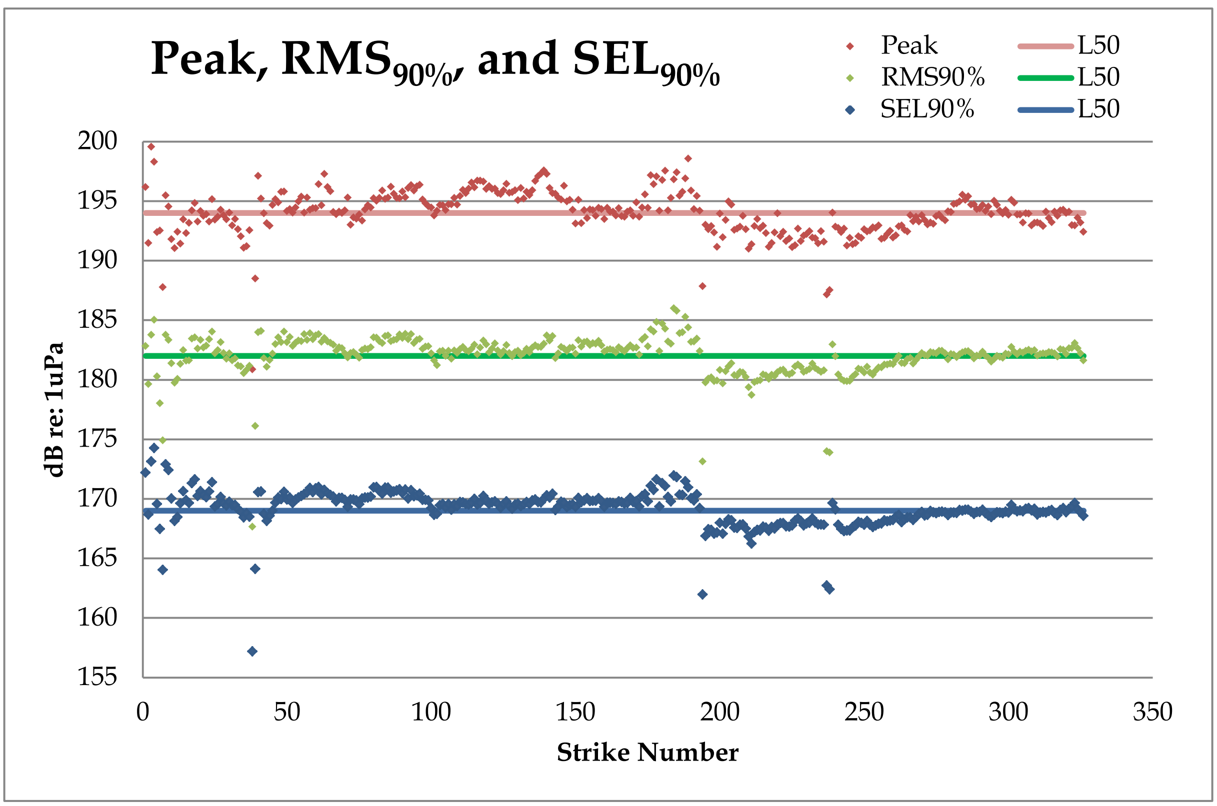
Pile 4

Pile 4 is located approximately 50 feet west of the Seattle waterfront (Figure 2). The pile was a 36-inch steel and had an absolute peak value of 199 dB_{peak} at 24 meters, an $RMS_{90\%}$ of 184 $dB_{RMS90\%}$ and a $SEL_{90\%}$ of 172 $dB_{SEL90\%}$. The cumulative SEL (cSEL) for Pile 4 was 195 dB_{cSEL} calculated based on the accumulation of the single strike $SEL_{90\%}$ for each pile strike (Table 2).

The dB_{peak}, $RMS_{90\%}$, $dB_{SEL90\%}$ for each pile strike are plotted in Figure 10. This plot is a typical scatterplot for steel pipe piles being impact driven over time with some degree of variability amongst the individual pile strikes represented by the diamond shapes. The solid horizontal lines in these figures represent the L_{50} of 194 for dB_{peak}, 182 for $RMS_{90\%}$, and 169 for $SEL_{90\%}$. This pile was driven multiple times, and the abrupt change in sound levels observed around strike 50, 200, and 250 is likely due to restarting pile driving operations or differences in the substrate which the pile is being driven through.

The dB_{peak}, $RMS_{90\%}$, $dB_{SEL90\%}$ for each pile strike are relatively similar between the two 36-inch steel piles. Pile 3 exhibited more variability than Pile 4, including sudden decreases in $RMS_{90\%}$ and $SEL_{90\%}$ at pile strike 400 in Pile 4. There was a similar but smaller decrease in $RMS_{90\%}$ and $SEL_{90\%}$ at pile strike 200 in Pile 3; however both of these decreases are likely due to starting and stopping of pile driving operations.

Figure 10: 36-inch Steel Pile 4, dB_{peak}, $RMS_{90\%}$, and $dB_{SEL90\%}$ levels for each pile strike with the L_{50}



The 36-inch steel Pile 4 was generally quieter than the 36-inch steel Pile 3 with dB_{peak} values of approximately 199 and 205 respectively. Figure 11 shows a single strike waveform comparison between Pile 3 and Pile 4. The waveform analysis shows that the two piles have similar characteristics to each other, but with Pile 3 exhibiting a greater amount of sound energy than Pile 4. Figure 12 shows a narrow band frequency comparison for Pile 3 and Pile 4. This comparison shows that both piles exhibit similar sound characteristics at all frequencies, but that Pile 3 has higher sound energy levels by approximately 3-5 dB for higher frequencies beginning around 5000 Hz. This analysis takes a conservative approach and assumes that the loudest individual pile from each pile type will be representative of that pile type. For this reason, only the loudest piles (Pile 3) will have their Narrow Band Frequencies and single strike waveform's compared to other pile types. Additionally, the 36-inch steel piles were used in the comparisons with the two types of concrete piles because the 24-inch steel 'control' piles were driven into an uncharacteristically soft substrate which is not representative of typical pile driving conditions. This sound energy level difference is shown above in Figure 9.

Figure 11: 36-inch Steel Pile 3 and 36-inch Steel Pile 4 Waveform Comparison

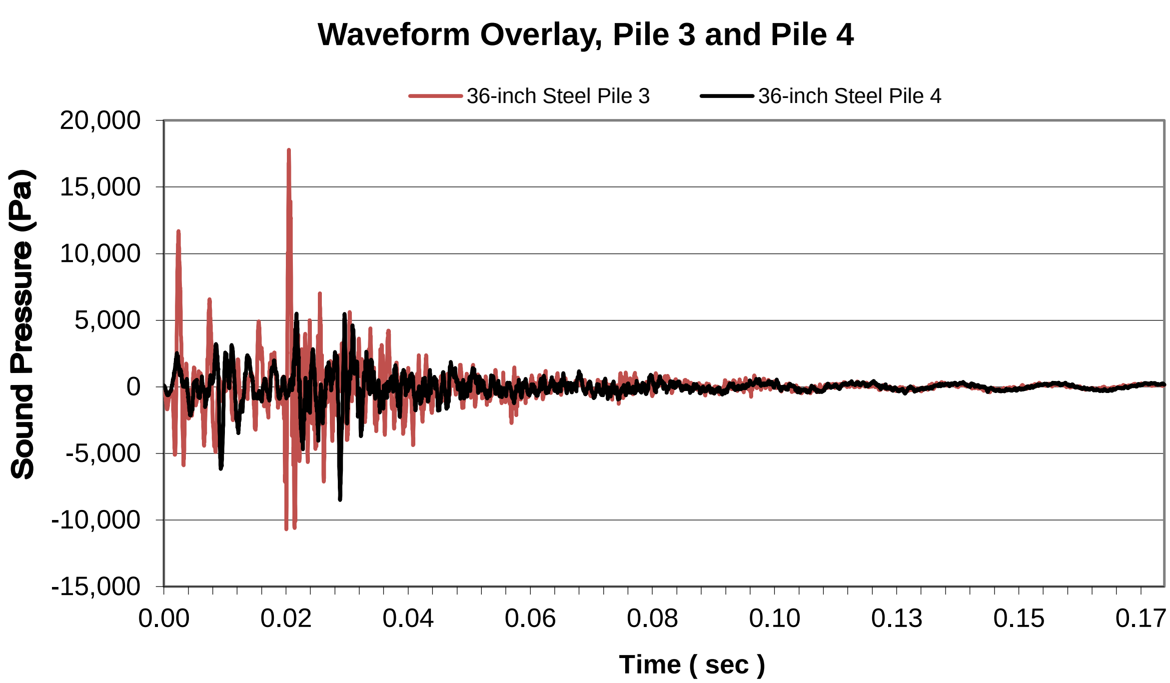
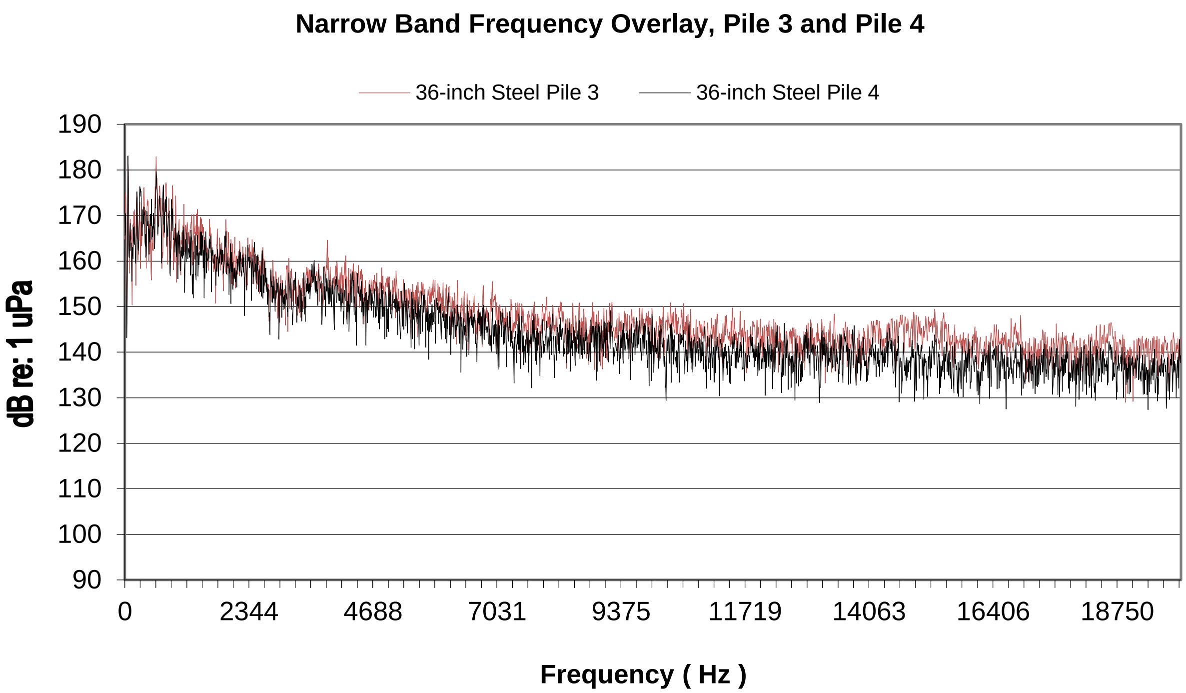


Figure 12: 36-inch Steel Pile 3 and 36-inch Steel Pile 4 Narrow Frequency Band Comparison

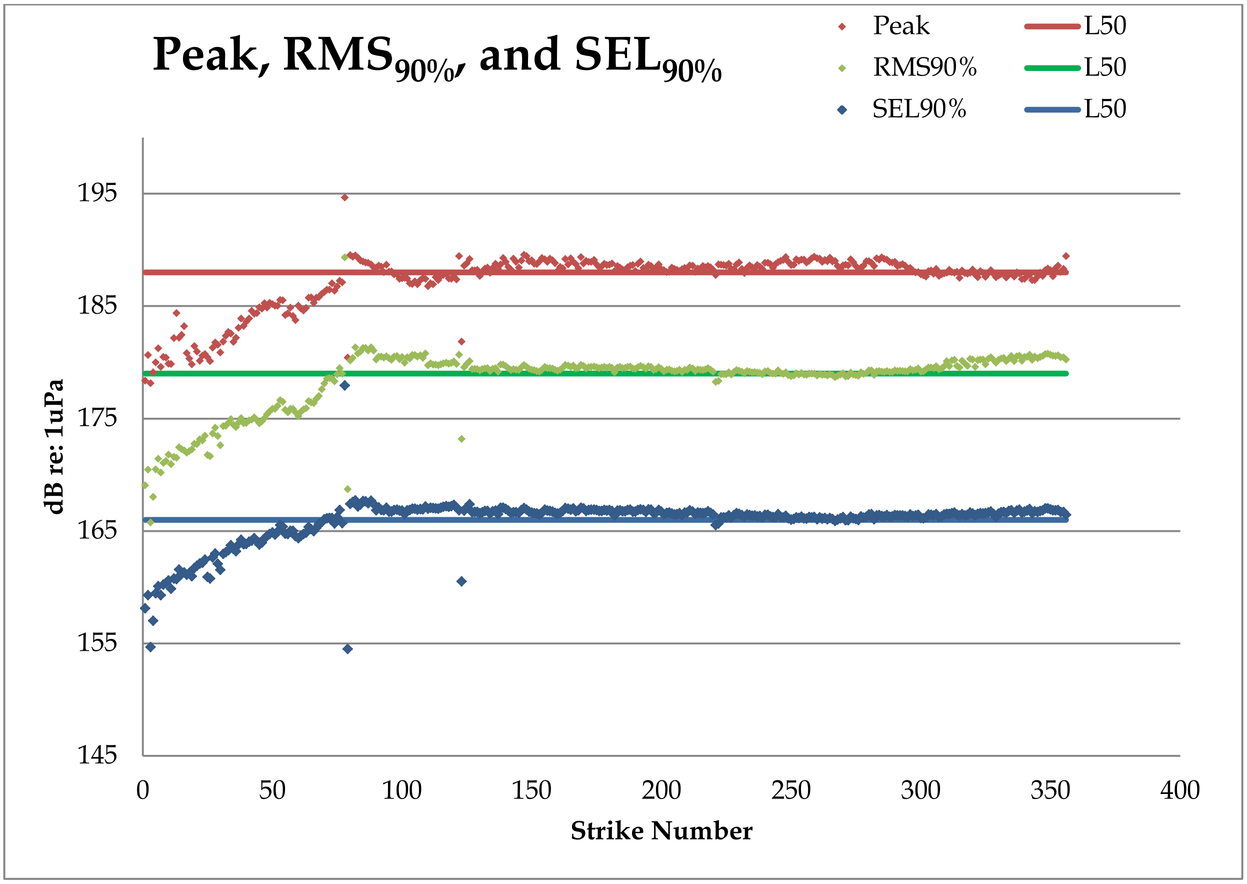


Pile 5

Pile 5 is located approximately 50 feet west of the Seattle waterfront (Figure 2). The pile was a 36-inch hollow concrete test pile and had an absolute peak value of 190 dB_{peak} at 12 meters, an $RMS_{90\%}$ of 180 $dB_{RMS90\%}$ and a $SEL_{90\%}$ of 168 $dB_{SEL90\%}$. The cumulative SEL (cSEL) for Pile 5 was 192 dB_{cSEL} calculated based on the accumulation of the single strike $SEL_{90\%}$ for each pile strike (Table 2).

The dB_{peak}, $RMS_{90\%}$, $dB_{SEL90\%}$ for each pile strike are plotted in Figure 13. This plot is different from the 24- and 36-inch steel scatterplot showing a steady increase at the beginning of the drive followed by an evening out of sound levels around the 100th Pile strike and a slight increase towards the end of the drive with some variability amongst the individual pile strikes represented by the diamond shapes. The solid horizontal lines in these figures represent the L_{50} of 188 for dB_{peak}, 179 for $RMS_{90\%}$, and 166 for $SEL_{90\%}$. This pile was driven multiple times, and the abrupt change in sound levels observed around strike 75 and 125 is likely due to restarting pile driving operations or differences in the substrate which the pile is being driven through.

Figure 13: 36-inch Hollow Concrete Pile 5, dB_{peak}, $RMS_{90\%}$, and $dB_{SEL90\%}$ levels for each pile strike with the L_{50}

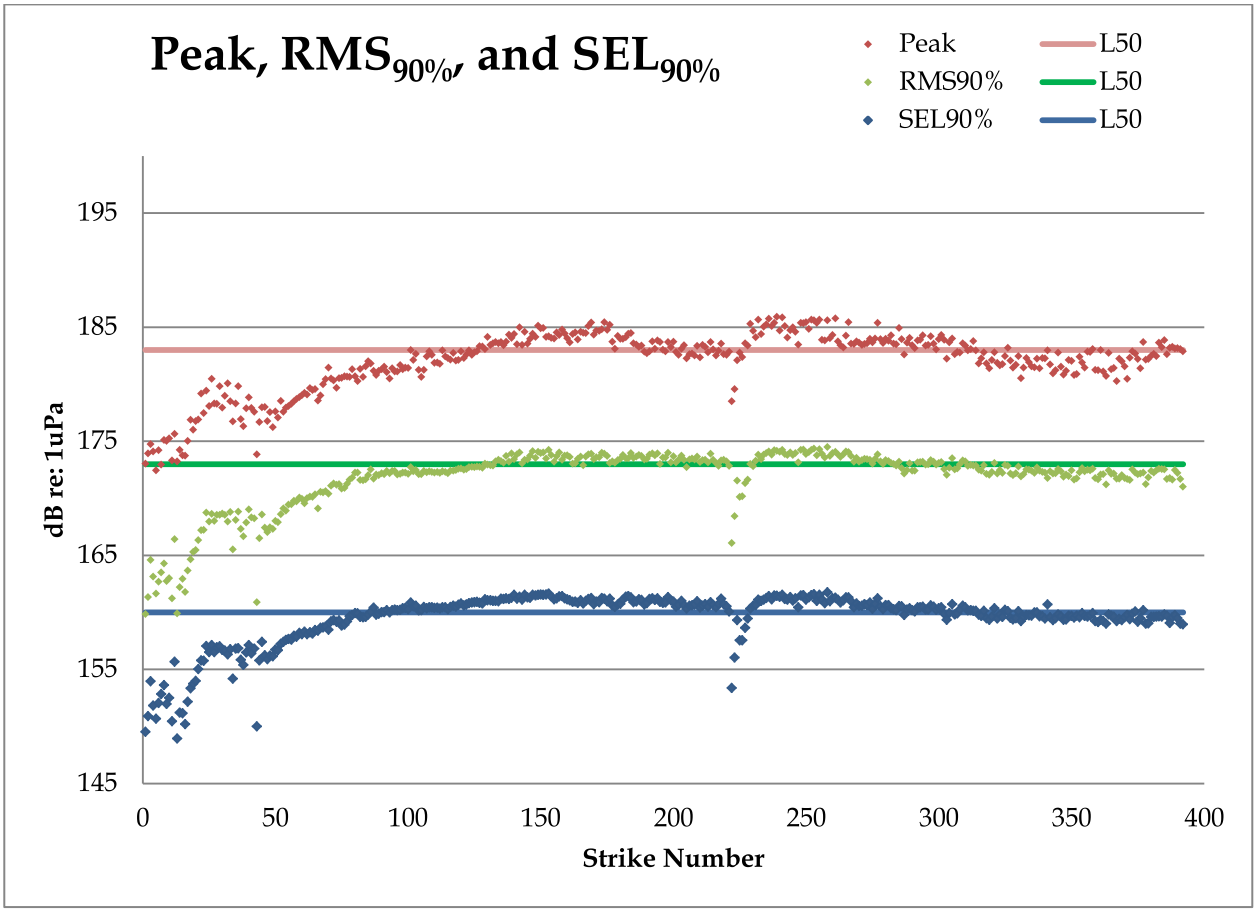


Pile 6

Pile 6 is located approximately 50 feet west of the Seattle waterfront (Figure 2). The pile was a 36-inch hollow concrete test pile and had an absolute peak value of 186 dB_{peak} at 19 meters, an $RMS_{90\%}$ of 174 $dB_{RMS90\%}$ and a $SEL_{90\%}$ of 162 $dB_{SEL90\%}$. The cumulative SEL (cSEL) for Pile 6 was 186 dB_{cSEL} calculated based on the accumulation of the single strike $SEL_{90\%}$ for each pile strike (Table 2).

The dB_{peak}, $RMS_{90\%}$, $dB_{SEL90\%}$ for each pile strike are plotted in Figure 14. This plot is different from the 36-inch steel pile scatterplot showing a steady increase at the beginning of the drive followed by an evening out of sound levels around the 150th Pile strike with some variability amongst the individual pile strikes represented by the diamond shapes. This pile was driven multiple times, and the abrupt change in sound levels observed around strike 50 and 225 is likely due to restarting pile driving operations or differences in the substrate which the pile is being driven through. The solid horizontal lines in these figures represent the L_{50} of 183 for dB_{peak}, 173 for $RMS_{90\%}$, and 160 for $SEL_{90\%}$.

Figure 14: 36-inch Hollow Concrete Pile 6, dB_{peak}, $RMS_{90\%}$, and $dB_{SEL90\%}$ levels for each pile strike with the L_{50}



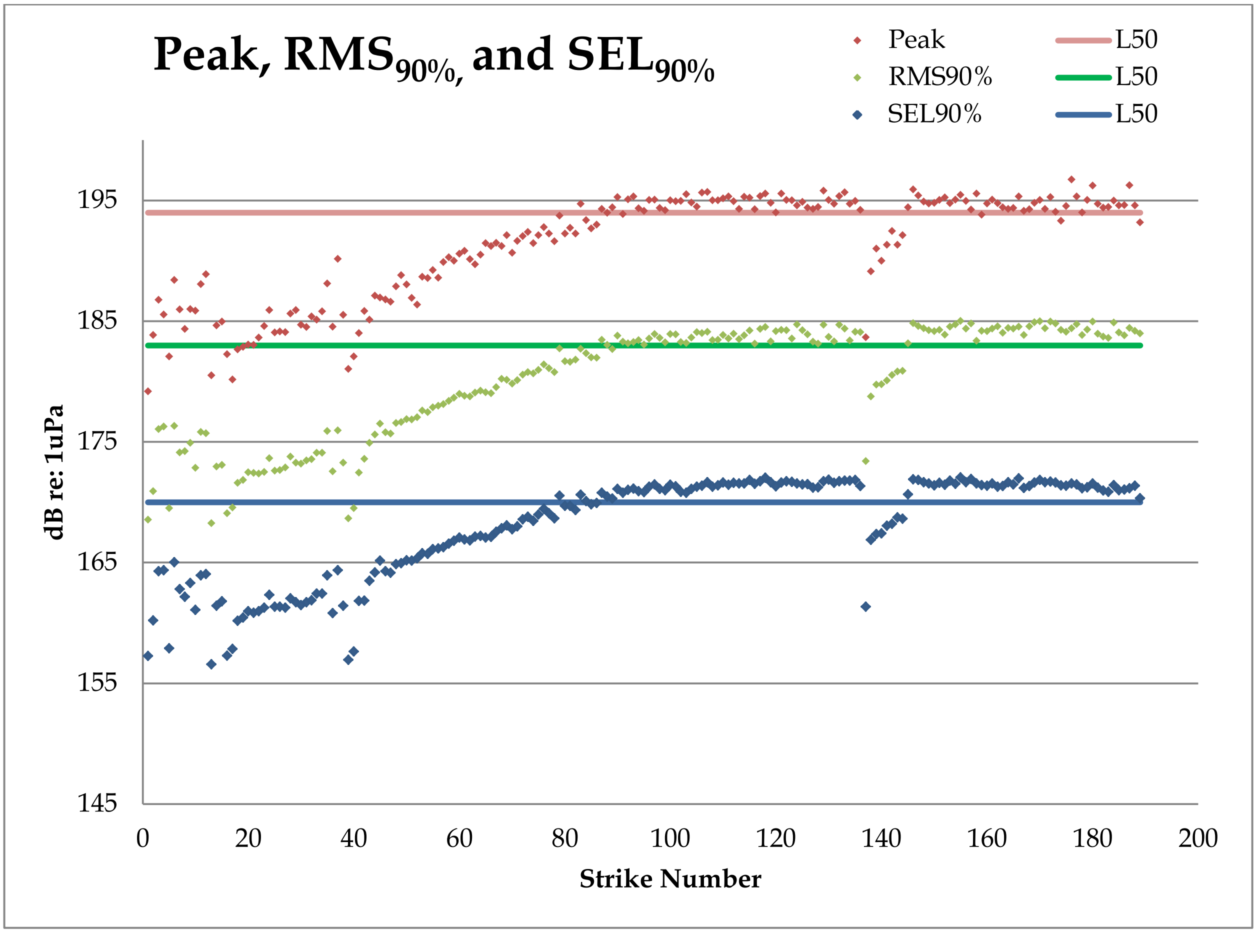
Pile 7

Pile 7 is located south of the Colman Dock Ferry Terminal (Figure 2). The pile was a 36-inch hollow concrete test pile and had an absolute peak value of 197 dB_{peak} at 10 meters, an $RMS_{90\%}$ of 184 $dB_{RMS90\%}$ and a $SEL_{90\%}$ of 172 $dB_{SEL90\%}$. The cumulative SEL (cSEL) for Pile 7 was 192 dB_{cSEL} calculated based on the accumulation of the single strike $SEL_{90\%}$ for each pile strike (Table 2).

The dB_{peak}, $RMS_{90\%}$, $dB_{SEL90\%}$ for each pile strike are plotted in Figure 13. This plot is different than the 36-inch steel pile scatterplot showing a steady increase at the beginning of the drive followed by an evening out of sound levels around the 100th Pile strike with some variability amongst the individual pile strikes represented by the diamond shapes. The solid horizontal lines in these figures represent the L_{50} of 194 for dB_{peak}, 183 for $RMS_{90\%}$, and 170 for $SEL_{90\%}$. We do not see this pattern in the 36-inch or 24-inch steel piles. This pile was driven multiple times, and the abrupt change in sound levels observed around strike 40 and 140 is likely due to restarting pile driving operations or differences in the substrate which the pile is being driven through.

The dB_{peak}, $RMS_{90\%}$, $dB_{SEL90\%}$ for each pile strike are all relatively similar between the three 36-inch hollow concrete piles. All three piles exhibit some variability early on in the drive while sound energy levels are generally increasing before eventually leveling off after roughly 100 pile strikes for all three piles. Pile 7 follows the same pattern as the Pile 5 and Pile 6; however Pile 7 exhibits generally higher sound energy levels. This difference in sound energy level is likely due to differences in the substrate, particularly because Pile 7 is located on a different side of Colman Dock than Pile 5 and Pile 6.

Figure 15: 36-inch Hollow Concrete Pile 7, dB_{peak}, $RMS_{90\%}$, and $dB_{SEL90\%}$ levels for each pile strike with the L_{50}



The 36-inch hollow concrete Pile 5 and Pile 6 was generally quieter than the 36-inch hollow concrete Pile 7. Figure 16 shows a single strike waveform comparison between Piles 5, 6 and 7. The waveform analysis shows that all three piles have similar characteristics to each other, but with Pile 7 exhibiting a greater amount of sound energy than Pile 5 or 6. Figure 17 shows a narrow band frequency comparison for Piles 5, 6 and 7. This comparison shows that all three piles exhibit similar sound characteristics at all frequencies, but that Pile 7 has higher sound energy levels by approximately 10-15 dB for higher frequencies beginning around 2000 Hz. Pile 6 also exhibits higher sound energy levels over Pile 5 by roughly 2 dB over the same frequency spectrum. This analysis takes a conservative approach and assumes that the loudest individual pile from each pile type will be representative of that pile type. For this reason, only the loudest piles (Pile 7) will have their Narrow Band Frequencies and single strike waveform's compared to other pile types.

Figure 16: 36-inch Hollow Concrete Pile 5, 36-inch Hollow Concrete Pile 6, and 36-inch Hollow Concrete Pile 7 Waveform Comparison

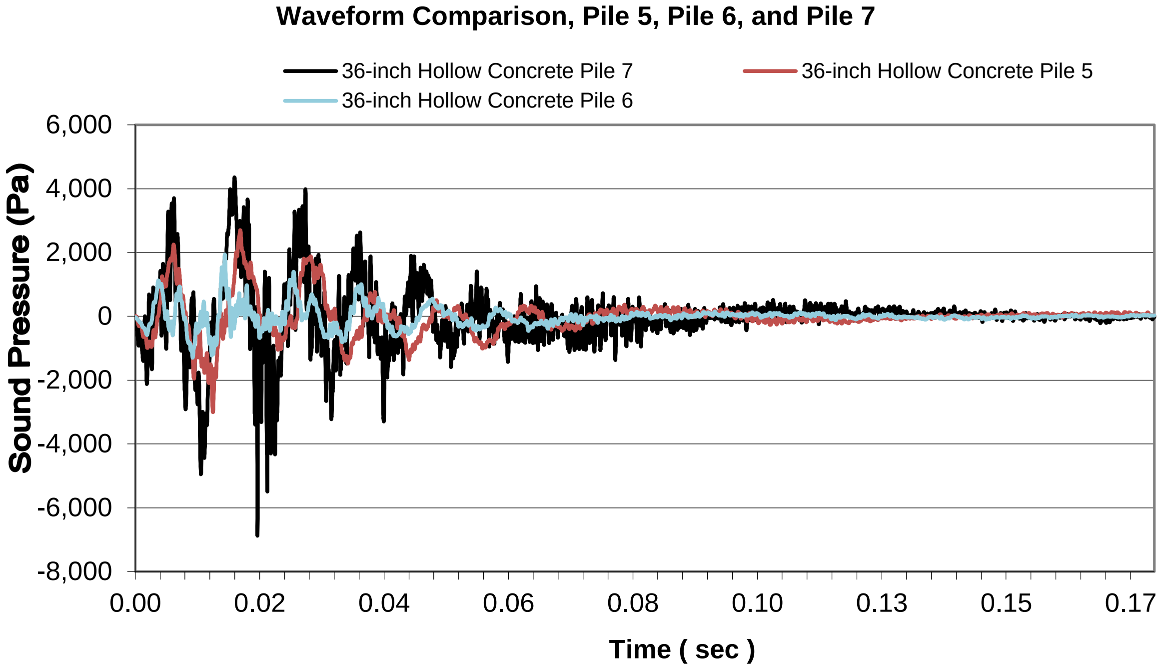


Figure 17: 36-inch Hollow Concrete Pile 5, 36-inch Hollow Concrete Pile 6, and 36-inch Hollow Concrete Pile 7 Narrow Band Frequency Comparison

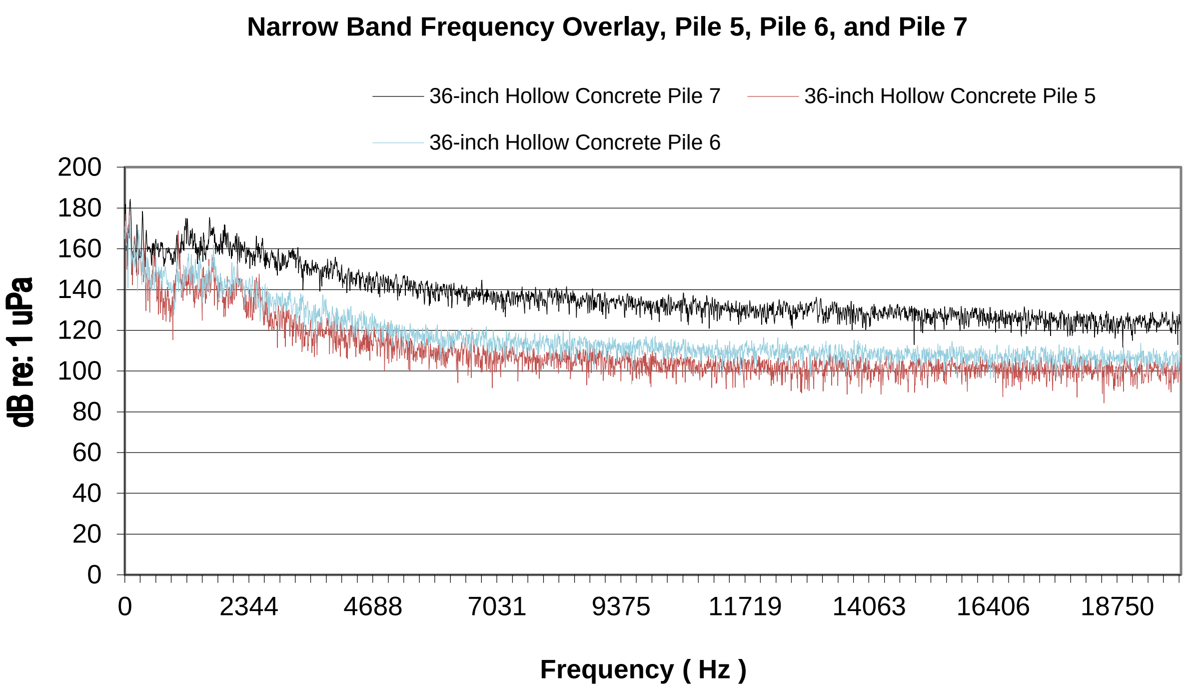
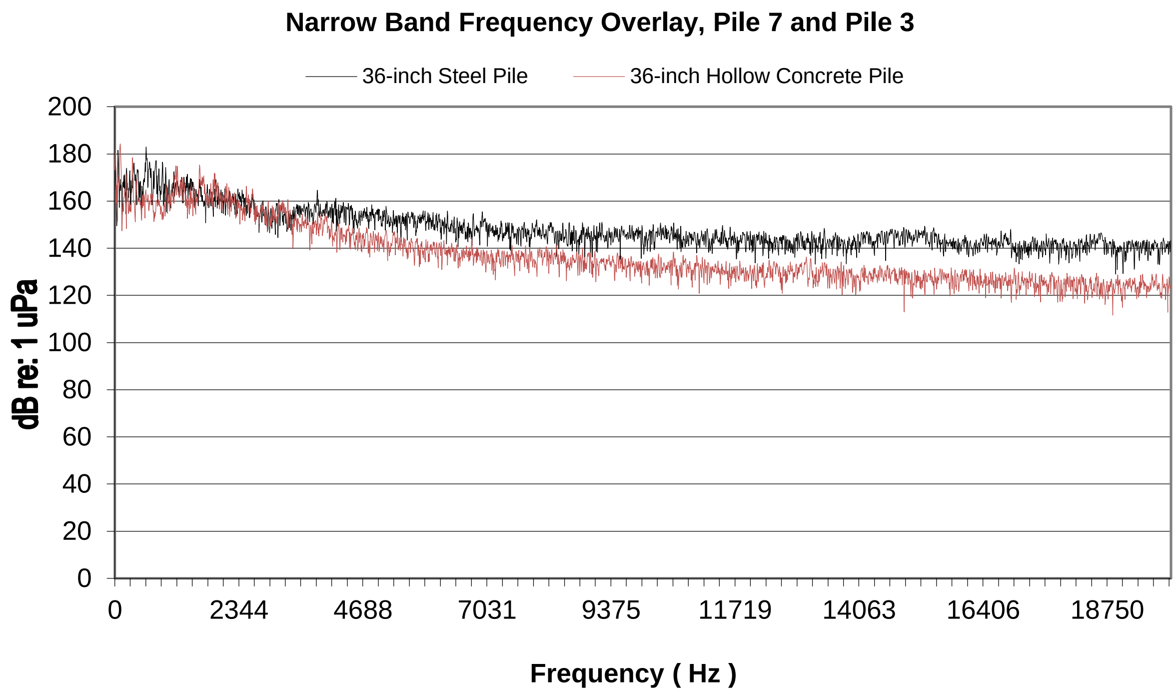


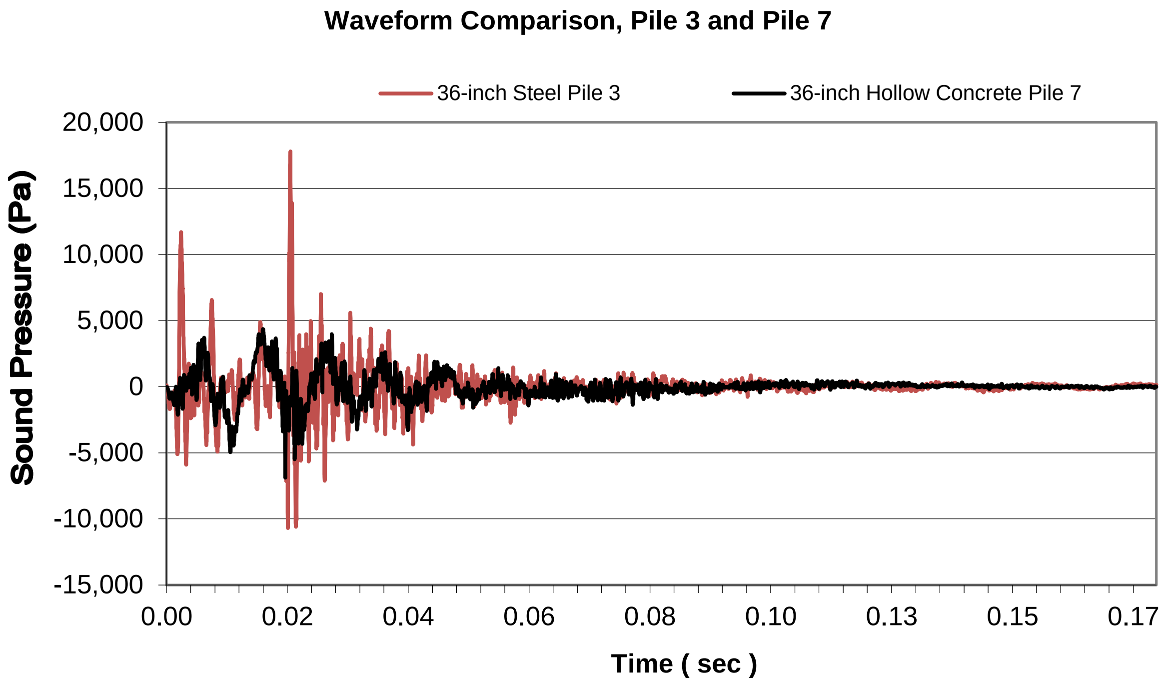
Figure 18 shows an overlay of the Narrow Band Frequency Spectra for the 36-inch hollow concrete Pile 7 and the 36-inch steel Pile 3. This figure shows the differences in the dB levels an average of three consecutive pile strikes recorded at various frequencies. This graph suggests that the two piles have similar dB levels in the low frequencies, but the 36-inch hollow concrete pile is approximately 10-20 dB quieter than the 36-inch steel pile at almost frequencies higher than roughly 3000 Hz.

Figure 18: Narrow Band Frequency Spectra overlay for 36-inch hollow concrete pile 7 and 36-inch steel pile 3



A waveform of a single pile strike for the 36-inch hollow concrete Pile 7 is shown in Figure 19. The figure shows the initial arrival of the sound wave from the pile (first wave) through the substrate. Then a relatively quiet period followed by the arrival of the second sound wave (second wave) and then a third and smaller sound wave (third wave) followed by relatively rapid attenuation of the sound. When compared to the single strike waveform for the 36-inch Steel pile in Figure 19, it can be seen that there is much less sound energy produced by the Hollow Concrete pile.

Figure 19: 36-inch Hollow Concrete Pile 7 vs. 36-inch Steel Pile 3, Single Pile Strike Waveform

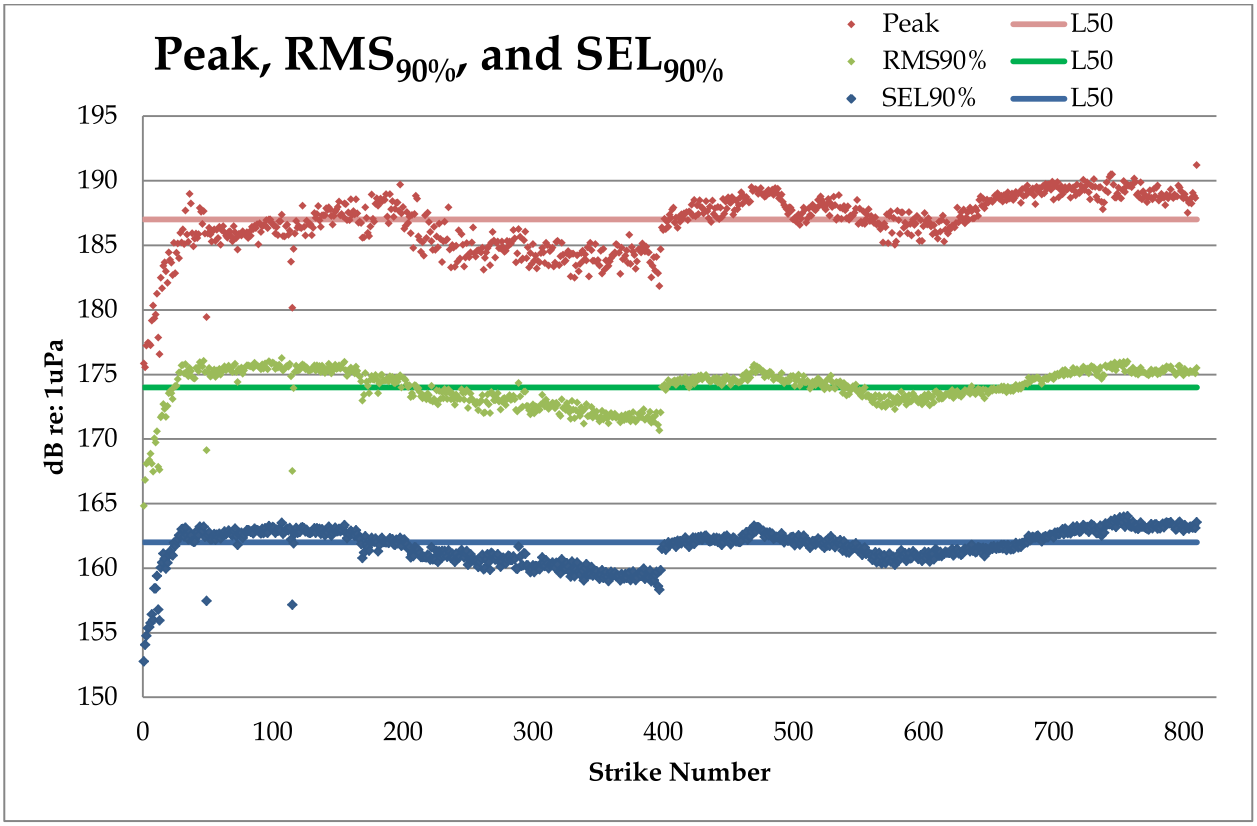


Pile 8

Pile 8 is located south of the Colman Dock Ferry Terminal (Figure 2). The pile was an 18-inch octagonal concrete test pile and had an absolute peak value of 190 dB_{peak} at 10 meters, an $RMS_{90\%}$ of 175 $dB_{RMS90\%}$ and a $SEL_{90\%}$ of 164 $dB_{SEL90\%}$. The cumulative SEL (cSEL) for Pile 8 was 191 dB_{cSEL} calculated based on the accumulation of the single strike $SEL_{90\%}$ for each pile strike (Table 2).

The dB_{peak}, $RMS_{90\%}$, $dB_{SEL90\%}$ for each pile strike are plotted in Figure 20. This plot is different than the 36-inch steel pile scatterplots showing a steady increase at the beginning of the drive followed by an evening out of sound levels around the 100th Pile strike with some variability amongst the individual pile strikes represented by the diamond shapes. The sound levels then decrease around the 200th pile strike and continue to fluctuate throughout the remainder of the driving activities. The solid horizontal lines in these figures represent the L_{50} of 187 for dB_{peak}, 174 for $RMS_{90\%}$, and 162 for $SEL_{90\%}$. We do not see this pattern in the 36-inch or 24-inch steel piles, but is similar to that seen in the hollow concrete piles, although the hollow concrete piles generally exhibit less fluctuation, which could be the result of the way energy is transferred through the wood pile cap into the concrete and then into the steel stinger absorbing some of the energy and reducing these fluctuations seen in the steel piles.. This pile was driven multiple times, and the abrupt change in sound levels observed around strike 50, 100, and 400 is likely due to restarting pile driving operations or differences in the substrate which the pile is being driven through.

Figure 20: 18-inch Octagonal Concrete Pile 8, dB_{peak}, $RMS_{90\%}$, and $dB_{SEL90\%}$ levels for each pile strike with the L_{50}



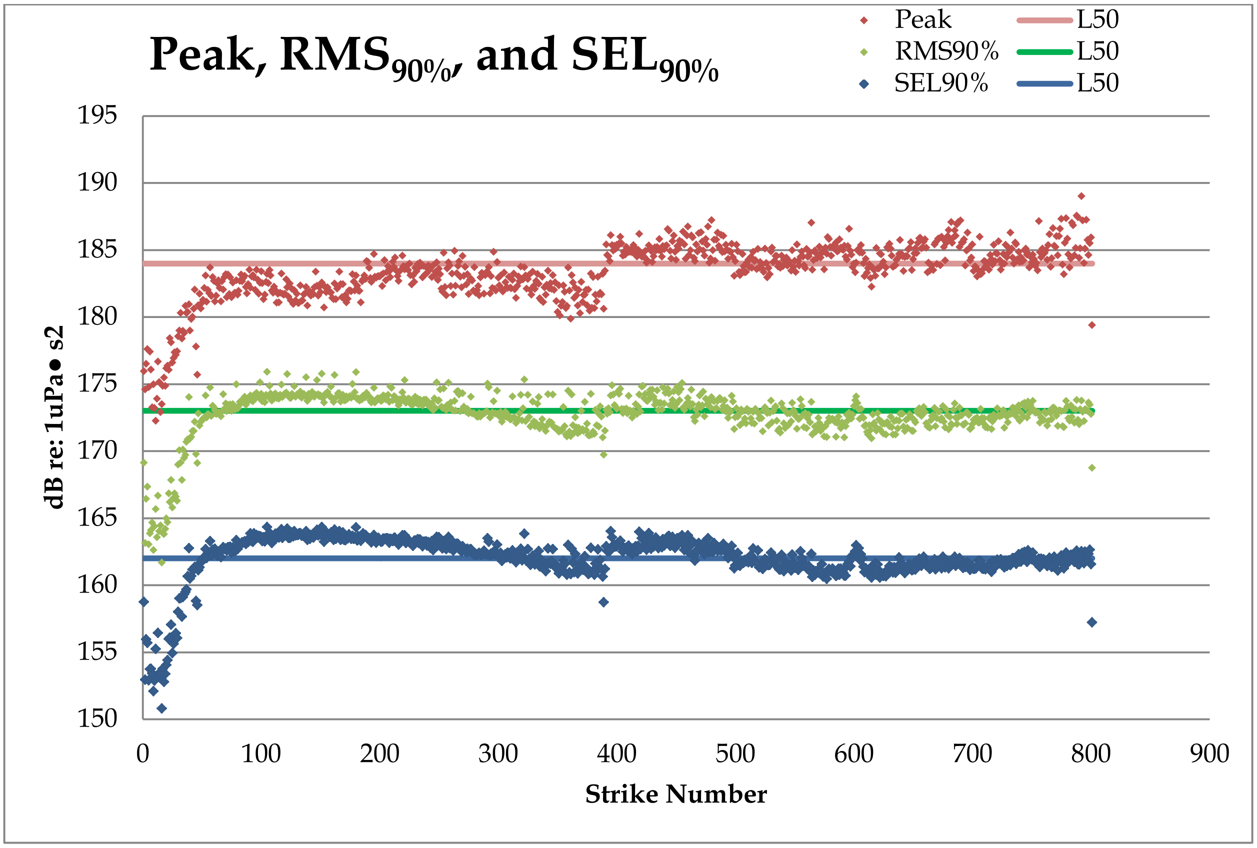
Pile 9

Pile 9 is located south of the Colman Dock Ferry Terminal (Figure 2). The pile was an 18-inch solid octagonal concrete test pile and had an absolute peak value of 189 dB_{peak} at 10 meters, an $RMS_{90\%}$ of 173 $dB_{RMS90\%}$ and a $SEL_{90\%}$ of 163 $dB_{SEL90\%}$. The cumulative SEL (cSEL) for Pile 9 was 191 dB_{cSEL} calculated based on the accumulation of the single strike $SEL_{90\%}$ for each pile strike (Table 2).

The dB_{peak}, $RMS_{90\%}$, $dB_{SEL90\%}$ for each pile strike are plotted in Figure 21. This plot is different from the 36-inch steel pile scatterplots showing a steady increase at the beginning of the drive followed by an evening out of sound levels around the 100th Pile strike with some variability amongst the individual pile strikes represented by the diamond shapes. The solid horizontal lines in these figures represent the L_{50} of 184 for dB_{peak}, 173 for $RMS_{90\%}$, and 162 for $SEL_{90\%}$. We do not see this pattern in the 36-inch or 24-inch steel piles, but is similar to that seen in the hollow concrete piles, although the hollow concrete piles generally exhibit less fluctuation, which could be the result of the way energy is transferred through the wood pile cap into the concrete and then into the steel stinger absorbing some of the energy and reducing these fluctuations seen in the steel piles. This pile was driven multiple times, and the abrupt change in sound levels observed around strike 400 is likely due to restarting pile driving operations or differences in the substrate which the pile is being driven through.

The dB_{peak}, $RMS_{90\%}$, $dB_{SEL90\%}$ for each pile strike are relatively similar between the two 18-inch octagonal concrete piles. Both piles have a steady increase in sound energy level early on before slowly decreasing at around pile strike 200. In both piles, there is a sudden jump around pile strike 400 which is likely due to a starting and stopping of pile driving activities. Both piles then continue at a relatively consistent sound energy level for the remainder of the drive.

Figure 21: 18-inch Octagonal Concrete Pile 9, dB_{peak}, $RMS_{90\%}$, and $dB_{SEL90\%}$ levels for each pile strike with the L_{50}



The 18-inch solid octagonal concrete Piles 8 and 9 were very similar in terms of sound energy levels during pile strikes. Figure 22 shows a single strike waveform comparison between Pile 8 and Pile 9. The waveform analysis shows that the two piles have similar characteristics to each other with Pile 8 exhibiting slightly higher sound energy levels. Figure 23 shows a narrow band frequency comparison for Pile 8 and Pile 9. This comparison shows that both piles exhibit similar sound characteristics at all frequencies, but that Pile 9 has higher sound energy levels by approximately 2 dB for higher frequencies beginning around 10,000 Hz. This analysis takes a conservative approach and assumes that the loudest individual pile from each pile type will be representative of that pile type. For this reason, only the loudest piles will have their Narrow Band Frequencies and single strike waveform's compared to other pile types. Since these two piles exhibit such similar sound level characteristics and there was no clearly loudest pile, Pile 8 was used as a comparison to other pile types.

Figure 22: 18-inch Solid Octagonal Concrete Pile 8 and 18-inch Solid Octagonal Concrete Pile 9 Waveform Comparison

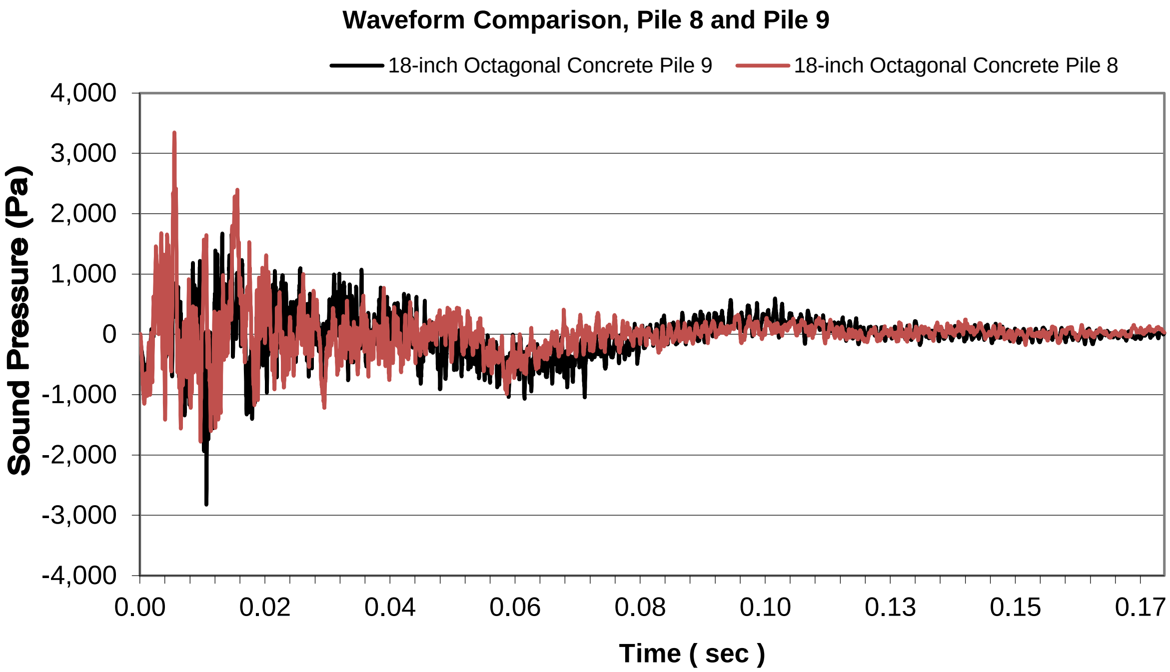


Figure 23: 18-inch Solid Octagonal Concrete Pile 8 and 18-inch Solid Octagonal Concrete Pile 9 Narrow Band Frequency Comparison

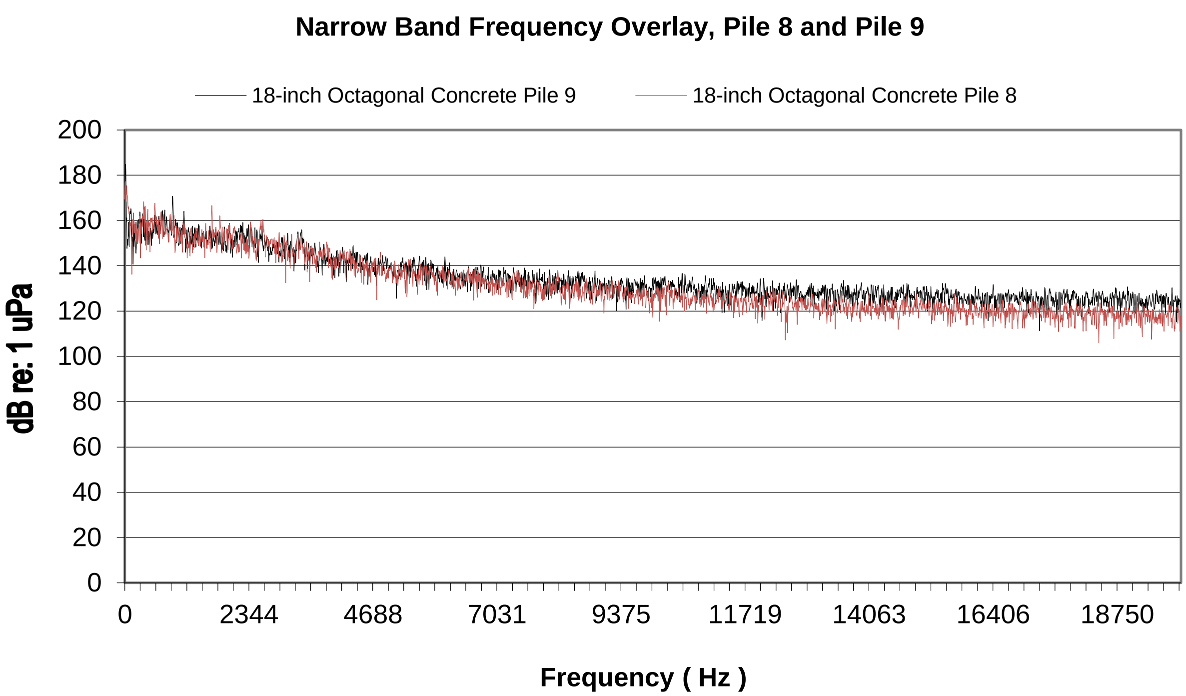
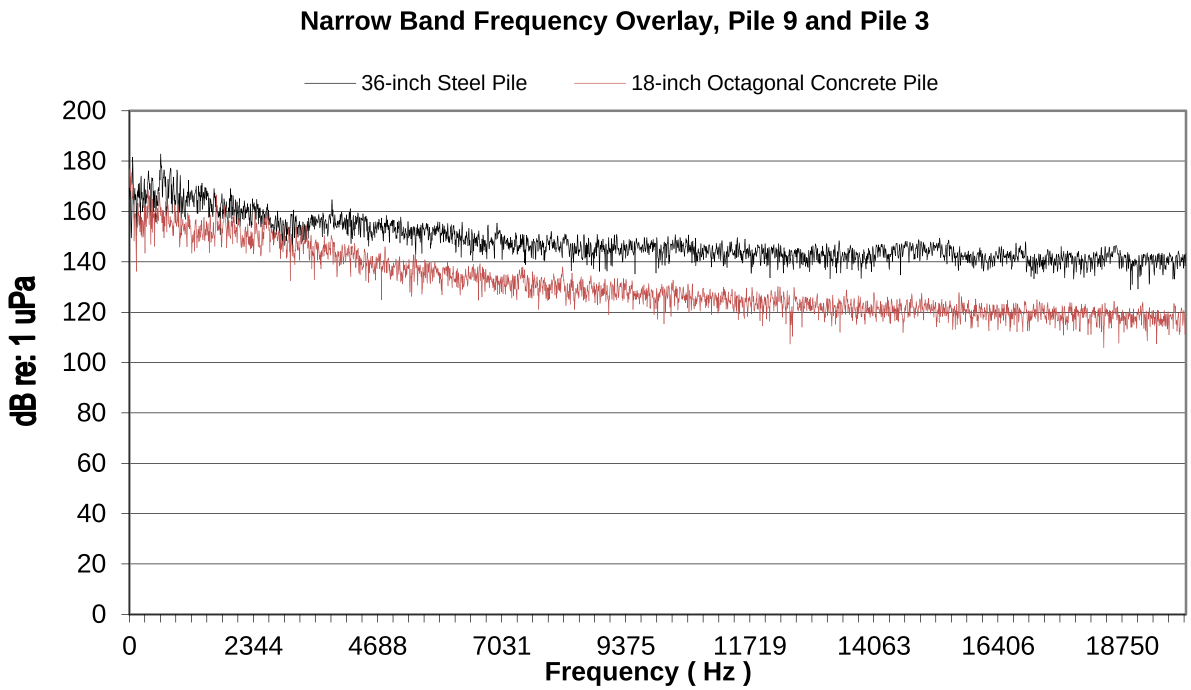


Figure 24 shows an overlay of the Narrow Band Frequency Spectra for the 18-inch solid octagonal concrete pile 8 and the 36-inch steel pile 3. This figure shows the differences in the dB levels an average of three consecutive pile strikes recorded at various frequencies. This graph suggests that the two piles have similar dB levels low frequencies, but the 18-inch octagonal concrete pile is notably quieter than the 36-inch steel pile at almost frequencies higher than roughly 3000 Hz.

Figure 24: Narrow Band Frequency Spectra overlay for 18-inch octagonal concrete Pile 9 and 36-inch steel pile 3



A waveform of a single pile strike for the 18-inch solid octagonal concrete Pile 8 is shown in Figure 25. When compared to the single strike waveform for the 36-inch steel pile in Figure 25, it can be seen that there is much less sound energy produced by the octagonal concrete pile.

Figure 25: 18-inch Octagonal Concrete Pile 8 vs. 36-inch Steel Pile 3, Single Pile Strike Waveform

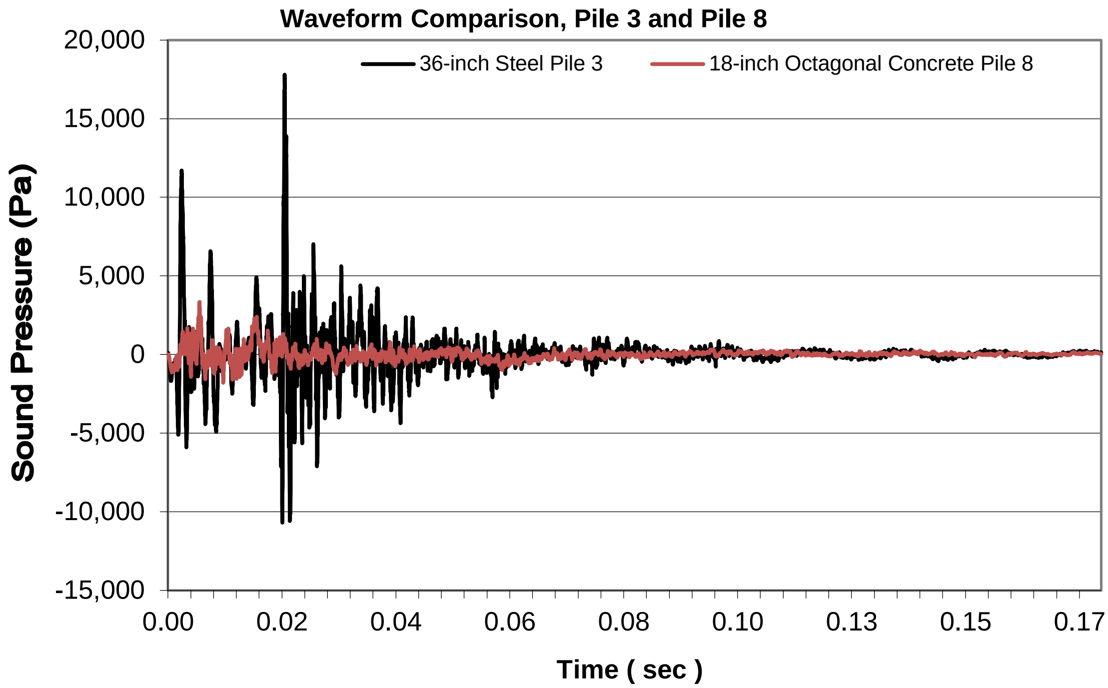


Table 2: Summary of Underwater Broadband Sound Levels for the Colman Dock Test Pile Project

Pile #	Date & Time	Pile Diameter (inches)	Hydrophone Range (m)	Hydrophone Depth (feet)	Pile Type	Total Number Of Strikes	Highest Absolute Peak (dB)	Peak L50	$RMS_{90\%}$ (dB)	RMS L50	Single Strike $SEL_{90\%}$ (dB)	SEL L50	Avg. Peak ± s.d. (Pascal)	Avg. RMS ± s.d. (Pascal)	Cumulative SEL (dB)
1	1/28/2016 11:44 AM	24	12	6	Steel Control	54	174	170	157	158	149	147	674 ± 1110	143 ± 206	171
2	1/28/2016 1:54 PM	24	15	3	Steel Control	64	180	*	165	*	155	*	*	*	173
3	2/2/2016 9:50 AM	36	14	3	Steel	529	205	200	189	185	176	172	6910 ± 5496	2058 ± 3727	193
4	2/2/2016 3:22 PM	36	24	3	Steel	328	199	194	184	182	172	169	4699 ± 1369	1233 ± 286	195
5	2/3/2016 1:15 PM	36	12	3	Hollow Concrete	383	190	188	180	179	168	166	1500 ± 398	543 ± 159	192
6	2/4/2016 8:19 AM	36	19	3	Hollow Concrete	394	186	183	174	173	162	160	691 ± 179	200 ± 60	186
7	2/5/2016 10:09 AM	36	10	5	Hollow Concrete	193	197	194	184	183	172	170	1750 ± 436	459 ± 107	192
8	2/5/2016 1:35 PM	18	10	5	Octagonal Concrete	835	190	187	175	174	164	162	1569 ± 578	459 ± 140	191
9	2/8/2016 11:39 AM	18	10	5	Octagonal Concrete	795	189	184	173	173	163	162	746 ± 210	239 ± 88	191

*Data could not be calculated or estimated due to corrupted data file

Daily Cumulative SEL

The daily cSEL's were calculated using the calculated $SEL_{90\%}$ for each individual pile strike for each day and accumulated over that period (Table 3).

Table 3: Summary of daily cumulative SEL's

Day	10-24M
1/28/2016	176
2/2/2016	209
2/3/2016	191
2/4/2016	187
2/5/20166	202
2/8/2016	191

The daily cumulative SEL values ranged from 176 to 209 dB at 10 to 24 meters from the pile.

Airborne Sound Levels

Both A-weighted and un-weighted airborne sound level measurements were collected from the nearest location to the pile on the ferry trestle, 10-23 meters from the piles. Five minute measurements were collected along with 1-second time histories to attempt to capture the sound levels for most of the pile strikes. Since the meter is able to collect a measurement every one second and pile strikes occur approximately every 1.5 seconds some pile strikes were not able to be recorded accurately and were eliminated from the plots below. Measurements were collected for all seven test piles, but not for the 24-inch steel control piles.

The A-weighted L_{Aeq} values for the entire pile drive ranged between 84 dBA and 98 dBA at 50 feet and the L_{max} ranged between 107 dBA and 114 dBA at 50 feet (Table 4). The measured levels are all standardized to a distance of 50 feet which is standard for reporting construction noise levels. The un-weighted L_{eq} values for the entire pile drive ranged between 88 and 102 dB at 50 feet and the L_{max} ranged between 110 dB and 119 dB at 50 feet.

Table 4: Summary of Control and test pile airborne A-weighted and un-weighted sound levels collected between January 28, 2016 and February 8, 2016

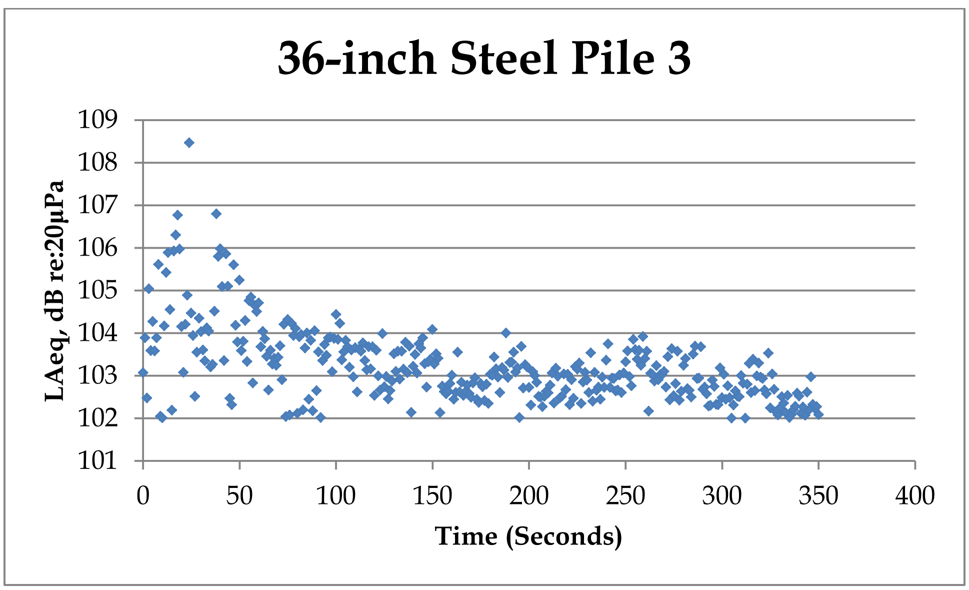
Pile #	Pile Type	Distance from Pile (m)	Measured L_{Aeq} (dBA)	L_{Aeq} at 50 feet (dBA)	Measured L_{max} (dBA)	L_{max} at 50 feet (dBA)
A-Weighted (dBA)						
3	36-inch Steel	13	85	84	109	108
4	36-inch Steel	23	93	97	110	114
5	36-inch Hollow Concrete	10	98	94	114	110
6	36-inch Hollow Concrete	20	93	95	108	110

7	36-inch Hollow Concrete	13	84	83	109	108
8	18-inch Octagonal Concrete	11	90	87	107	104
9	18-inch Octagonal Concrete	11	92	89	111	108
Un-weighted (dB)						
3	36-inch Steel	13	93	92	112	111
4	36-inch Steel	23	97	101	112	116
5	36-inch Hollow Concrete	10	102	98	119	115
6	36-inch Hollow Concrete	20	96	98	110	112
7	36-inch Hollow Concrete	13	88	87	110	109
8	18-inch Octagonal Concrete	11	96	93	110	107
9	18-inch Octagonal Concrete	11	97	94	111	108

A-weighted Results

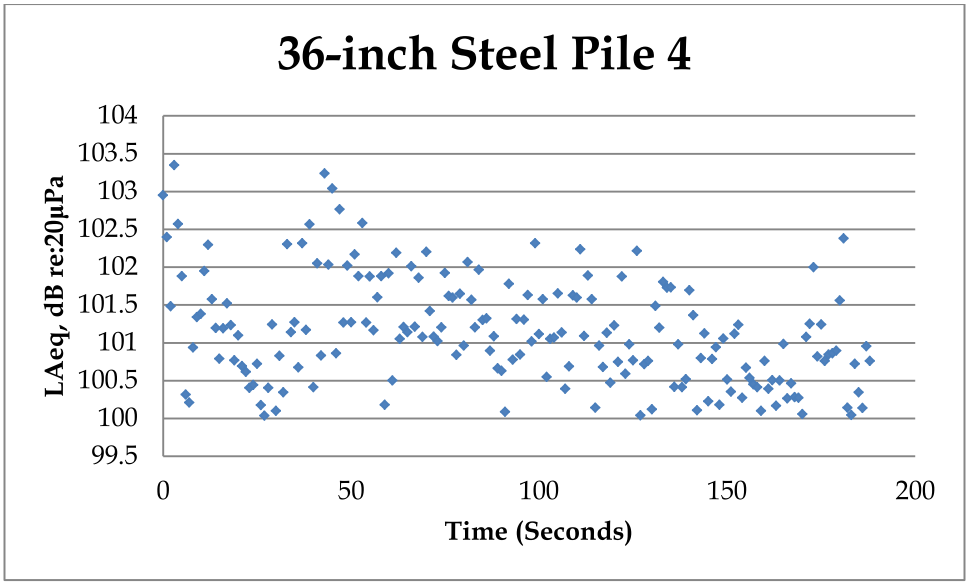
The time history plot of A-weighted airborne sound levels for each individual pile strike measured for the 36-inch Steel piles, 36-inch hollow concrete piles, and 18-inch solid octagonal concrete piles are shown in Figures 26-32. The L_{Aeq} sound levels for each pile strike for the 36-inch steel Pile 3 ranged between approximately 102 dBA and 108 dBA. The dB levels for each pile strike are shown in Figure 26 below.

Figure 26: Time history of L_{Aeq} airborne sound levels for each pile strike for the 36-inch Steel Pile 3



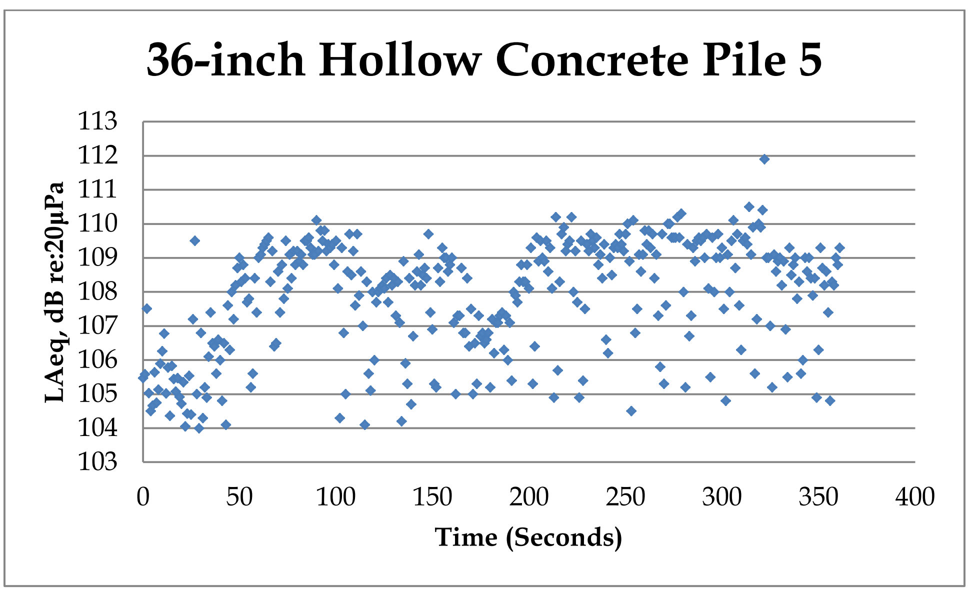
The L_{Aeq} sound levels for each pile strike for the 36-inch steel pile 4 ranged between approximately 98 dBA and 103 dBA. The dB levels for each pile strike are shown in Figure 27 below.

Figure 27: Time history of L_{Aeq} airborne sound levels for each pile strike for the 36-inch Steel Pile 4



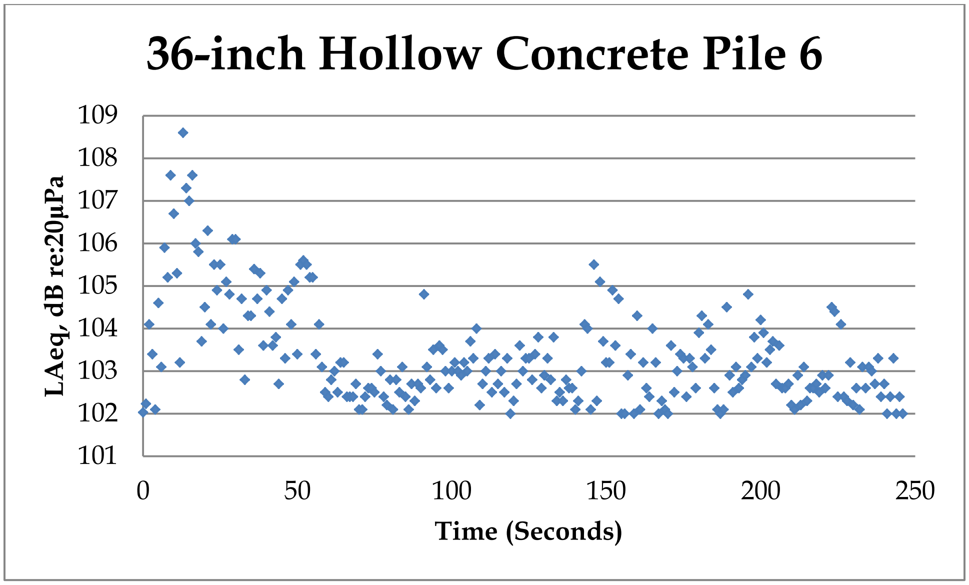
The L_{Aeq} sound levels for each pile strike for the 36-inch hollow concrete pile 5 ranged between approximately 94 dBA and 112 dBA. The dB levels for each pile strike are shown in Figure 28 below.

Figure 28: Time history of L_{Aeq} airborne sound levels for each pile strike for the 36-inch Hollow Concrete Pile 5



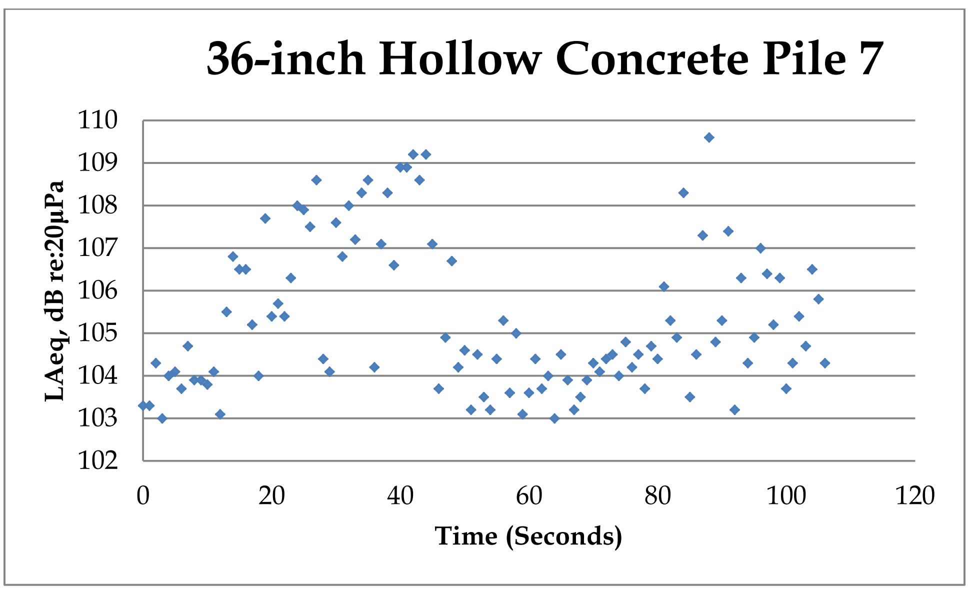
The L_{Aeq} sound levels for each pile strike for the 36-inch hollow concrete pile 6 ranged between approximately 96 dBA and 108 dBA. The dB levels for each pile strike are shown in Figure 29 below.

Figure 29: Time history of L_{Aeq} airborne sound levels for each pile strike for the 36-inch Hollow Concrete Pile 6



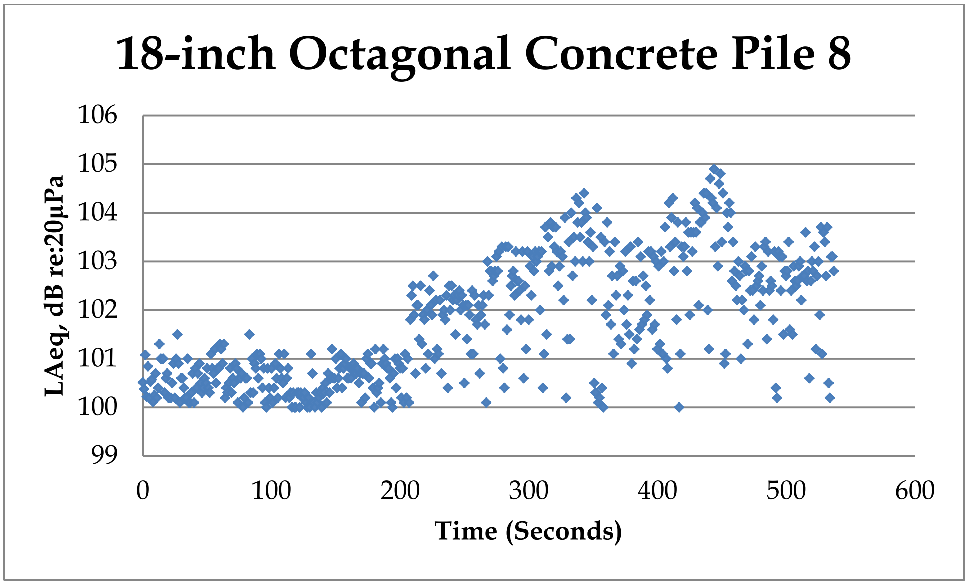
The L_{Aeq} sound levels for each pile strike for the 36-inch hollow concrete pile 7 ranged between approximately 95 dBA and 110 dBA. The dB levels for each pile strike are shown in Figure 30 below.

Figure 30: Time history of L_{Aeq} airborne sound levels for each pile strike for the 36-inch Hollow Concrete Pile 7



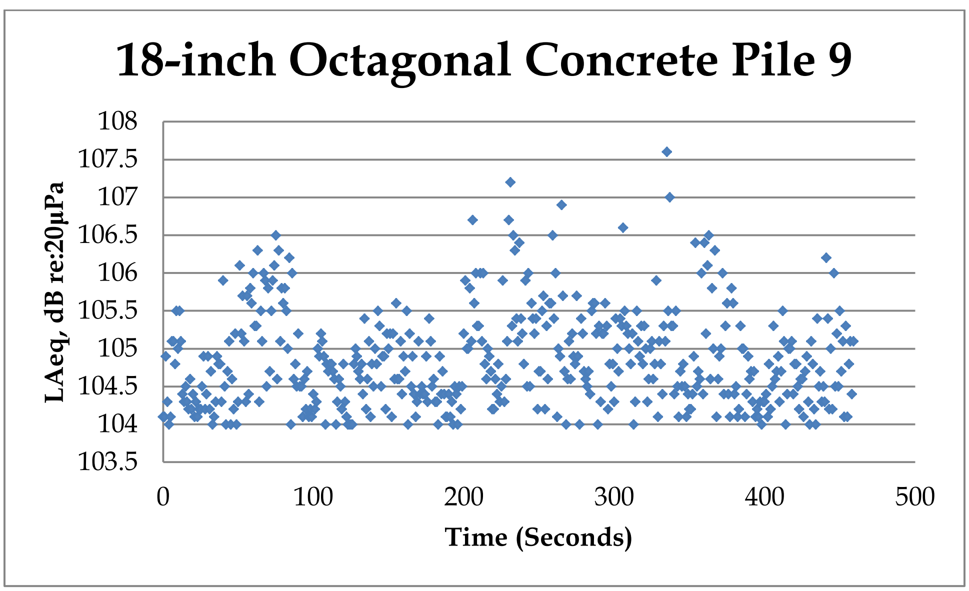
The L_{Aeq} sound levels for each pile strike for the 18-inch octagonal concrete pile 8 ranged between approximately 98 dBA and 105 dBA. The dB levels for each pile strike are shown in Figure 31 below.

Figure 31: Time history of L_{Aeq} airborne sound levels for each pile strike for the 18-Inch Octagonal Concrete Pile 8



The L_{Aeq} sound levels for each pile strike for the 18-inch Octagonal Concrete Pile 9 ranged between approximately 102 dBA and 108 dBA. The dB levels for each pile strike are shown in Figure 32 below.

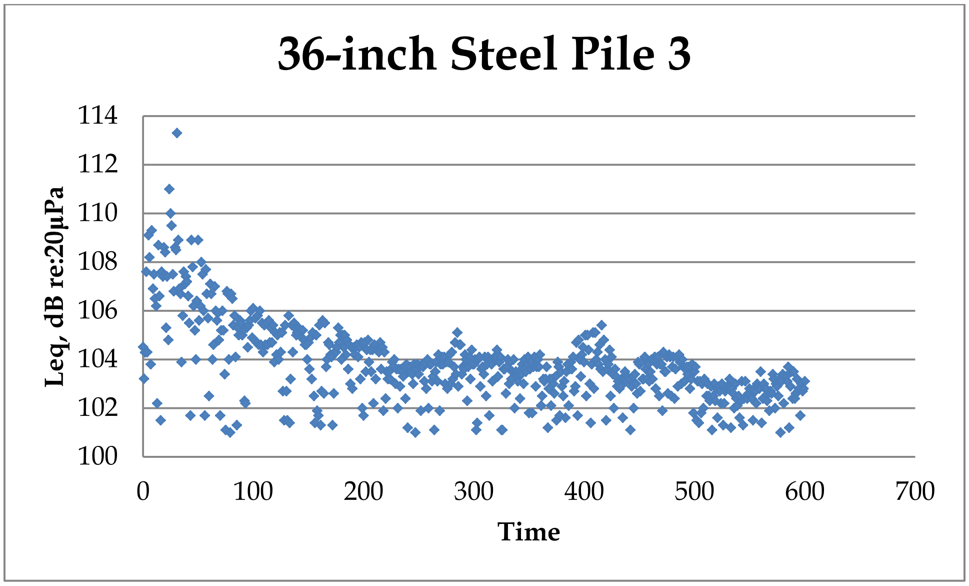
Figure 32: Time history of L_{Aeq} airborne sound levels for each pile strike for the 18-inch Octagonal Concrete Pile 9



Un-weighted Results

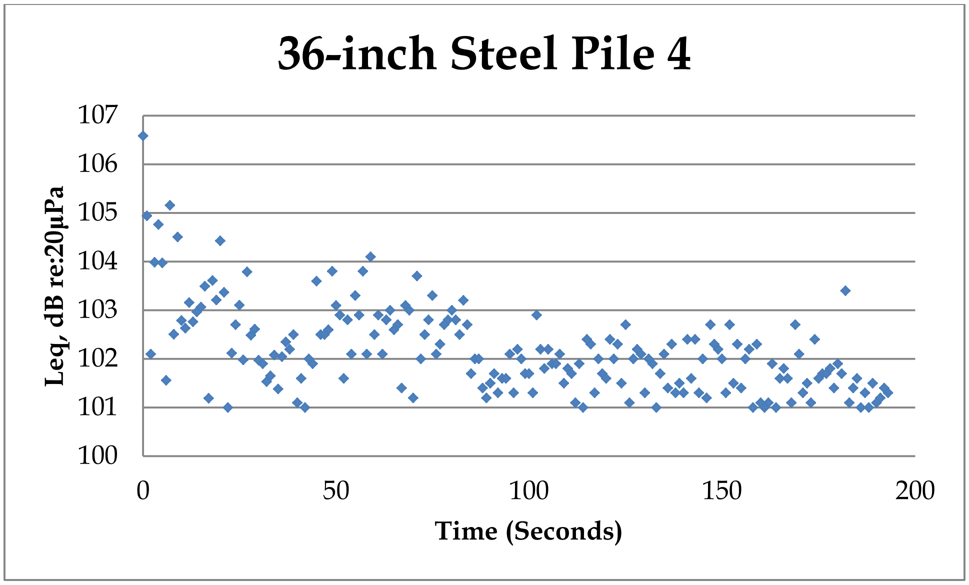
The time history plot of un-weighted airborne sound levels for each individual pile strike measured for the 36-inch Steel piles, 36-inch Hollow Concrete piles, and 18-inch Octagonal Concrete piles are shown in Figures 33-39. The L_{eq} sound levels for each pile strike for the 36-inch Steel pile 3 ranged between approximately 96 dB and 114 dB. The dB levels for each pile strike are shown in Figure 33 below.

Figure 33: Time history of L_{eq} airborne sound levels for each pile strike for the 36-inch Steel Pile 3



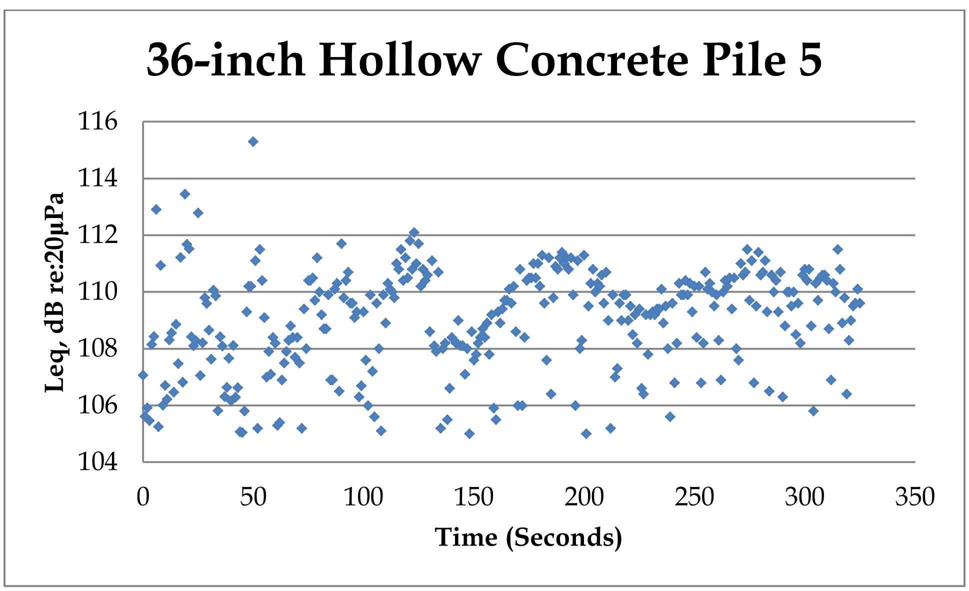
The L_{eq} sound levels for each pile strike for the 36-inch Steel pile 4 ranged between approximately 97 dB and 105 dB. The dB levels for each pile strike are shown in Figure 34 below.

Figure 34: Time history of L_{eq} airborne sound levels for each pile strike for the 36-inch Steel Pile 4



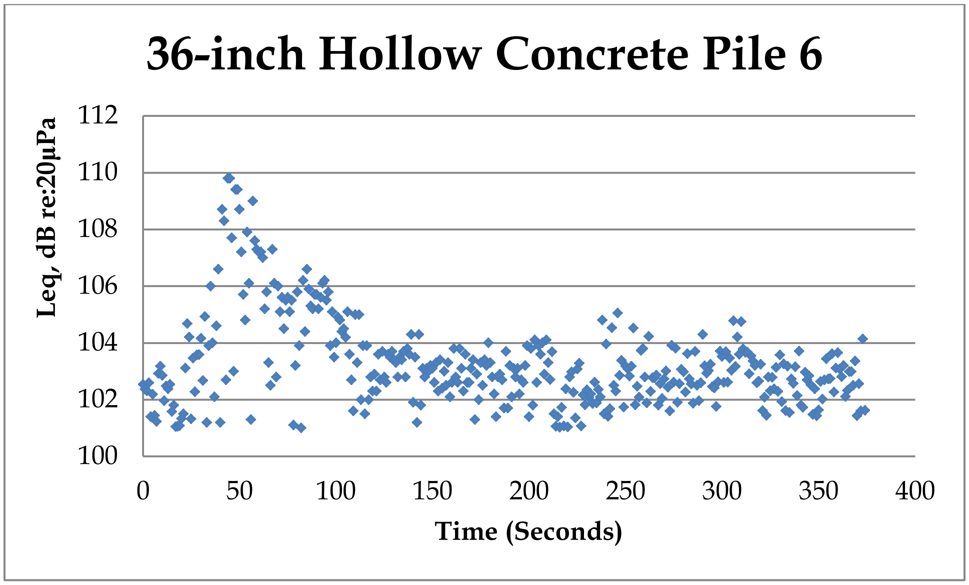
The L_{eq} sound levels for each pile strike for the 36-inch hollow concrete pile 5 ranged between approximately 95 dB and 115 dB. The dB levels for each pile strike are shown in Figure 35 below.

Figure 35: Time history of L_{eq} airborne sound levels for each pile strike for the 36-inch Hollow Concrete Pile 5



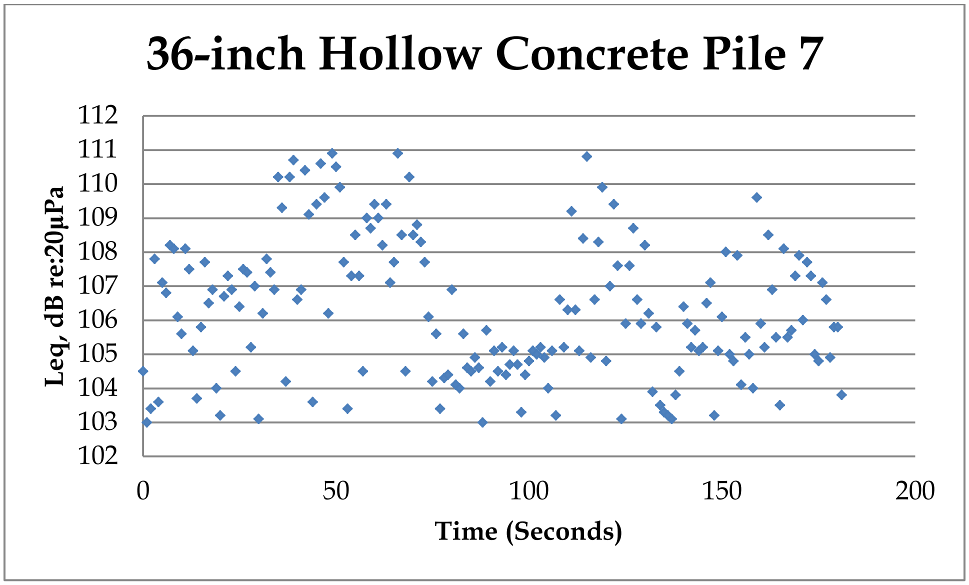
The L_{eq} sound levels for each pile strike for the 36-inch hollow concrete pile 6 ranged between approximately 95 dB and 110 dB. The dB levels for each pile strike are shown in Figure 36 below.

Figure 36: Time history of L_{eq} airborne sound levels for each pile strike for the 36-inch Hollow Concrete Pile 6



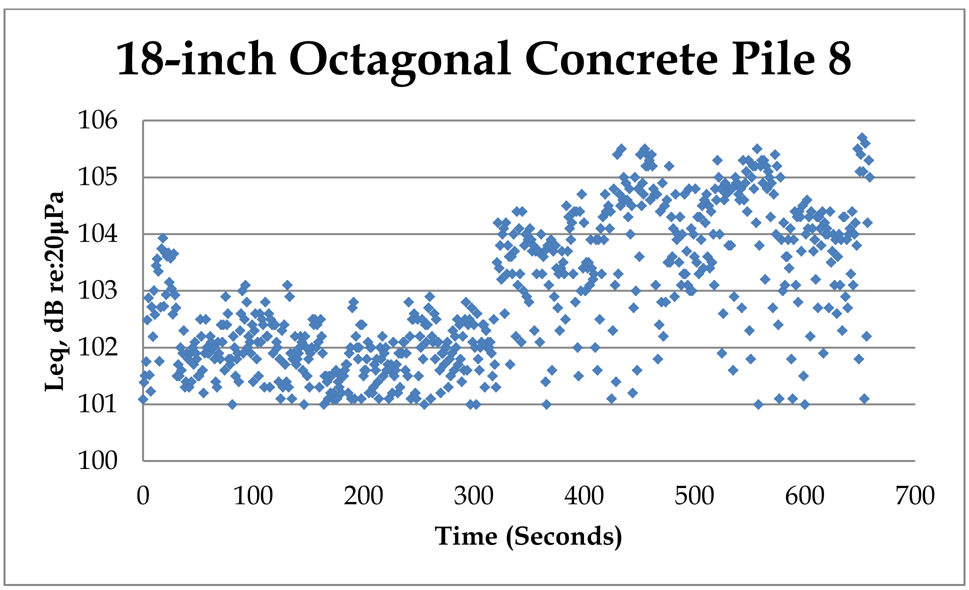
The L_{eq} sound levels for each pile strike for the 36-inch hollow concrete pile 7 ranged between approximately 95 dB and 111 dB. The dB levels for each pile strike are shown in Figure 37 below.

Figure 37: Time history of L_{eq} airborne sound levels for each pile strike for the 36-inch Hollow Concrete Pile 7



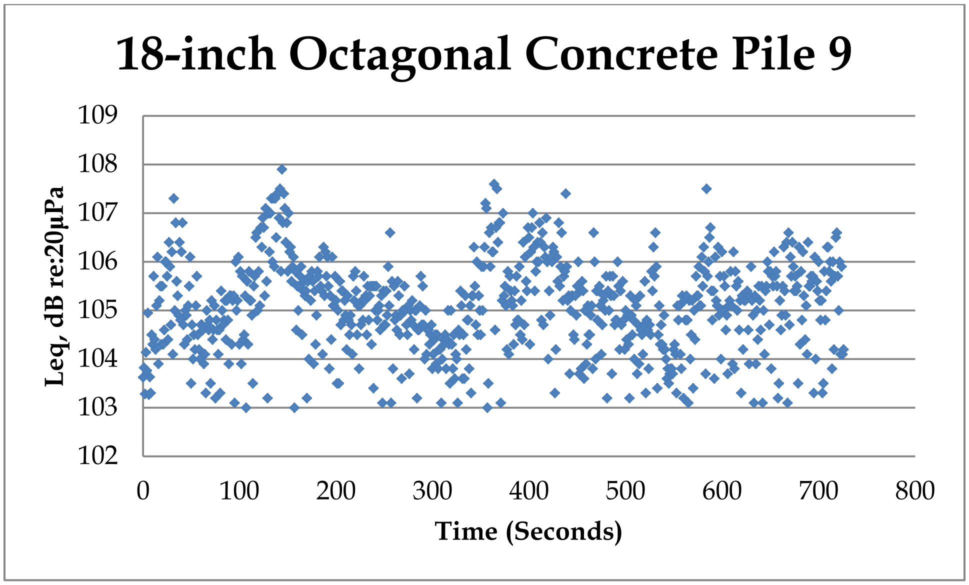
The L_{eq} sound levels for each pile strike for the 18-inch octagonal concrete pile 8 ranged between approximately 94 dB and 106 dB. The dB levels for each pile strike are shown in Figure 38 below.

Figure 38: Time history of L_{eq} airborne sound levels for each pile strike for the 36-inch Octagonal Concrete Pile 8



The L_{eq} sound levels for each pile strike for the 18-inch octagonal concrete pile 9 ranged between approximately 95 dB and 108 dB. The dB levels for each pile strike are shown in Figure 39 below.

Figure 39: Time history of L_{eq} airborne sound levels for each pile strike for the 36-inch Octagonal Concrete Pile 9



For each of the seven test piles the overall airborne 1/3rd octave band frequencies for both A-weighted and un-weighted sound were averaged using multiple 5 minute measurements for each pile and plotted in Figures 40 and 41. Figure 40 shows a relatively normal distribution of sound levels between 40 Hz and 20 kHz with the dominant frequency at approximately 2000 Hz for the 36-inch Steel Piles which is atypical for airborne sound levels during impact driving of steel piles, which are usually in the 400 Hz to 800 Hz range. The 36-inch hollow concrete piles have a dominant frequency between 400 Hz and 2000 Hz. These piles exhibit the typical airborne sound level frequency range during impact driving of steel piles, but also extend into higher frequency ranges nearing 2000 Hz. The 18-inch octagonal concrete piles are dominant between 2000 Hz and 6300 Hz, higher frequencies than the other two types of test piles. The 18-inch octagonal concrete piles also exhibit a peak at a relatively low frequency of 100 Hz.

Figure 40: Averaged A-weighted overall 1/3rd octave band frequencies (L_{eq}) for impact driving of the 36-inch Steel Piles, 36-inch Hollow Concrete Piles, and 18-inch Octagonal Concrete Piles

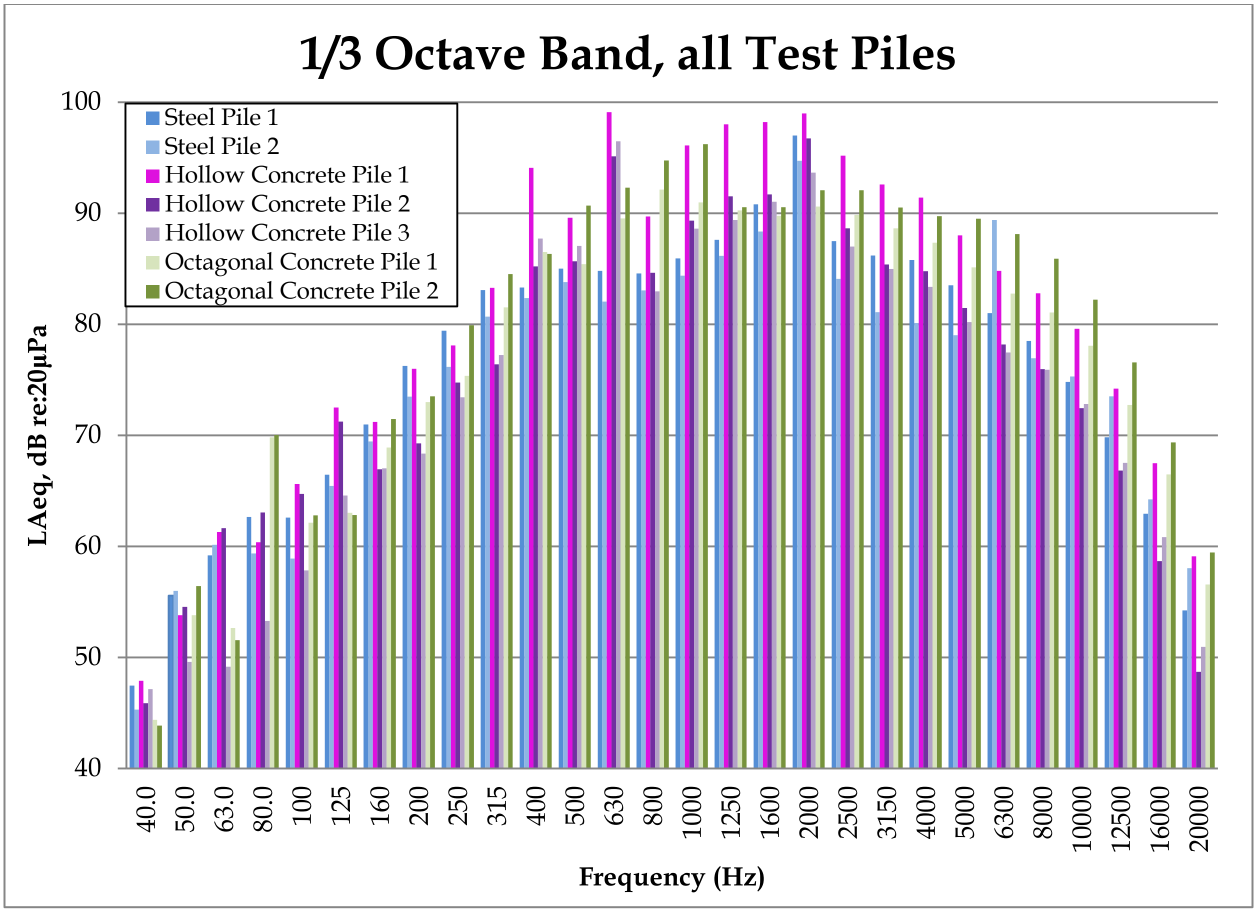
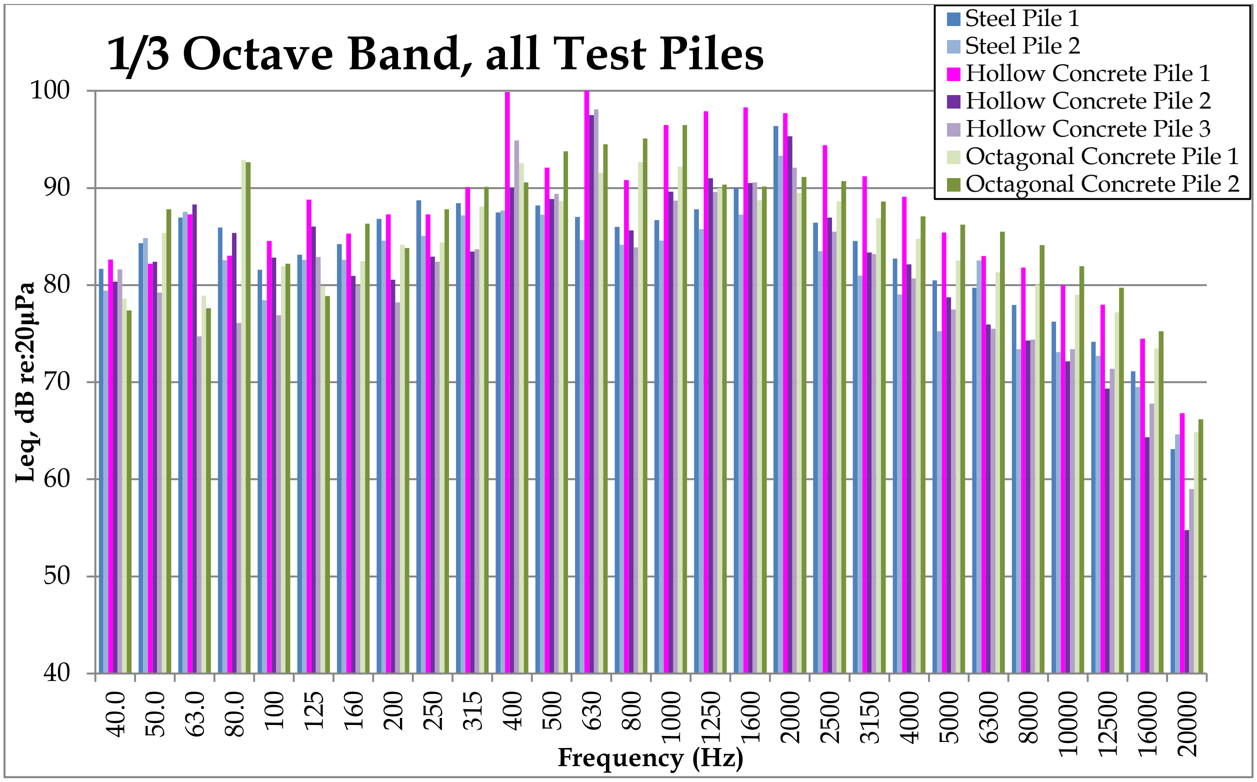


Figure 41 shows a relatively normal distribution of un-weighted sound levels between 40 Hz and 20 kHz with the dominant frequency at approximately 2000 Hz for the 36-inch Steel Piles which is atypical for airborne sound levels during impact driving of steel piles, which are usually in the 400 Hz to 800 Hz range. The 36-inch hollow concrete piles have a dominant frequency between 400 Hz and 2000 Hz. These piles exhibit the typical airborne sound level frequency range during impact driving of steel piles, but also extend into higher frequency ranges nearing 2000 Hz. The 18-inch octagonal concrete piles are dominant between 500 Hz and 1250 Hz. The 18-inch octagonal concrete piles also exhibit a peak at a relatively low frequency of 80 Hz and are comparatively louder at higher frequencies, from approximately 4000 Hz to 12,500 Hz, than the other pile types. The dominant un-weighted frequencies for each pile type are similar to the dominant A-weighted frequencies.

Figure 41: Averaged un-weighted overall 1/3rd octave band frequencies (L_{eq}) for impact driving of the 36-inch Steel Piles, 36-inch Hollow Concrete Piles, and 18-inch Octagonal Concrete Piles



CONCLUSIONS

Two 24-inch steel control piles, two 36-inch steel piles, three 36-inch hollow concrete test piles with a 24-inch steel stinger, and two 18-inch solid octagonal concrete test piles with a 12-inch steel stinger, were monitored for the Colman Dock Pile Project. The underwater sound levels analyzed, produced the following results.

- Peak underwater sound levels from 10 to 24 meters varied in a range between 174-180 dB_{Peak} for the 24-inch steel control piles, 199-205 dB_{Peak} for the 36-inch steel piles, 186-197 dB_{Peak} for the Hollow Concrete piles, and 189-190 dB_{Peak} for the octagonal concrete piles.
- The measured $RMS_{90\%}$ levels ranged between 157-165 $dB_{RMS90\%}$ for the 24-inch steel control piles, 184-189 $dB_{RMS90\%}$ for the 36-inch steel piles, 174-184 $dB_{RMS90\%}$ for the hollow concrete piles, and 173-175 $dB_{RMS90\%}$ for the octagonal concrete piles.
- The measured $SEL_{90\%}$ levels ranged between 149-155 $dB_{SEL90\%}$ for the 24-inch steel control piles, 172-176 $dB_{sel90\%}$ for the 36-inch steel piles, 162-172 $dB_{SEL90\%}$ for the hollow concrete piles, and 162 $dB_{SEL90\%}$ for both of the octagonal concrete piles
- Cumulative Sound Exposure Levels (cSEL) for all piles driven on a particular 12-hour period, ranged between 176 dB_{cSEL} and 209 dB_{cSEL}.
- The 36-inch hollow concrete piles and 18-inch octagonal concrete piles produced results that were notably different than the 36-inch steel piles, with increasing sound energy levels early in the drive, leveling out after roughly 100 strikes, and fluctuating up and down from there. These piles were generally quieter than the 36-inch steel piles after comparing their Narrow Band Frequencies and single strike waveforms.

All seven test piles were also monitored for airborne sound levels during impact driving. The measurements produced the following results.

- Overall L_{Aeq} sound levels were measured to be between 84 and 98 dB re: 20 µPa at 50 feet with L_{max} levels ranging between 107 and 111 dB re: 20 µPa at 50 feet.
- One of the three 36-inch hollow concrete piles was the loudest of these type of piles at 98 dB L_{Aeq}, but the other 2 such piles were similar to the 36-inch steel piles and 18-inch octagonal concrete piles.
- L_{Aeq} levels were calculated at 84 dB and 97dB at 50 feet for the two 36-inch Steel Piles.
- L_{Aeq} levels were calculated at 94 dB, 95 dB, and 83 dB at 50 feet for the three 36-inch hollow concrete piles.
- L_{Aeq} levels were calculated at 87 dB and 89 dB at 50 feet for the two 18-inch octagonal concrete piles.

APPENDIX A WAVEFORM ANALYSIS FIGURES

Figure 42: Colman Dock Test Piles: 24 inch Control Pile 1

Colman Dock Test Piles 24 in Control Pile 1 at 10m Broadband

Figure a. Waveform

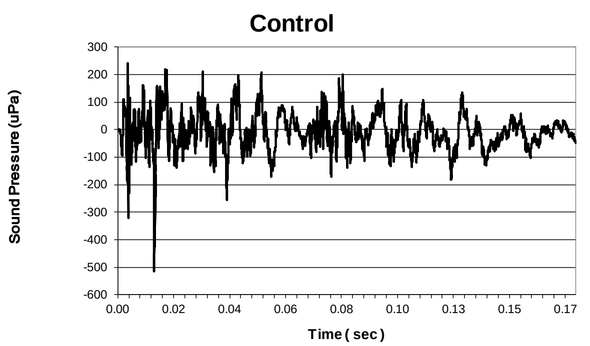


Figure b. Narrow Band Frequency Spectra

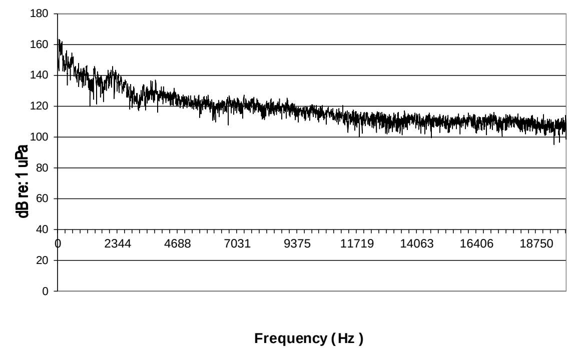


Figure c. Accumulation of Sound Energy

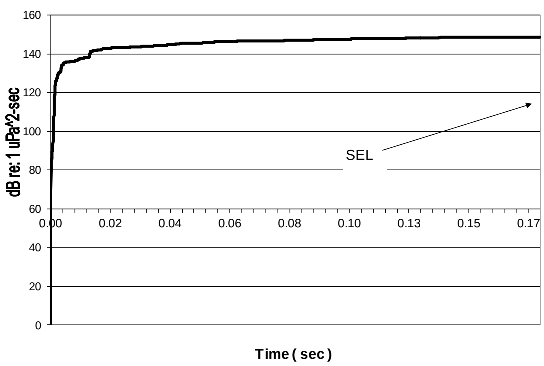


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
10 feet	174	157	149

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

Figure 43: Colman Dock Test Piles: 24 inch Control Pile 2

Pile 2 was not analyzed due to corrupted data.

Figure 44: Colman Dock Test Piles: 36-inch Steel Pile 3

Colman 36-inch at 10 meters broadband

Figure a. Waveform

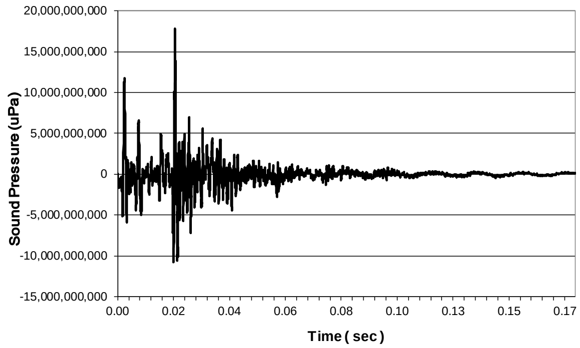


Figure b. Narrow Band Frequency Spectra

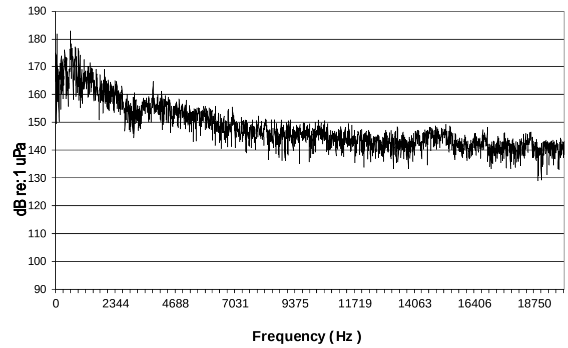


Figure c. Accumulation of Sound Energy

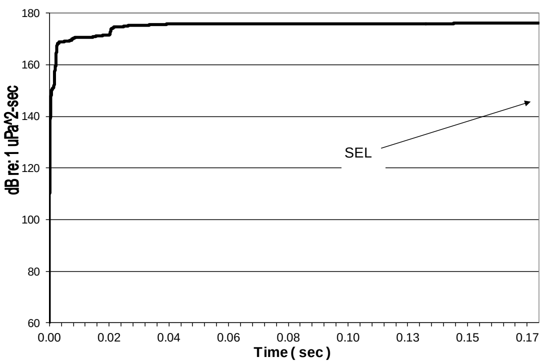


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
9-feet	205	189	176

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

Figure 45: Colman Dock Test Piles: 36-inch Steel Pile 4

Colman 36 inch Test Pile 2 at 15 meters broadband

Figure a. Waveform

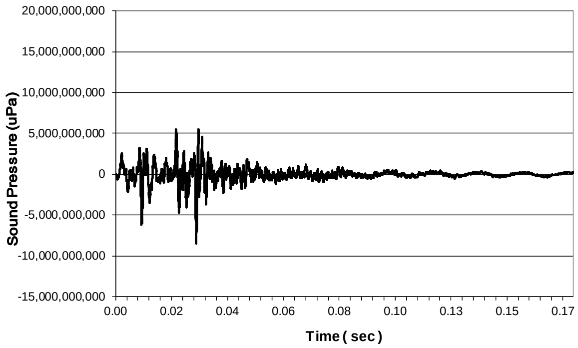


Figure b. Narrow Band Frequency Spectra

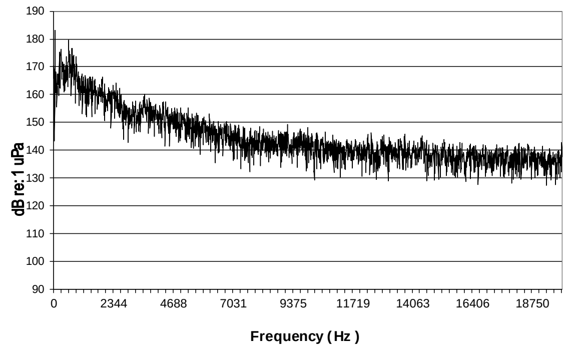


Figure c. Accumulation of Sound Energy

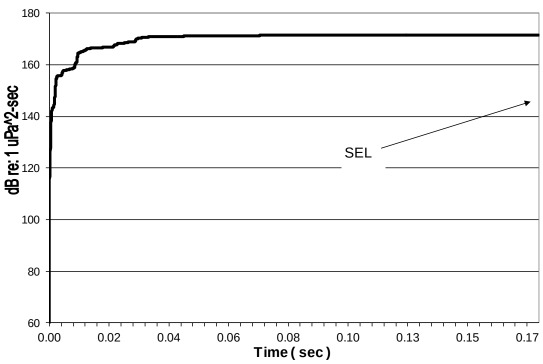


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	$RMS_{90\%}$*	SEL
11 feet	199	184	172

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

Figure 46: **Colman Dock Test Piles: 36-inch Hollow Concrete 5**

Colman Dock 36 inch Test Pile 3 at 10m Broadband

Figure a. Waveform

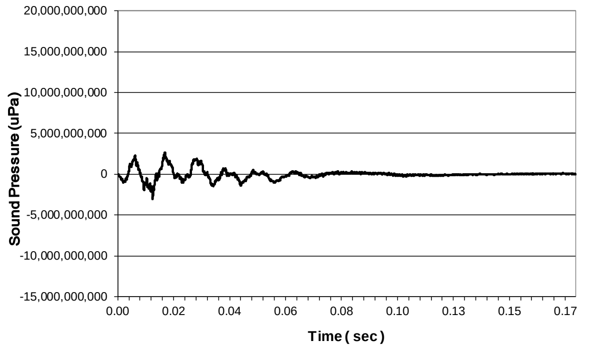


Figure b. Narrow Band Frequency Spectra

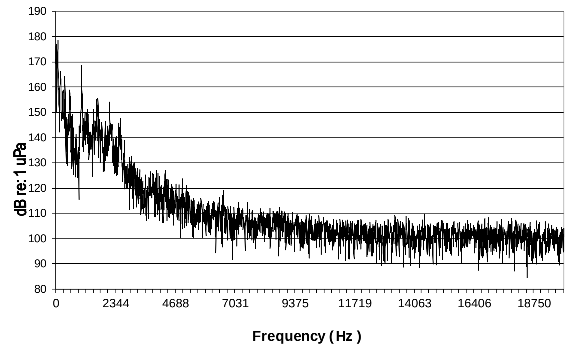


Figure c. Accumulation of Sound Energy

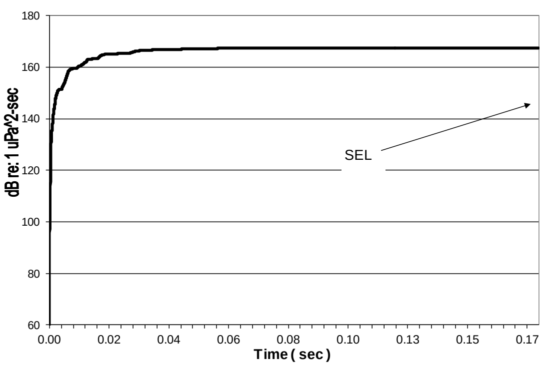


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
11.5 feet	190	180	168

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

Figure 47: Colman Dock Test Piles: 36-inch Hollow Concrete 6

Colman Dock 36 inch test Pile 4 at 19m Broadband

Figure a. Waveform

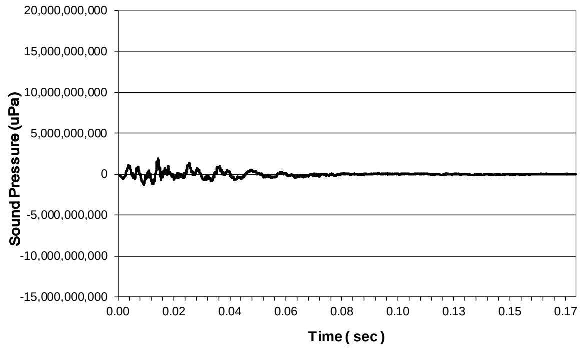


Figure b. Narrow Band Frequency Spectra

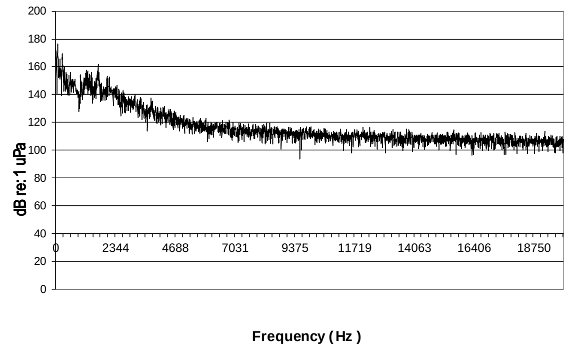


Figure c. Accumulation of Sound Energy

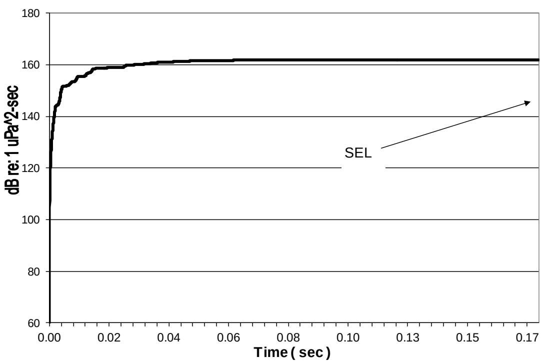


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
10.5 feet	186	174	162

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

Figure 48: Colman Dock Test Piles: 36-inch Hollow Concrete 7

Colman Dock 36 inch test Pile 5 at 10m Broadband

Figure a. Waveform

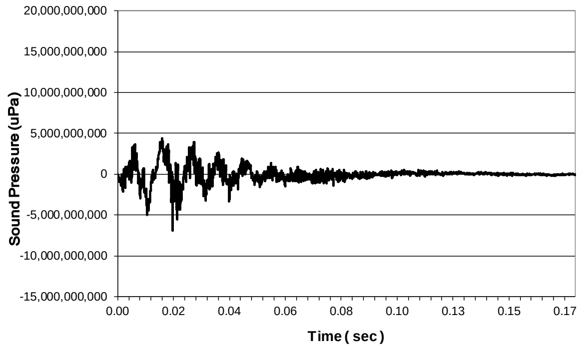


Figure b. Narrow Band Frequency Spectra

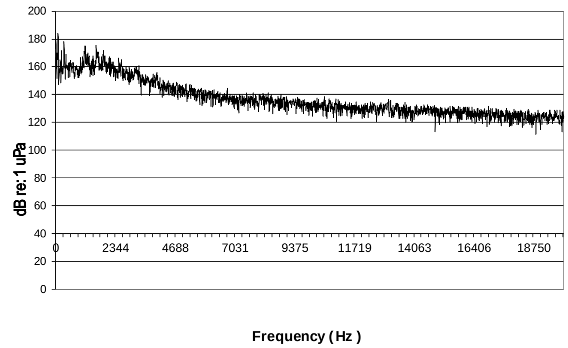


Figure c. Accumulation of Sound Energy

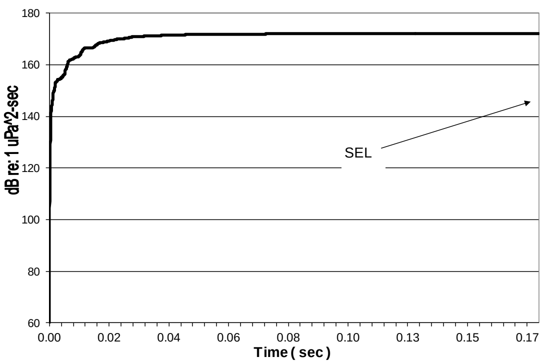


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
18 feet	197	184	172

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

Figure 49: Colman Dock Test Piles: 18-inch Octagonal Concrete 8

Colman Dock 18 inch test Pile 6 at 10m Broadband

Figure a. Waveform

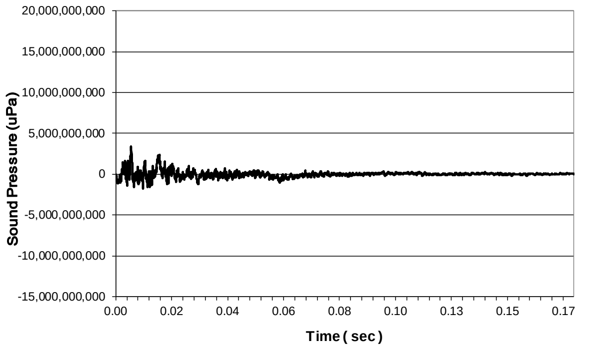


Figure b. Narrow Band Frequency Spectra

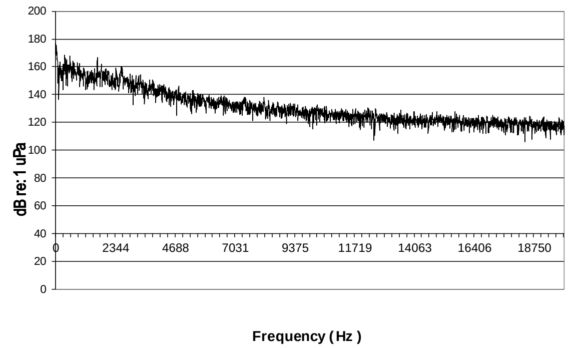


Figure c. Accumulation of Sound Energy

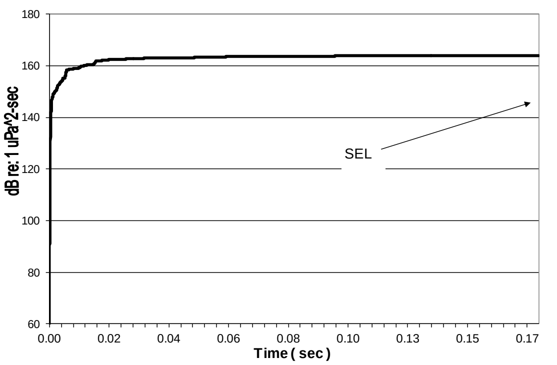


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
18 feet	190	175	164

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

Figure 50: Colman Dock Test Piles: 18-inch Octagonal Concrete 9

Colman Dock 36 inch test Pile 7 at 10m Broadband

Figure a. Waveform

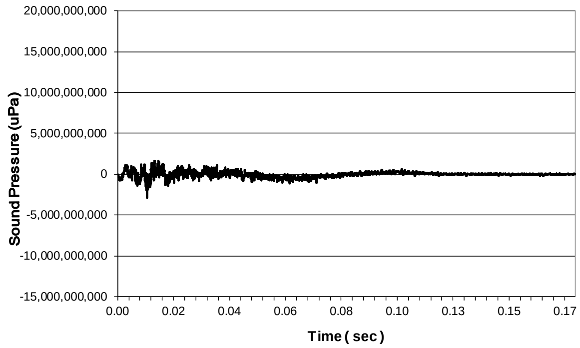


Figure b. Narrow Band Frequency Spectra

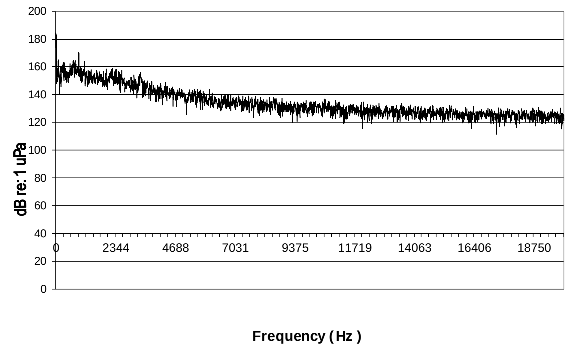


Figure c. Accumulation of Sound Energy

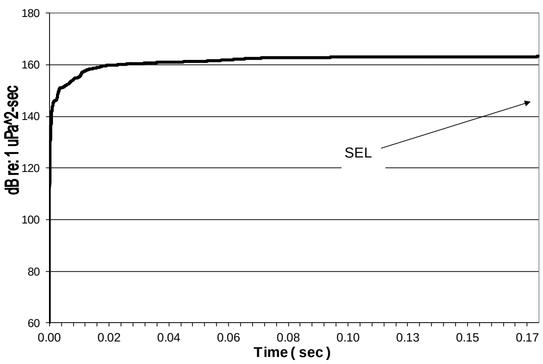


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

Sensor Depth	Peak	RMS90%*	SEL
18 feet	189	173	163

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