SR 520 WEST CONNECTION BRIDGE

Underwater Sound Level Report: Permanent Bridge Replacement

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ACRONYMS AND ABBREVIATIONS

dB	decibel
Hz	hertz
μPa	micro-Pascal
NIST	National Institute of Standards and Technology
Pa	Pascal
RMS	route mean squared
s.d.	standard deviation
SEL	Sound Exposure Level
SL	sound level, regardless of descriptor
SPL	sound pressure level
USFWS	U.S. Fish and Wildlife Service
WSDOT	Washington State Department of Transportation

EXECUTIVE SUMMARY

This technical report describes the data collected during impact pile driving and monitoring of underwater sound levels from driving the 24-inch and 30-inch steel piles for the Washington State Department of Transportation (WSDOT) State Route (SR) 520 West Connection Bridge Project between December 2013 and March 2014. Data was collected for twenty-two 24-inch and six 30-inch piles. Confined bubble curtains were deployed for all piles impact driven to attenuate potential underwater noise effects. All measurements were collected 10 meters from the pile and at 3H from the pile where H is the water depth at the pile with 3H ranging between 15 meters and 35 meters.

Some data was not able to be saved and post processed due to an incompatibility issue with the recording software and Windows 7, however, real-time field notes were able to determine the peak and estimate the cumulative Sound Exposure Level (cSEL) for each pile.

The cumulative Sound Exposure Level (cSEL) for the 21 out of 28 piles monitored exceeded the peak threshold of 187 dB. The peak attenuated sound levels measured ranged between 175 dB peak and 204 dB peak while monitoring the impact pile driving operation as shown in Table 1. The daily cSEL for all days monitored exceeded the threshold of 187 dB_{peak} at 10 meters except for the two piles driven on 1/14/14 and all days except for the last day (3/2/14) at the 3H location.

Table 1: Summary of 24-inch and 30-inch Pile Attenuated Underwater Sound Levels.

Pile #	Date	Hydrophone Range (m)	Peak (dB)	Exceedence?	RMS (dB)	Single Strike SEL (dB)	Cumulative SEL (dB)
1	12/5/13	10	186	N	179	167	194
		15	185	N	181	167	195
2a[2]	12/5/13	10	188	Y	179	167	192
		15	185	N	179	167	192
2b	12/6/13	10	188	Y	176	166	187
		15	185	N	178	168	189
3	12/5/13	10	187	N	180	168	195
		25	181	N	177	164	191
4	12/5/13	10	185	N	177	166	194
		25	180	N	178	164	192
5	12/6/13	10	188	Y	181	172	194

Pile #	Date	Hydrophone Range (m)	Peak (dB)	Exceedence?	RMS (dB)	Single Strike SEL (dB)	Cumulative SEL (dB)
		35	176	N	173	160	187
6	12/6/13	10	190	Y	183	171	197
		35	175	N	172	160	187
7	12/10/13	10	187	N	173	163	192
		10	204[4]	Y	189	174	-
		15	202[4]	Y	185	173	-
		15	181	N	172	161	192
8	12/6/13	10	186	N	170	160	192
		16	178	N	170	160	185
9[3]	12/11/13	10	185	N	175	163	190
		25	180	N	172	162	187
10	12/11/13	13	184	N	174	163	190
		25	175	N	171	160	187
11	1/13/14	10	185	N	174	165	189
		16	177	N	172	160	185
	1/14/14	10	185[5]	N	174[5]	165[5]	188
		16	n.s.	n.s.	n.s.	n.s.	n.s.
12[2]	11/13/14	10	189	Y	n.s.	169[1]	199[1]
		21	n.s.	n.s.	n.s.	n.s.	n.s.
13[2]	1/13/14	12	178	N	n.s.	158[1]	182[1]
		25	n.s.	n.s.	n.s.	n.s.	n.s.
14[2]	1/14/14	10	189	Y	n.s.	169[1]	200[1]
		16	n.s.	n.s.	n.s.	n.s.	n.s.
15*	1/16/14	11	190	Y	175	162	187
		16	192	Y	176	165	191
16	1/25/14	14	195	Y	178	166	194
		19	193	Y	177	166	196
17	1/27/14	17	197	Y	182	168	194
18*	1/28/14	10	202	Y	185	173	197
		17	196	Y	176	167	193
19*	1/29/14	17	200	Y	184	170	195
		23	196	Y	177	167	186
20		10	185	N	171	160	190
		20	182	N	169	159	188

Pile #	Date	Hydrophone Range (m)	Peak (dB)	Exceedence?	RMS (dB)	Single Strike SEL (dB)	Cumulative SEL (dB)
21		11	183	N	170	158	186
		21	178	N	167	158	186
22[2]	2/27/14	11	179	N	173	160	180
		21	177	N	173	160	178
23		11	178	N	168	158	184
		21	178	N	174	162	188
24		10	184	N	177	164	190
		21	175	N	169	157	185
25		10	188	Y	171	160	191
		21	177	N	168	158	186
26[2]		10	185	N	179	167	187
		21	179	N	166	157	174
27		15	186	N	172	161	190
		26	179	N	164	155	181
28*	3/2/14	10	190	Y	173	163	188
		25	182	N	169	159	184

1 – These data are approximated by subtracting 20 dB from the peak to obtain the single strike SEL and then using this value to calculate the cumulative SEL based on the total number of strikes.
2 – Top of pile mushroomed so the pile driving was stopped prematurely.
3 – Pile broken subsurface. n.s. – Data not saved due to software malfunction.
* - Battered Pile
4 – Bubble Curtain off
5 – The highest peak values occurred on the previous day for this same pile

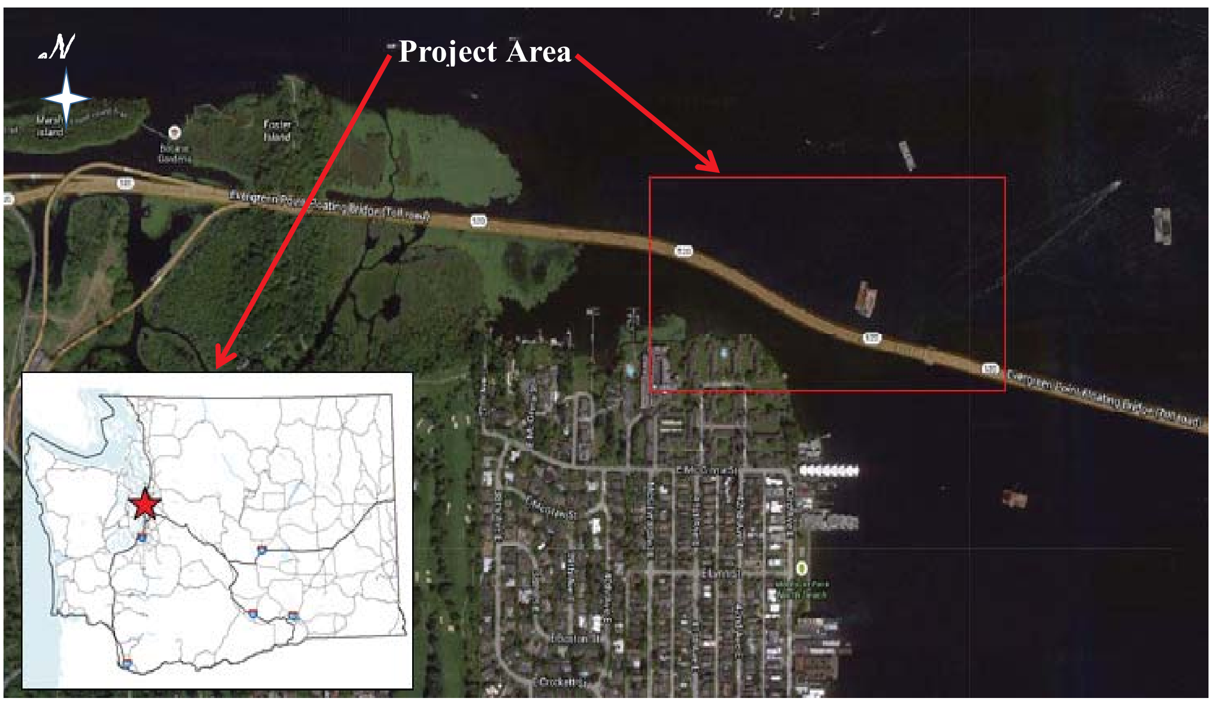
INTRODUCTION

The Washington State Department of Transportation (WSDOT) proposes to construct additional work temporary platforms adjacent to the West Connection Bridge (WCB). The additional platforms are necessary because there is concern that a pressurized underground aquifer that will be encountered during drilled shaft construction may require deep casings in order to prevent caving and undermining during excavation. This is particularly an issue for drilled shafts that will be constructed adjacent to existing SR 520 bridge columns. The drilled shafts will be constructed deeper than the existing bridge columns, which will expose the existing bridge to risk of settlement if undermining occurs. Oscillators provide means of torsionally installing deep casings for stability in certain soil conditions or where debris is anticipated that could hamper installation by conventional means (i.e. vibratory pile driving). Oscillators will likely be needed to install these casings near the existing bridge in order to mitigate the risk of damage to the existing in-service bridge. Because oscillators produce more torque and reaction forces than can safely be resisted by a barge or other floating work platform, a highly stable work platform would be required.

PROJECT AREA

The project is located on the west end of SR 520 (Figure 1) between Union Bay and the west approach of the floating bridge just east of Foster Island. The work platform project impacted up to 100, 24-inch to 30-inch steel piles to bearing capacity to support the work platforms. All piles were driven with a vibratory hammer initially, but the "reaction" piles will need to be proofed to ensure that sufficient bearing capacity has been reached. The actual location and orientation of each work platform will also depend on the contractor's means of construction and available equipment. Each work platform will need to be oriented so that the shaft or shafts can be reached by the drilling equipment and also in such a way that barges and skiffs carrying workers, equipment, and supplies can also access the platform. The conceptual extent of the work platforms is shown in Figure 2.

Figure 1: SR 520 West Connection Bridge Project work platforms



PILE INSTALLATION LOCATION

Figure 2 indicates the location of the proposed work platforms. There were a total of up to 100 piles proofed with an impact hammer for the work platforms.

Although there is an estimated total of 160 piles needed for all the work platforms, not all of the platforms will require proofing with an impact hammer. The easterly five platforms will be supported by piles installed by vibratory means only. The westerly six platforms will need to support an oscillator rig and will require reaction piles proofed for bearing capacity. The hydrophones will be located at 10 meters and 3H, where H is the water depth of the pile, from each of the piles to be monitored. There will be a clear line-of-sight between the pile and the hydrophone.

Hydroacoustic monitoring was conducted during the first ten piles struck with an impact hammer, five piles in the middle and five piles at the end of the impact driving schedule for. An additional 8 piles were monitored due to some challenges encountered while driving piles at Pier 30 for a total of 28 piles. Hydroacoustic monitoring of steel pile driving included:

- Monitoring of 28 steel piles (total) with five monitored initially, five near the completion, and the remainder intermediate piles selected according to the criteria identified in the USFWS T & C's,
- Testing sound attenuation system effectiveness on one pile,
- Measurement of noise levels at 10 meters from the pile and at 3H where H is the water depth at the pile.

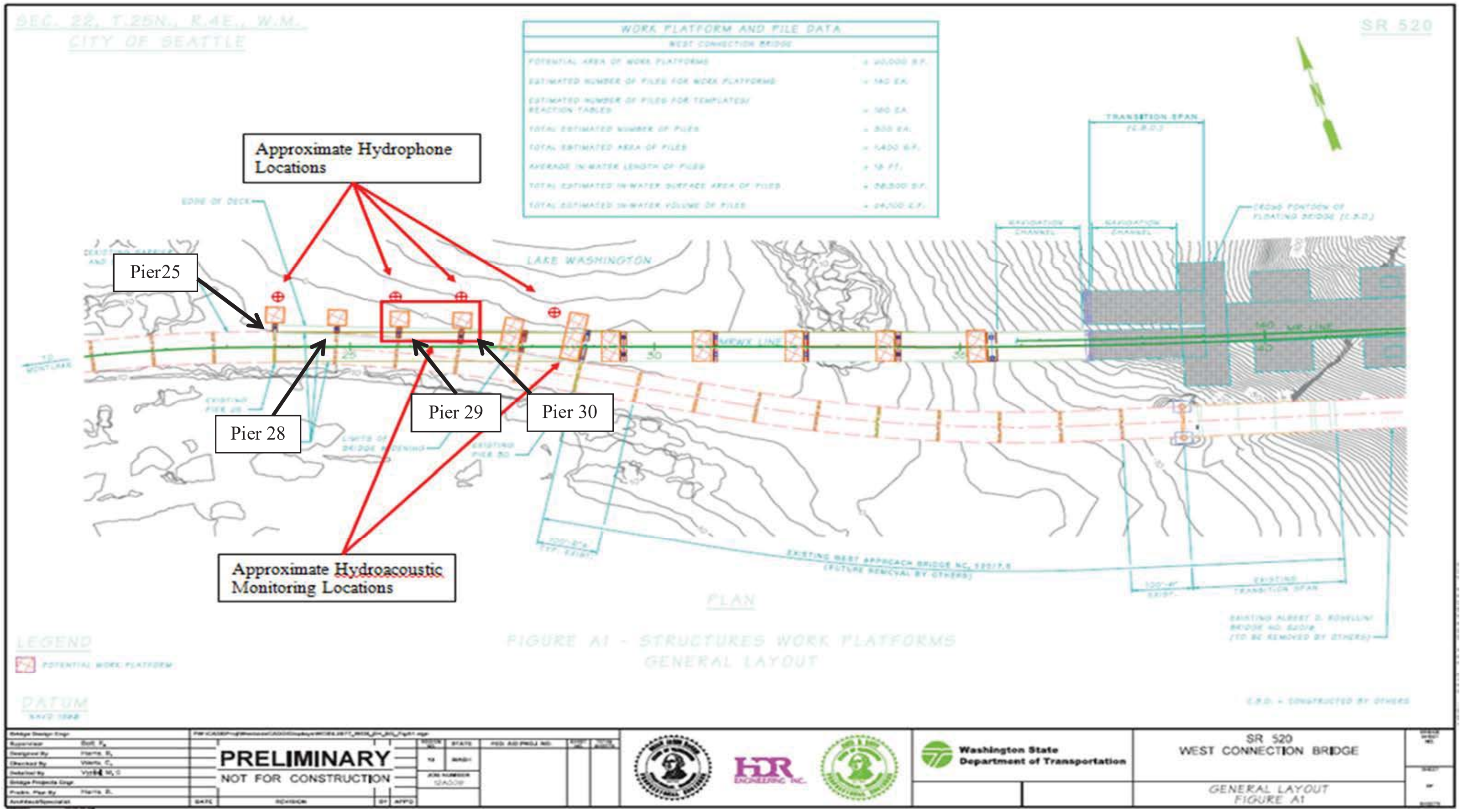
Figure 2 indicates the location of the piles monitored and the approximate hydrophone locations for each pile being monitored. All hydrophones are placed at least 1 m (3.3 feet) below the surface with one hydrophone at a range of 10 meters and midwater depth. A second hydrophone is located at a range of 3H where H is the water depth of the pile being monitored and at a depth of 0.8 of the water depth at the hydrophone location. Each pile has a clear acoustic line-of-sight between the pile and the hydrophone.

Table 2 lists the structure installed, the water depth, and the number and size of piles installed.

Table 2. Structures to be installed for the SR 520 West Connection Bridge

Structure	Water Depth	Structural Components Installed
Steel Pipe Pile	*16 feet to 22 feet*	*100 18-inch to 30-inch hollow steel piles*

Figure 2: monitored pile locations



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

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

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

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.

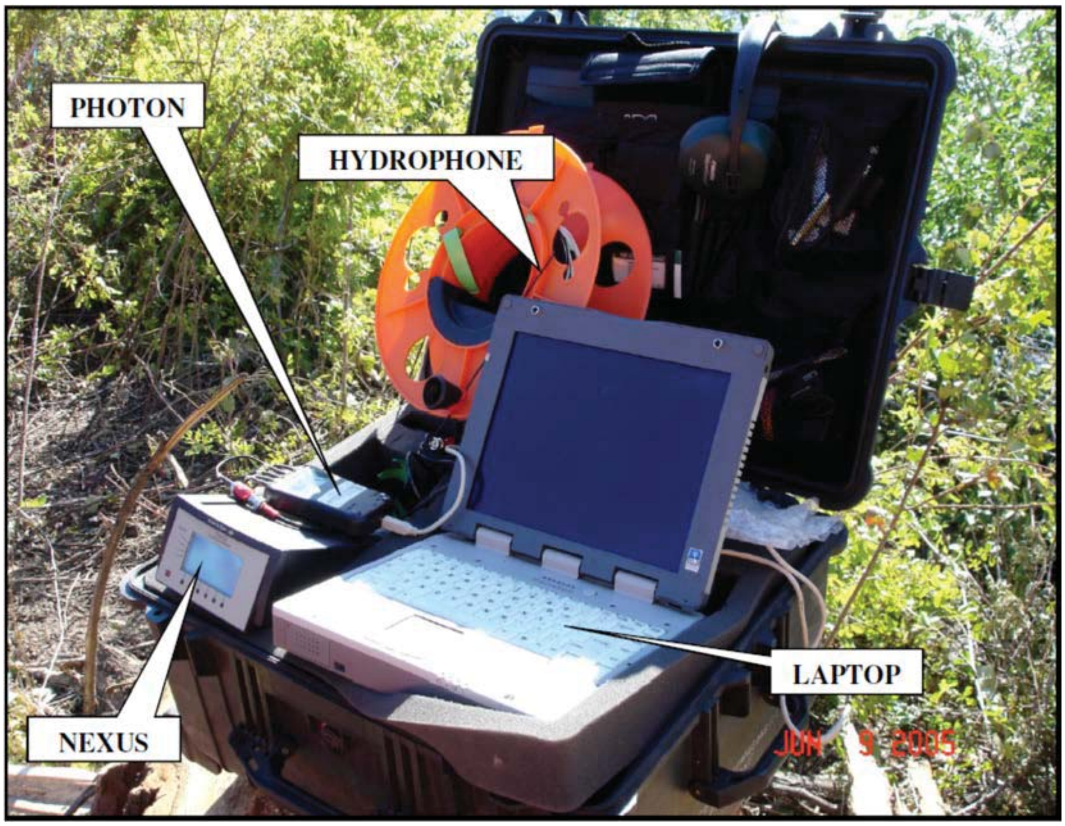
METHODOLOGY

Typical Equipment Deployment

The hydrophones were deployed from the crane barge. The monitoring equipment is outlined below and shown in Figure 3. The hydrophones were stationed and fixed with anchors and a surface float at a distance of 10 meters and 3H from the pile, where H is the water depth at the pile with 3H ranging between 15 meters and 35 meters.

Bubble curtains were deployed for all piles driven to mitigate potential underwater noise effects.

Figure 3: Near Field Acoustical Monitoring Equipment.



Twenty-eight impact driven piles, except for three short periods, were monitored with the sound attenuation bubble curtain system active. Un-attenuated pile strikes were measured for Pile 7 for approximately 1 minute at the beginning and towards the end of the drive.

Underwater sound levels were measured near the piles using two Reson TC 4013 hydrophones deployed on a weighted nylon cord from the crane barge. The hydrophones were positioned at a distance of 10 meters and 3H from each pile, at mid-water depth and 0.8 water depth respectively. The measurement system includes a Brüel and Kjær Nexus type 2692 4-channel signal conditioner, which kept the high underwater sound levels within the dynamic range of the signal analyzer Figure 3. The output of the Nexus signal conditioner is received by a 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 15.3 µs (25,600 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.

The $RMS_{90\%}$ was calculated for each individual impact strike. 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.

The peak threshold of 187 dB_{peak} applies to this project.

RESULTS

Underwater Sound Levels

WSDOT monitored twenty, 24-inch and eight, 30-inch steel piles for underwater noise. Due to an upgrade to the Windows 7 operating system and incompatibility with the sound recording software just prior to the measurements being collected in the field the total waveform for three of the piles monitored was not recorded and so the full analysis is not able to be conducted on these piles. Real-time field notes of the peak values are documented in the field are provided for the piles not recorded. All other piles are analyzed in the paragraphs below and summarized in Table 3. In some instances the reported sound levels for the 3H locations were higher than the closer 10 meter locations. This is likely due to the additional un-attenuated sound source entering the water from the substrate beyond the 10 meter hydrophone location and increasing the attenuated sound levels measured at the 3H location. Additionally, the 10 meter distance at one hydrophone was not always possible due to safety issues and risk of tangling the hydrophone in the air hoses so some of distances vary.

Pier 30, Pile 1

Pile 1 is located near the bridge Pier 30, west of Pile 2 and south of Pile 4. The pile had an absolute attenuated peak value of 186 dB_{peak} at 10 meters and 185 dB_{peak} at 3H (15 meters). This is below the 187 dB_{peak} threshold. The attenuated $RMS_{90\%}$ at 10 meters is 179 dB_{RMS} and at 3H is181 dB_{RMS}. The cSEL calculated based on each measured pile strike at 10 meters is 194 dB_{SEL} and at 3H is 195 dB_{SEL}. The distance to the 187 dB_{peak} threshold using the practical spreading model from the 3H location is 36 feet.

Pier 30, Pile 2a

Pile 2 was driven on two separate days due to the top of the pile mushrooming during the first driving attempt. Therefore, the recording and analysis is divided up into Pile 2a and Pile 2b representing the two separate drives. Pile 2a is located near bridge Pier 30, east of Pile 1 and north of Pile 3. The substrate was particularly dense at Pier 30 and it made driving the piles challenging. The top of this pile mushroomed and the pile driving was stopped prematurely. However, for this drive of Pile 2 it had an absolute attenuated peak level of 188 dB_{peak} at 10 meters and 185 dB_{peak} at 3H (15 meters). This pile exceeded the 187 dB_{peak} threshold at 10 meters for only 13 of the 411 attenuated strikes. The attenuated $RMS_{90\%}$ at both 10 meters and 3H is 179 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 36 feet from the 3H location. The cSEL calculated based on each measured pile strike at 10 meters and 3H is 192 dB_{SEL}.

Pier 30, Pile 2b

Pile 2b is the final drive of Pile 2a. When the top of Pile 2a mushroomed the top of the pile was cut off and driven again the following day. This pile drive had an absolute attenuated peak level of 189 dB_{peak} at 10 meters and 185 dB_{peak} at 3H (15 meters). This pile exceeded the 187 dB_{peak} threshold for fish at 10 meters for only 4 of the 182 attenuated strikes. The attenuated $RMS_{90\%}$ at 10 meters is 176 dB_{RMS} and at 3H is 178 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 36 feet from the 3H location. The cSEL calculated based on each measured pile strike at 10 meters is 187 dB_{SEL} and at 3H is 189 dB_{SEL}.

Table 3: Summary of Underwater Broadband Sound Levels for the SR 520 West Connection Bridge Project

Pier #	Pile #	Date & Time	Pile Diameter (inches)	Hydrophone Range (m)	Hydrophone Depth (feet)	Bubble Curtain Status	Total Number Of Strikes	Highest Absolute Peak (dB)	$RMS_{90\%}$ (dB)	Single Strike $SEL_{90\%}$ (dB)	Avg. Peak ± s.d. (Pascal)	Avg. RMS ± s.d. (Pascal)	Avg. Noise Reduction (dB)	Cumulative SEL (dB)
30	1	12/5/13 9:00 AM	24	10	8.5	On	1580	186	179	167	1474±148	571±83	-	194
				15	14	On		185	181	167	1434±115	703±96	-	195
	2a[2]	12/5/13 12:46 PM	24	10	8.5	On	411	188	179	167	1733±228	723±78	-	192
				15	14	On		185	179	167	1581±116	788±51	-	192
	2b	12/6/13 9:37 AM	24	10	8.5	On	182	189	176	166	1681±218	611±41	-	187
				15	14	On		185	178	168	1661±66	796±40	-	189
	3	12/5/13 1:29 PM	24	10	8.5	On	730	187	180	168	1856±226	825±110	-	195
				25	14	On		181	177	164	953±109	633±93	-	191
	4	12/5/13 2:08 PM	24	10	8.5	On	1103	185	177	166	1290±212	618±115	-	194
				25	14	On		180	178	164	848±80	560±83	-	192
	5	12/6/13 10:42 AM	24	10	8.5	On	614	188	181	172	1719±263	848±151	-	194
				35	14	On		176	173	160	554±23	356±48	-	187
	6	12/6/13 1:42 PM	24	10	8.5	On	704	190	183	171	2525±268	1099±100	-	197
				35	14	On		175	172	160	516±36	302±35	-	187
28	7	12/10/13 1:53 PM	24	10	8.5	On	2173	187	173	163	1459±260	343±53	17	192
					14	Off	123	204	189	174	10517±1566	2399±314	-	-
				15	8.5	On	2173	181	172	161	687±102	280±28	23	192
					14	Off	123	202	185	173	9498±1910	1176±202	-	-
	8	12/6/13 8:36 AM	24	10	8.5	On	879	186	170	160	2181±2396	511±550	-	192
				16	14	On		178	170	160	497±46	198±41	-	185
	9	12/11/13 10:11 AM	24	10	8.5	On	707	185	175	163	1019±284	431±59	-	190
				25	14	On		180	172	162	582±91	297±33	-	187
	10	12/11/13 10:47 PM	24	13	8.5	On	1766	184	174	163	1023±187	339±54	-	190
				25	14	On		175	171	160	442±32	203±21	-	187
25	11	1/13/13 11:38 AM	24	10	8.5	On	527	185	174	165	1245±272	438±84	-	189
				16	14	On		177	172	160	615±69	303±41	-	185
		1/14/14 2:45 PM		10	8.5	On	374	185[4]	174[4]	165[4]	1435±129	557±53	-	188
				16	14	On		n.s.	n.s.	n.s.	n.s.	n.s.	-	n.s.
	12	1/13/14 1:12 PM	24	10	8.5	On	914	189	n.s.	n.s.	n.s.	n.s.	-	199[1]
				21	14	On		n.s.	n.s.	n.s.	n.s.	n.s.	-	n.s.
	13	1/13/14 1:42 PM	24	12	8.5	On	255	178	n.s.	n.s.	n.s.	n.s.	-	182[1]
				25	14	On		n.s.	n.s.	n.s.	n.s.	n.s.	-	n.s.
	14	1/14/14 12:57 PM	24	10	8.5	On	1241	189	n.s.	n.s.	n.s.	n.s.	-	200[1]
				16	14	On		n.s.	n.s.	n.s.	n.s.	n.s.	-	n.s.
	15*	1/16/14	30	11	8.5	On	1280	190	175	162	1533±374	262±55	-	187

Pier #	Pile #	Date & Time	Pile Diameter (inches)	Hydrophone Range (m)	Hydro phone Depth (feet)	Bubble Curtain Status	Total Number Of Strikes	Highest Absolute Peak (dB)	$RMS_{90\%}$ (dB)	Single Strike $SEL_{90\%}$ (dB)	Avg. Peak ± s.d. (Pascal)	Avg. RMS ± s.d. (Pascal)	Avg. Noise Reducti on (dB)	Cumulative SEL (dB)
		2:42 PM		16	14	On		192	176	165	1529±244	455±100	-	191
30	16*	1/25/14 1:54 PM	30	14	8.5	On	1038	195	178	166	3228±595	645±66	-	194
				19	14	On		193	177	166	2891±380	739±57	-	196
	17*	1/27/14 11:25 AM	30	17	8.5	On	1088	193	177	166	3005±725	608±159	-	194
	18*	1/28/14 10:53 AM	30	10	8.5	On	727	202	185	173	6099±1633	1097±166	-	197
				17	14	On		196	177	167	3495±852	542±66	-	193
	19*	1/29/14 11:06 AM	30	17	8.5	On	951	200	184	170	4086±1086	837±215	-	195
				23	14	On		196	177	167	3075±630	512±98	-	186
	20	1/29/14 1:07 PM	30	10	8.5	On	1156	185	171	160	1080±191	355±27	-	190
				20	14	On		185	171	160	557±106	245±27	-	188
	21	1/29/14 1:52 PM	24	11	8.5	On	1083	183	170	158	701±143	226±32	-	186
				21	14	On		178	167	158	531±91	166±26	-	186
29	22	2/27/14 9:00 AM	24	11	8.5	On	113	179	173	160	763±63	420±61	-	180
				21	14	On		177	173	160	550±69	318±53	-	178
	23	2/27/14 9:14 AM	24	11	8.5	On	666	178	168	158	531±60	242±59	-	184
				21	14	On		178	174	162	620±81	329±50	-	188
	24	2/27/14 10:15AM	24	10	8.5	On	835	184	177	164	994±186	441±120	-	190
				21	14	On		175	169	157	442±56	214±27	-	185
	25	2/27/14 10:46 AM	24	10	8.5	On	795	188	171	160	1127±221	497±116	-	191
				21	14	On		177	168	158	511±121	267±70	-	186
	26	2/27/14 11:20 AM	24	10	8.5	On	154	185	179	167	1415±144	715±100	-	187
				21	14	On		179	166	157	330±192	132±58	-	174
	27	2/27/14 1:37 PM	24	15	8.5	On	1064	186	172	161	1075±204	361±34	-	190
				26	14	On		179	164	155	336±196	112±48	-	181
	28	3/2/14 10:27 AM	24	10	8.5	On	597	190	173	163	1586±349	333±36	-	188
				25	14	On		182	169	159	617±124	203±42	-	184

1 – These data are approximated by subtracting 20 dB from the peak to obtain the single strike SEL and then using this value to calculate the cumulative SEL based on the total number of strikes.
2 – Top of pile mushroomed so the pile driving was stopped prematurely.
3 – Pile broken subsurface. n.s. – Data not saved due to software malfunction.
4 - The highest peak values occurred on the previous day for this same pile
* - Battered Pile
A – Bubble Curtain off

Pier 30, Pile 3

Pile 3 is located near bridge Pier 30 between Piles 2 and 6 and east of Pile 4. This pile had an absolute attenuated peak value of 187 dB_{peak} at 10 meters and 181 dB_{peak} at 3H (25 meters). This pile did not exceed the 187 dB_{peak} threshold. The attenuated $RMS_{90\%}$ at 10 meters is 180 dB_{RMS} and at 3H is177 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 33 feet from the 3H location. The cSEL calculated based on each measured pile strike at 10 meters is 195 dB_{SEL} and at 3H is 191 dB_{SEL}.

Pier 30, Pile 4

Pile 4 is located near bridge Pier 30 between piles 1 and 5 and west of Pile 3. This pile had an absolute attenuated peak value of 185 dB_{peak} at 10 meters and 180 dB_{peak} at 3H (25 meters). This is below the 187 dB_{peak} threshold. The attenuated $RMS_{90\%}$ at 10 meters is 177 dB_{RMS} and at 3H is178 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 28 feet from the 3H location. The cSEL calculated based on each measured pile strike at 10 meters is 194 dB_{SEL} and at 3H is 192 dB_{SEL}.

Pier 30, Pile 5

Pile 5 is located immediately next to the bridge on the north side of Pier 30 and south of Pile 4. This pile had an absolute attenuated peak value of 188 dB_{peak} at 10 meters and 176 dB_{peak} at 3H (35 meters). This pile exceeded the 187 dB_{peak} threshold for fish at the 10 meters for only 4 of the 614 attenuated strikes. The attenuated $RMS_{90\%}$ at 10 meters is 181 dB_{RMS} and at 3H is173 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 21 feet from the 3H location. The cSEL calculated based on each measured pile strike at 10 meters is 194 dB_{SEL} and at 3H is 187 dB_{SEL}.

Pier 30, Pile 6

Pile 6 is located immediately next to the bridge on the north side of Pier 30 and south of Pile 3. This pile had an absolute attenuated peak value of 190 dB_{peak} at 10 meters and 175 dB_{peak} at 3H (35 meters). This pile exceeded the 187 dB_{peak} threshold for fish at the 10 meters for only 4 of the 614 attenuated strikes. The attenuated $RMS_{90\%}$ at 10 meters is 183 dB_{RMS} and at 3H is 172 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 18 feet from the 3H location. The cSEL calculated based on each measured pile strike at 10 meters is 197 dB_{SEL} and at 3H is 187 dB_{SEL}.

Pier 28, Pile 7

Pile 7 is located near bridge Pier 28, north of Pile 9 and east of Pile 8. This pile was the only pile that was tested with the bubble curtain off at the beginning and end of the drive. For the bubbles on condition it had an absolute attenuated peak value of 187 dB_{peak} at 10 meters and 181 dB_{peak} at 3H (15 meters). This pile did not exceed the 187 dB_{peak} threshold. The attenuated $RMS_{90\%}$ at 10 meters is 173 dB_{RMS} and at 3H is172 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 20 feet from the 3H location. The cSEL calculated based on each measured pile strike at both 10 meters and 3H is 192 dB_{SEL}.

For the bubbles off condition it had an absolute un-attenuated peak value of 204 dB_{peak} at 10 meters and 202 dB_{peak} at 3H (15 meters). This exceeded the 187 dB_{peak} threshold. The un-attenuated $RMS_{90\%}$ at 10 meters is 189 dB_{RMS} and at 3H is185 dB_{RMS}. The average peak values were calculated for the entire bubbles on and bubbles off condition and found that the average attenuation of the bubble curtain was 17 dB at 10 meters and 23 dB at 3H. The additional attenuation at 3H is likely due to the relatively soft overlying substrate providing additional attenuation over distance.

Figure 4 shows the frequency distribution (spectrum) for Pile 7 both attenuated and un-attenuated measurements at 10 meters. This figure shows that the bubble curtain was providing a substantial amount of noise reduction at a broad spectrum of frequencies with the possible exception of the lowest frequencies measured.

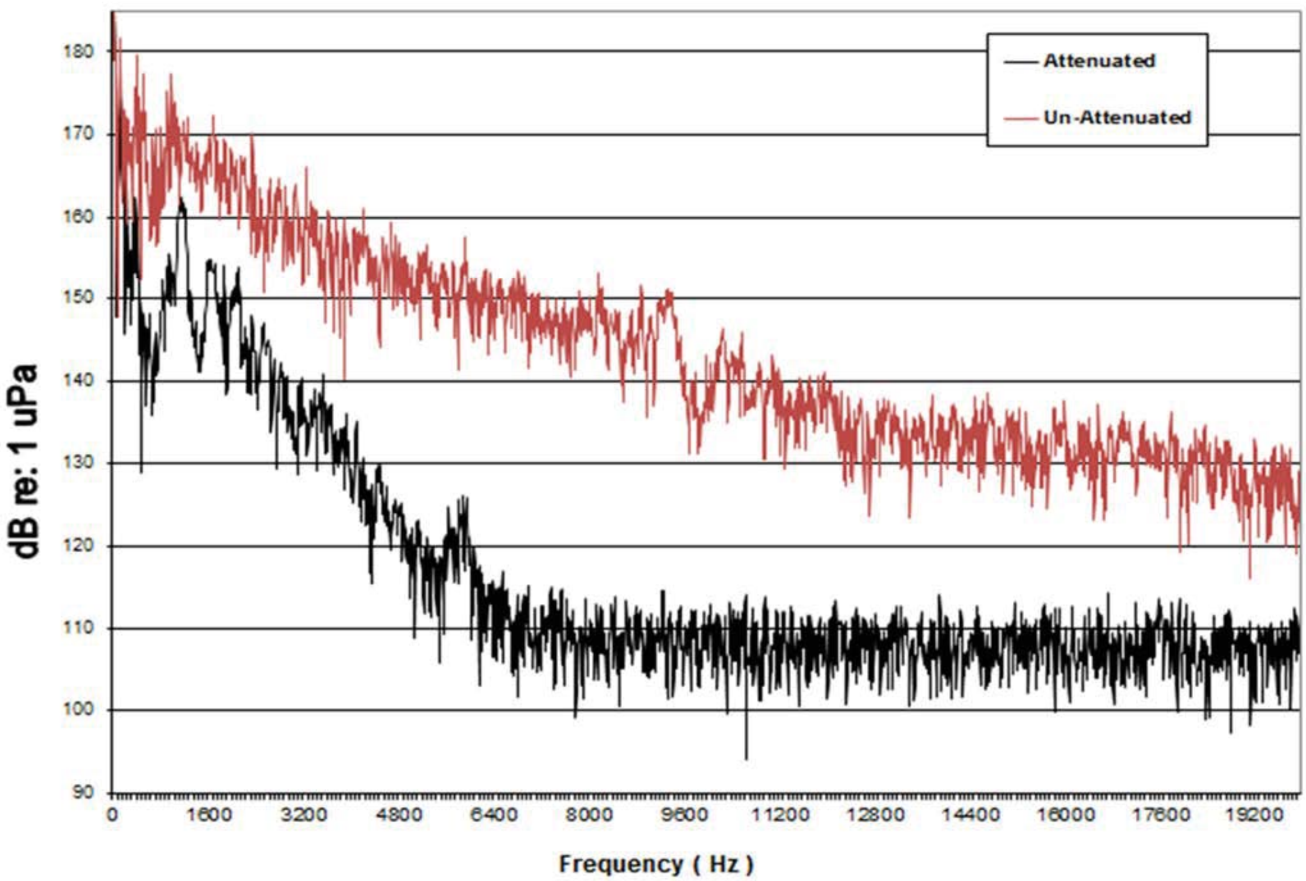


Figure 4: Comparison of frequency spectra for attenuated & un-attenuated, Pile 7 at 10 meters.

Figure 5 below shows the frequency distribution (spectrum) for Pile 7 both attenuated and un-attenuated measurements at 3H (15 meters). This figure also shows that the bubble curtain was providing a substantial amount of noise reduction for a broad spectrum of frequencies except for the lowest frequencies measured.

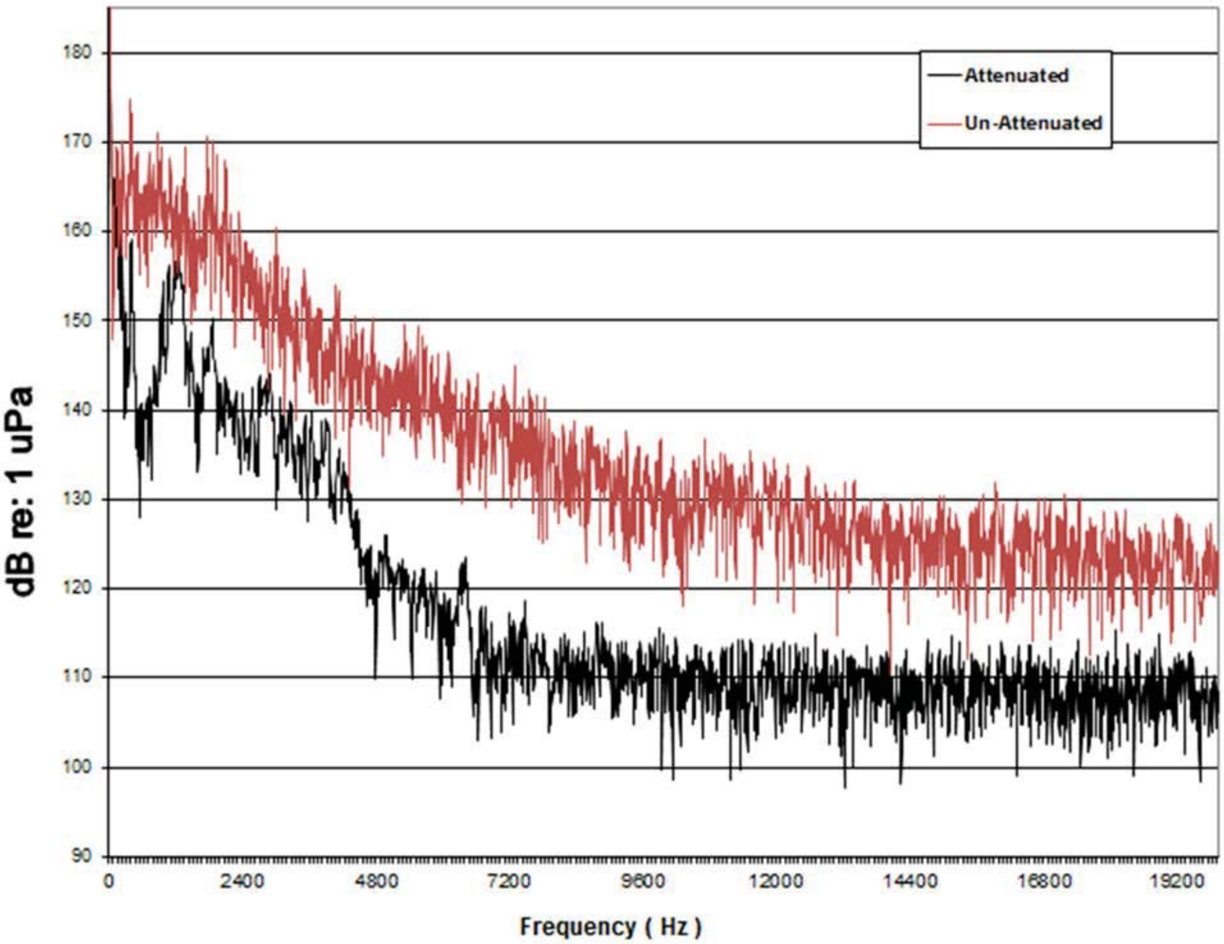


Figure 5: Comparison of frequency spectra for attenuated & un-attenuated, Pile 7 at 3H.

Pier 28, Pile 8

Pile 8 is located near bridge Pier 28, west of Pile 7 and north of Pile 10. This pile had an absolute attenuated peak value of 186 dB_{peak} at 10 meters and 178 dB_{peak} at 3H (16 meters). This is below the 187 dB_{peak} threshold. The attenuated $RMS_{90\%}$ at 10 meters and the 3H location is 170 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 13 feet from the 3H location. The cSEL calculated based on each measured pile strike at 10 meters is 192 dB_{SEL} and at 3H is 185 dB_{SEL}.

Pier 28, Pile 9

Pile 9 is located immediately next to the bridge on the north side of Pier 28 and south of Pile 7. This pile had an absolute attenuated peak value of 185 dB_{peak} at 10 meters and 180 dB_{peak} at 3H (25 meters). This is below the 187 dB_{peak} threshold. The attenuated $RMS_{90\%}$ at 10 meters is 175 dB_{RMS} and at 3H is172 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 28 feet from the 3H location. The cSEL calculated based on each measured pile strike at 10 meters is 190 dB_{SEL} and at 3H is 187 dB_{SEL}.

Pier 28, Pile 10

Pile 10 is located immediately next to the bridge on the north side of Pier 28 and south of Pile 8. This pile had an absolute attenuated peak value of 184 dB_{peak} at 13 meters and 175 dB_{peak} at 3H (25 meters). This is below the 187 dB_{peak} threshold. The attenuated $RMS_{90\%}$ at 13 meters is 174 dB_{RMS} and at 3H is171 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 13 feet from the 3H location. The cSEL calculated based on each measured pile strike at 13 meters is 190 dB_{SEL} and at 3H is 187 dB_{SEL}.

Pier 25, Pile 11

Pile 11 was located near the bridge Pier 25 and, north of Pile 13 and west of Pile 14. The initial drive on 1/13/14 mushroomed the top of the pile and the top was cut off and driving resumed the following day until it mushroomed again. The highest absolute attenuated peak value at 10 meters for this pile was 185 dB_{peak} on the first day which is below the 187 dB_{peak} threshold. The distance to the 187 dB_{peak} threshold from 10 meters using the practical spreading model is 11 feet. The cSEL calculated based on each measured pile strike at 10 meters is 189 dB_{SEL} and 185 dB_{SEL} at the 3H location.

Pier 25, Pile 12

Pile 12 is located immediately next to the bridge at Pier 25 and south of Pile 14. The waveform recording for this pile was not able to be saved due to incompatibility with Windows 7. Field notes indicate that the highest absolute attenuated peak value at 10 meters was 189 dB_{peak}. This exceeded the 187 dB_{peak} threshold. The distance to the 187 dB_{peak} threshold from 10 meters using the practical spreading model is 45 feet. The cSEL calculated by subtracting 20 dB from the absolute peak level and adding this number to the product of the Log of the total number of strikes multiplied by 10 was 199 dB_{SEL} at 10 meters.

Pier 25, Pile 13

Pile 13 is located immediately next to the bridge Pier 25 and south of pile 14. The waveform recording for this pile was not able to be saved due to incompatibility with Windows 7. Field notes indicate that the highest absolute attenuated peak value at 12 meters was 178 dB_{peak}. This is well below the 187 dB_{peak} threshold. The distance to the 187 dB_{peak} threshold from 12 meters using the practical spreading model is 10 feet. The cSEL calculated by subtracting 20 dB from the absolute peak level and adding this number to the product of the Log of the total number of strikes multiplied by 10 was 182 dB_{SEL} at 10 meters.

Pier 25, Pile 14

Pile 14 is located near Pier 25 and north of Pile 12. The waveform recording for this pile was not able to be saved due to incompatibility with Windows 7. Field notes indicate that the highest absolute attenuated peak value at 10 meters was 189 dB_{peak}. This exceeded the 187 dB_{peak} threshold. The distance to the 187 dB_{peak} threshold from 10 meters using the practical spreading model is 14 feet. The cSEL calculated by subtracting 20 dB from the absolute peak level and adding this number to the product of the Log of the total number of strikes multiplied by 10 was 200 dB_{SEL} at 10 meters.

Pier 25, Pile 15

Pile 15 is a battered pile (driven at an angle) located near Pier 25. The highest absolute attenuated peak value at 11 meters was 190 dB_{peak} and 192 dB_{peak} at 3H (16 meters). This exceeded the 187 dB_{peak} threshold for this project for 58 strikes at 11 meters and 14 strikes at 3H of the 1,280 pile strikes. The attenuated $RMS_{90\%}$ at 10 meters is 175 dB_{RMS} and at 3H is176 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 34 feet from 3H. The cSEL calculated based on each measured pile strike at 11 meters is 187 dB_{SEL} and at 3H is 191 dB_{SEL}.

Pier 30, Pile 16

Pile 16 is a battered pile located near Pier 30. This pile had an absolute attenuated peak value of 195 dB_{peak} at 14 meters and 193 dB_{peak} at 3H (19 meters). This exceeded the 187 dB_{peak} threshold for this project for 1,002 strikes at 14 meters and 992 strikes at 3H of the 1,029 pile strikes. The attenuated $RMS_{90\%}$ at 14 meters is 178 dB_{RMS} and at 3H is 177 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 157 feet from the 3H location. The cSEL calculated based on each measured pile strike at 19 meters is 194 dB_{SEL} and at 3H is 196 dB_{SEL}.

The reason why the battered piles had more exceedences even though they were using a confined bubble curtain was probably due to the physical connection the battered piles had to other plumb piles to maintain the angle of the battered pile. The battered piles were in contact with other plumb piles that were driven previously but were not attenuated for this drive. This physical connection allowed some of the sound energy to travel from the battered pile to the plumb piles and into the water un-attenuated.

Pier 30, Pile 17

Pile 17 is a battered pile located immediately adjacent to the bridge Pier 30 and to Pile 5. This pile had an absolute attenuated peak value of 193 dB_{peak} at 17 meters (3H not collected). This exceeded the 187 dB_{peak} threshold for this project for 950 strikes at 17 meters of the 1,087 pile strikes. The attenuated $RMS_{90\%}$ at 17 meters is 177 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 140 feet from 17 meters. The cSEL calculated based on each measured pile strike at 17 meters is 194 dB_{SEL}.

Pier 30, Pile 18

Pile 18 is a battered pile located near bridge Pier 30 and immediately adjacent to Pile 2. This pile had an absolute attenuated peak value of 202 dB_{peak} at 10 meters and 196 dB_{peak} at 3H (17 meters). This exceeded the 187 dB_{peak} threshold for this project for most of the 727 pile strikes. The attenuated $RMS_{90\%}$ at 10 meters is 185 dB_{RMS} and at 3H is177 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 222 feet from the 3H location. The cSEL calculated based on each measured pile strike at 10 meters is 197 dB_{SEL} and at 3H is 193 dB_{SEL}.

Pier 30, Pile 19

Pile 19 is located near bridge Pier 30 and immediately next to Pile 1. This pile had an absolute attenuated peak value of 200 dB_{peak} at 17 meters and 196 dB_{peak} at 3H (23 meters). This exceeded the 187 dB_{peak} threshold for this project for all of the 951 pile strikes. The attenuated

$RMS_{90\%}$ at 17 meters is 184 dB_{RMS} and at 3H is 177 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 300 feet from the 3H location. The cSEL calculated based on each measured pile strike at 17 meters is 195 dB_{SEL} and at 3H is 186 dB_{SEL}.

Pier 30, Pile 20

Pile 20 had an absolute attenuated peak value of 185 dB_{peak} for both the 11 meter and 3H (20 meters). This pile did not exceed the 187 dB_{peak} threshold. The attenuated $RMS_{90\%}$ is 171 dB_{RMS} at both locations, at 10 meters and at 3H. The distance to the 187 dB_{peak} threshold using the practical spreading model is 48 feet from the 3H location. The cSEL calculated based on each measured pile strike at 10 meters is 190 dB_{SEL} and at 3H is 188 dB_{SEL}.

Pier 30, Pile 21

Pile 21 had an absolute attenuated peak value of 183 dB_{peak} at 11 meters and 178 dB_{peak} at 3H (21 meters). This pile did not exceed the 187 dB_{peak} threshold. The attenuated $RMS_{90\%}$ at 11 meters is 170 dB_{RMS} and at 3H is 167 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 17 feet from the 3H location. The cSEL calculated based on each measured pile strike at 11 meters and at 3H is 186 dB_{SEL}.

Pier 29, Pile 22

Pile 22 had an absolute attenuated peak value of 179 dB_{peak} at 11 meters and 177 dB_{peak} at 3H (21 meters). This pile did not exceed 187 dB_{peak} threshold. The attenuated $RMS_{90\%}$ at both 11 meters and at 3H is 173 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 15 feet from the 3H location. The cSEL calculated based on each measured pile strike at 11 meters is 180 dB_{SEL} and at 3H is 178 dB_{SEL}.

Pier 29, Pile 23

Pile 23 had an absolute attenuated peak value of 178 dB_{peak} for both the 11 meter and 3H (21 meters) location. This pile did not exceed the 187 dB_{peak} threshold. The attenuated $RMS_{90\%}$ at both 11 meters and 3H is 168 dB_{RMS} . The distance to the 187 dB_{peak} threshold using the practical spreading model is 17 feet from the 3H location. The cSEL calculated based on each measured pile strike at 11 meters is 184 dB_{SEL} and at 3H is 188 dB_{SEL}.

Pier 29, Pile 24

Pile 24 had an absolute attenuated peak value of 184 dB_{peak} at 10 meters and 175 dB_{peak} at 3H (21 meters). This pile did not exceed the 187 dB_{peak} threshold. The attenuated $RMS_{90\%}$ at 10 meters is 177 dB_{RMS} and at 3H is 169 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 11 feet from the 3H location. The cSEL calculated based on each measured pile strike at 10 meters is 190 dB_{SEL} and at 3H is 185 dB_{SEL}.

Pier 29, Pile 25

The highest absolute attenuated peak value at 10 meters for Pile 25 was 188 dB_{peak} and 177 dB_{peak} at 3H (21 meters). This exceeded the 187 dB_{peak} threshold for this project and 2 strikes at 10 meters and 14 strikes at 3H of the 795 pile strikes exceeded the 187 dB_{peak} threshold. The attenuated $RMS_{90\%}$ at 10 meters is 171 dB_{RMS} and at 3H is 168 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 15 feet from the 3H location. The cSEL calculated using the single strike SEL for each pile strike was 191 dB_{SEL} which is above the 186 dB_{SEL}.

Pier 29, Pile 26

Pile 26 had an absolute attenuated peak value of 185 dB_{peak} at 10 meters and 179 dB_{peak} at 3H (21 meters). This is below the 187 dB_{peak} threshold. The attenuated $RMS_{90\%}$ at 10 meters is 179 dB_{RMS} and at 3H is 166 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 20 feet from the 3H location. The cSEL calculated based on each measured pile strike at 10 meters is 187 dB_{SEL} and at 3H is 174 dB_{SEL}.

Pier 29, Pile 27

Pile 27 had an absolute attenuated peak value of 186 dB_{peak} at 15 meters and 179 dB_{peak} at 3H (26 meters). This is below the 187 dB_{peak} threshold. The attenuated $RMS_{90\%}$ at 15 meters is 172 dB_{RMS} and at 3H is 164 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 25 feet from the 3H location. The cSEL calculated based on each measured pile strike at 15 meters is 190 dB_{SEL} and at 3H is 181 dB_{SEL}.

Pier 29, Pile 28

Pile 29 is a battered pile and had an absolute attenuated peak value of 190 dB_{peak} at 10 meters and 182 dB_{peak} at 3H (25 meters). This exceeded the 187 dB_{peak} threshold for this project for 15 of the 597 pile strikes at 10 meters. The attenuated $RMS_{90\%}$ at 10 meters is 173 dB_{RMS} and at 3H is 169 dB_{RMS}. The distance to the 187 dB_{peak} threshold using the practical spreading model is 38 feet from the 3H location. The cSEL calculated based on each measured pile strike at 10 meters is 188 dB_{SEL} and at 3H is 184 dB_{SEL}.

Scholte or Seismic Waves

Scholte or seismic waves are created at the boundary of the sediment water interface. It is a slow moving low frequency but generally high amplitude wave that is generated through the flexure of the substrate at the interface. In most cases the actual peak value occurred well after the initial strike (see example in Figure 6 and other examples in Appendix A) which represents the Scholte wave. The peak value of the actual pile strike was often 2 dB to 28 dB lower than the amplitude of the Scholte wave. The seismic waves were more subtle for the unattenuated pile strikes on Pile 7. We typically see Scholte waves where pile driving occurs in relatively soft substrates but rarely does the amplitude exceed the peak pile strike amplitude as we saw for this project. It would be similar to driving a pile through a layer of Jello. The peak values of these types of waveforms are unlikely to cause injury to fish due to their relatively low frequency.

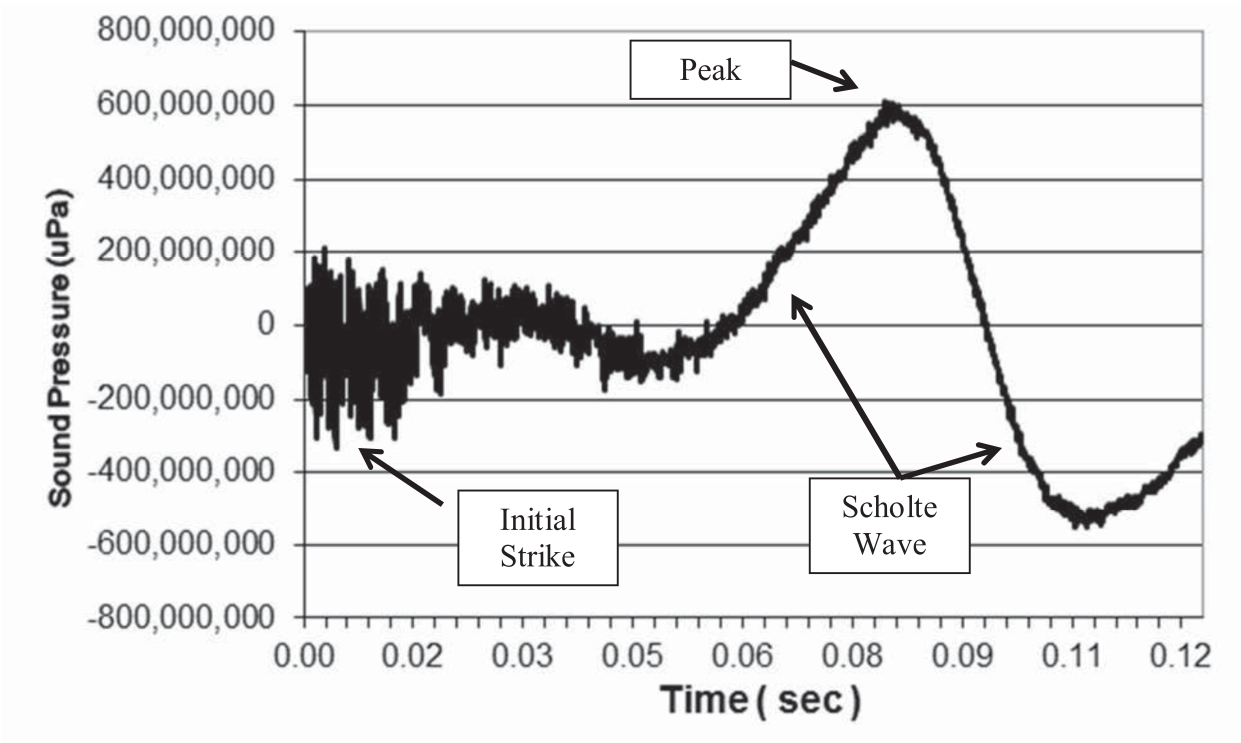


Figure 6: Example of a Scholte or seismic wave which was observed during post analysis of the SR 520 WCB pile monitoring data.

Daily Cumulative SEL

Where waveform recordings were not available daily cumulative SEL's (cSEL's) were calculated based on an estimate calculated by subtracting 20 dB from the absolute peak level and adding this number to the product of the Log of the total number of strikes multiplied by 10 where no waveform recording was available. Where a waveform recording was available the daily cSEL's were calculated using an actual $SEL_{90\%}$ for each individual pile strike for each day and accumulated over that period (Table 4).

Table 4: Summary of daily cumulative SEL's

Day	10M	3H
12/5	200	199
12/6	200	193
12/10	192	192
12/11	190	190
1/13	200*	200*
1/14	197*	-
1/16	187	191
1/25	194	196
1/27	194	-
1/28	197	193
1/29	197	195

Day	10M	3H
2/27	196	192
3/2	188	184

* - Based upon total number of strikes. Unable to calculate SEL for each individual strike due to equipment malfunction.

The daily cumulative SEL values ranged from 188 to 200 dB at the 10 meter location and from 184 to 200 dB at the 3H location.

Airborne Sound Levels

WSDOT monitored the background sound levels near the Edgewater Apartments south of the project area, six 24-inch impact pile drives were measured at distances between 15 meters and 27 meters on the crane barge. Two piles were each monitored during impact and vibratory driving near the Edgewater Apartments at approximately 300 feet from the piles. Impact driving measurements were collected in 1-second intervals to capture the sound level for each pile strike. Those measurements that did not represent a pile strike were filtered out of the dataset and the pile strike data was averaged to determine the average L_{Aeq} and L_{max} sound levels. All measurements were A-weighted. No effective noise abatement techniques are currently available for airborne noise from impact pile driving.

Background Airborne Sound Levels

Background sound levels were monitored for 15-minute periods at two locations near the Edgewater Apartments just south of the project area (Figure 7). The background sound levels were collected February 4, 2014 and are dominated by traffic noise from SR 520. The distance to the West Connection Bridge (WCB) project from Site 1 is 118 meters (387 feet) and 130 meters (427 feet) to Site 2. The L_{Aeq} is 69 dBA for Site 1 and 67 dBA for Site 2. The L_{max} levels, which are the highest measured levels during the 15-minute measurement, are 77 dBA for Site 1 and 73 dBA for Site 2.

Impact Driving Sound Levels

The measurements were collected from the crane barge between 14 meters (46 feet) and 27 meters (89 feet) from the piles. The L_{Aeq} values for the entire pile drive ranged between 96 dBA and 102 dBA and the L_{max} ranged between 104 dBA and 115 dBA (Table 5). The different distances were due to the changes in distance of each pile monitored from the barge location which remained constant.

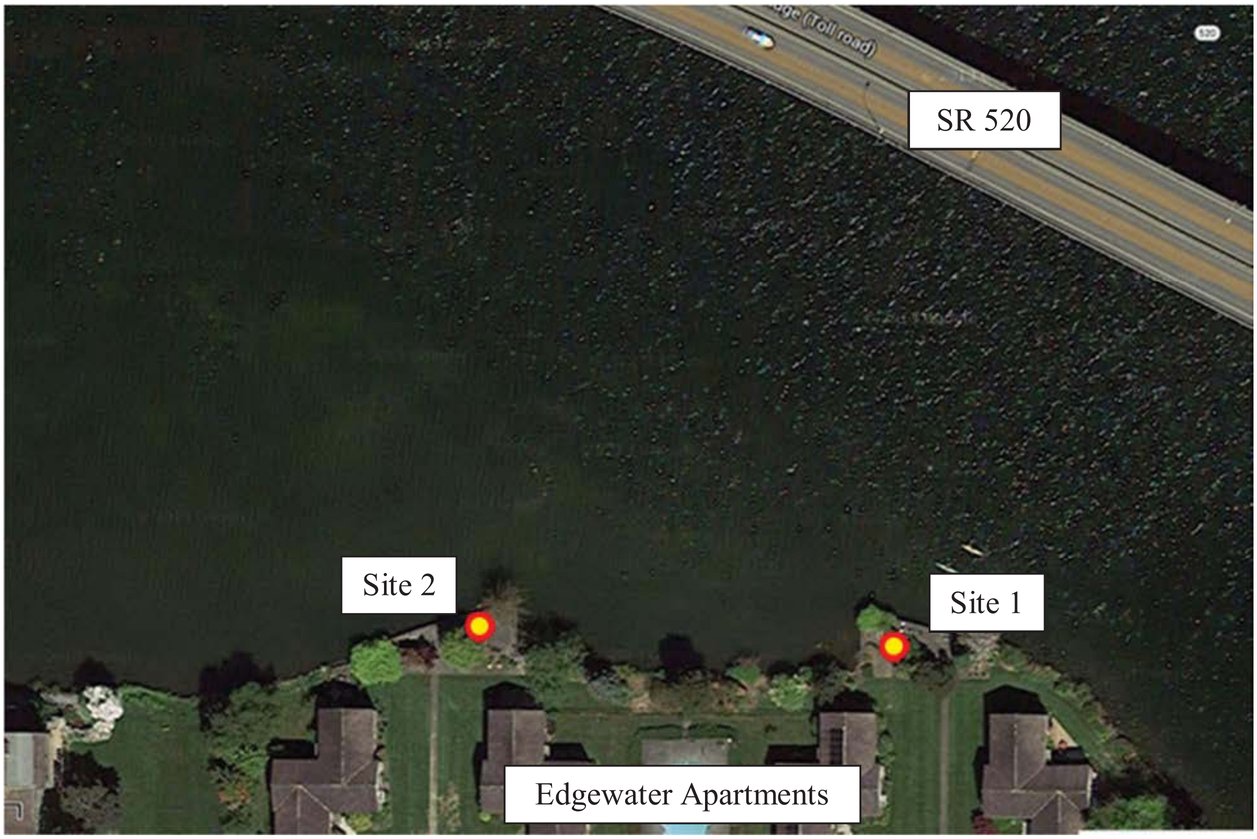


Figure 7: Locations of the airborne background sound level measurements.

Table 5: Summary of 24-inch pile airborne sound levels collected February 27, 2014.

Pile #	Distance from Pile (m)	L_{Aeq} (dBA)	L_{max} (dBA)
22	15	101	115
23	14	101	110
		102	113
24	20	98	107
		99	108
25	20	97	106
		97	106
26	20	98	109
		98	107
27	27	96	104
		96	105

The time history plot of each individual pile strike measured for Pile 22 is shown in Figure 8. These results are typical of each pile measured. The L_{Aeq} sound levels for each pile strike for Pile 22 range between approximately 101 dBA and 106 dBA with one pile strike initially at 108 dBA.

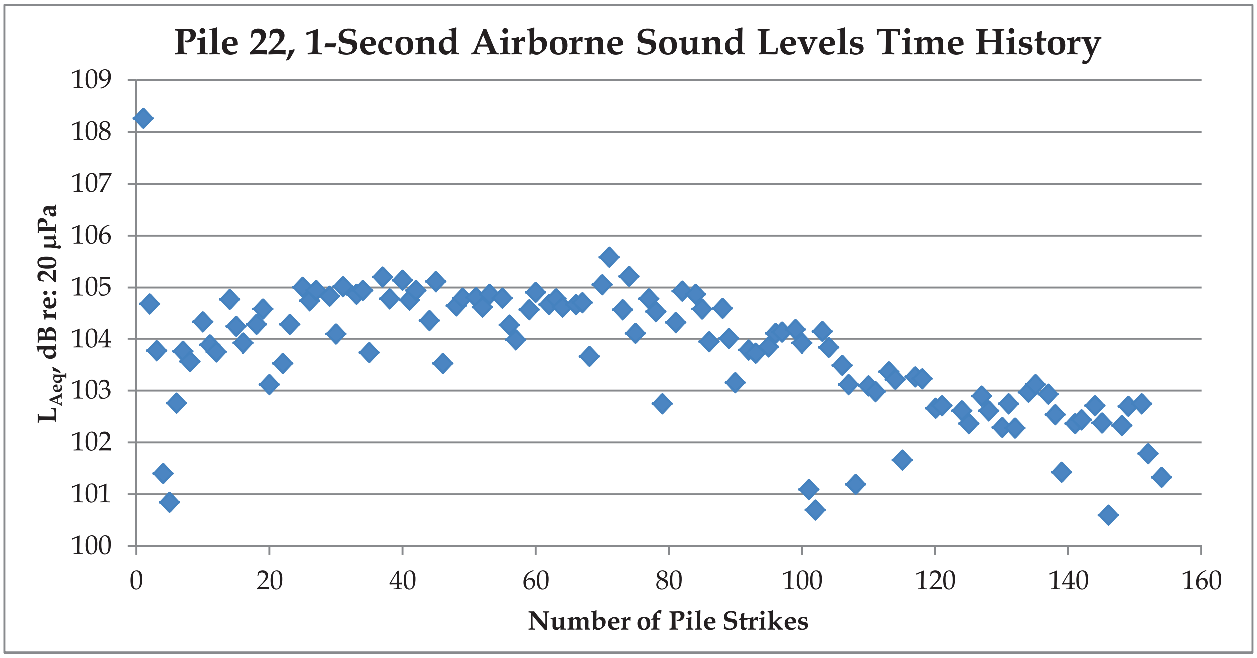


Figure 8: Time history of L_{Aeq} airborne sound levels for each pile strike for Pile 22.

The 1/3rd octave band frequencies were averaged for each pile strike of Pile 22 and plotted in Figure 9. The plot shows a relatively normal distribution of sound levels between 63 Hz and 20 kHz with the dominant frequency at approximately 1 kHz which is typical of impact pile driving sound levels. These results are typical of the other piles measured.

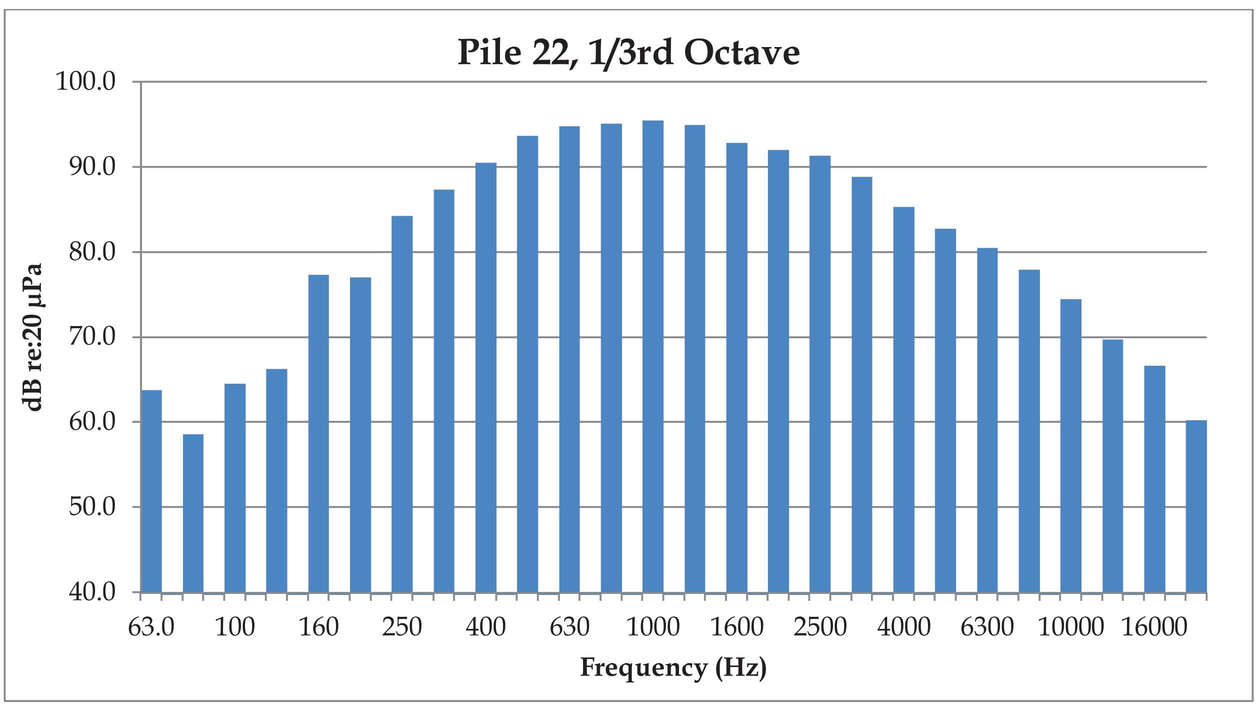


Figure 9: Average 1/3rd octave band frequencies (L_{Aeq}) for impact driving of Pile 22.

Airborne noise measurements of impact pile driving activities were also collected on February 12th near the Edgewater Apartments south of the project (Figure 10). Table 6 summarizes the results of the airborne noise measurements. The L_{Aeq} ranged from 76 dBA to 77 dBA and the L_{max} ranged between 85 dBA and 88 dBA. The statistical data in the remaining columns of Table 6 correspond to the daytime noise thresholds established in the Seattle Municipal Code for impact sound levels during construction (SMC 25.08.425(C)(1-4)). The SMC states:

> *Sounds created by impact types of equipment, including but not limited to pavement breakers, piledrivers, jackhammers, sandblasting tools, or by other types of equipment that create impulse sound or impact sound or are used as impact equipment, as measured at the property line or 50 feet from the equipment, whichever is greater, may exceed the exterior sound level limits established in subsection 25.08.425.B in any one hour period between the hours of 8 a.m. and 5 p.m. on weekdays and 9 a.m. and 5 p.m. on weekends and legal holidays, but in no event may the sound level exceed the following:*
> 1. *Leq 90 dB(A) continuously;*
> 2. *Leq 93 dB(A) for 30 minutes* (L_{50})*;*
> 3. *Leq 96 dB(A) for 15 minutes* (L_{25})*; or*
> 4. *Leq 99 dB(A) for 7 1/2 minutes* ($L_{12.5}$)*;*
>
> *provided that sound levels in excess of Leq 99 dB(A) are prohibited unless authorized by variance obtained from the Administrator; and provided further that sources producing sound levels less than 90 dB(A) shall comply with subsection 25.08.425.A and B of this section during those hours not covered by this subsection 25.08.425.C.*

The $L_{12.5}$ and L_{25} are substantially below the SMC thresholds at Site 2 and so there were no exceedences of the SMC code levels during the impact pile driving. WSDOT was not able to collect the L_{50} data due to an instrument programming error, however, it is assumed that since these impact pile driving levels were measured during impact driving only and were substantially below the other thresholds the levels would also be below the L_{50} threshold, which is only 3 decibels less, and would include less pile driving activity in the 30 minute period.

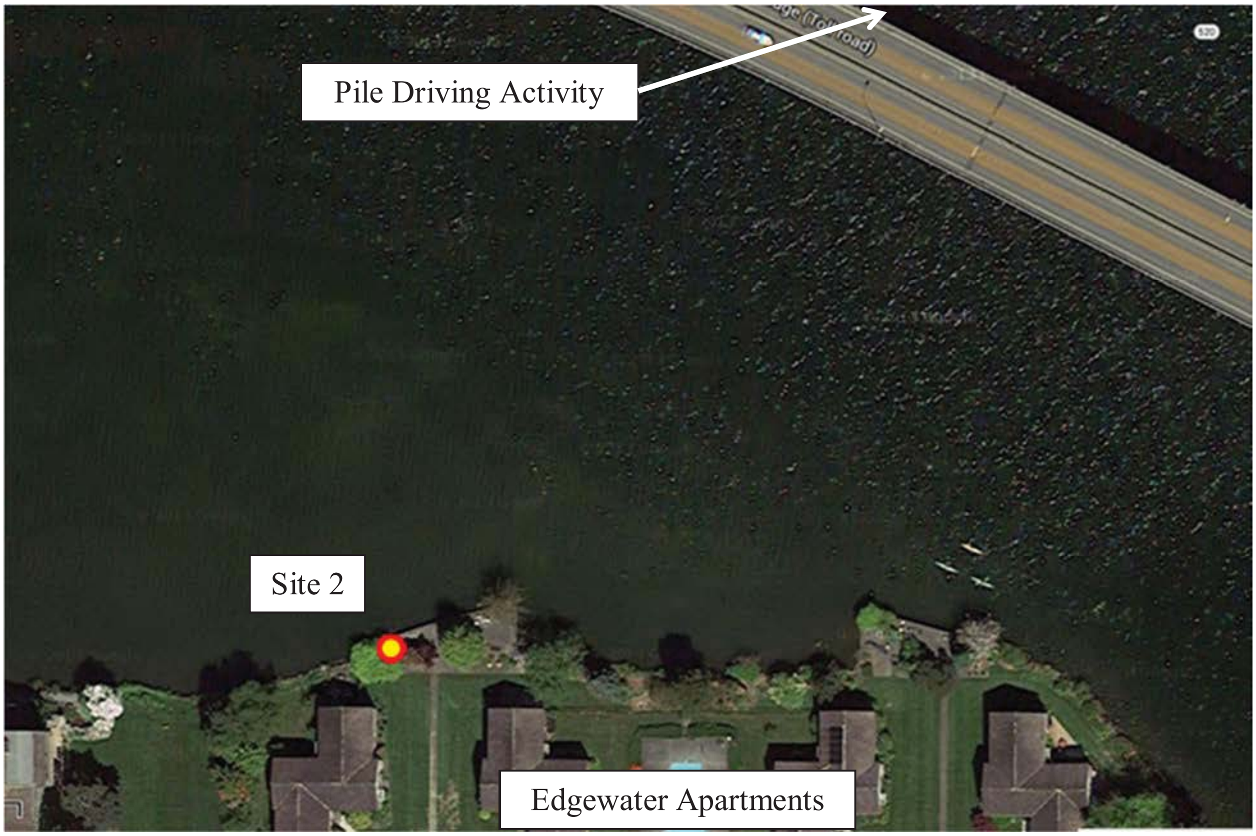


Figure 10: Locations of the airborne impact driving sound level measurements.

Table 6: Summary of 24-inch pile airborne sound levels collected February 27, 2014.

Distance (meters)	Leq (dBA)	Lmax (dBA)	$L_{12.5}$ (dBA)	L_{25} (dBA)
91	76	85	80	78
	77	87	82	79
	77	88	82	79

Vibratory Driving Sound Levels

The vibratory driving measurements were collected from the same Site 2 location in Figure 4 on February 11, 2014 at 91 meters (300 feet) from the piles. The L_{Aeq} values for the entire pile drive ranged between 64 dBA and 67 dBA and the L_{max} ranged between 70 dBA and 84 dBA.

The time history plot of each 30-second vibratory pile driving measurement is shown in Figure 11. These results are typical of each pile measured during vibratory pile driving. The L_{Aeq} sound levels range between approximately 64 dBA and 70 dBA. Background sound levels were measured to be 67 dBA at this site and so approximately half of the sound levels measured during vibratory driving are below background levels and are being masked by SR 520 traffic. The other measurements showed similar trends or were completely masked by SR 520 traffic.

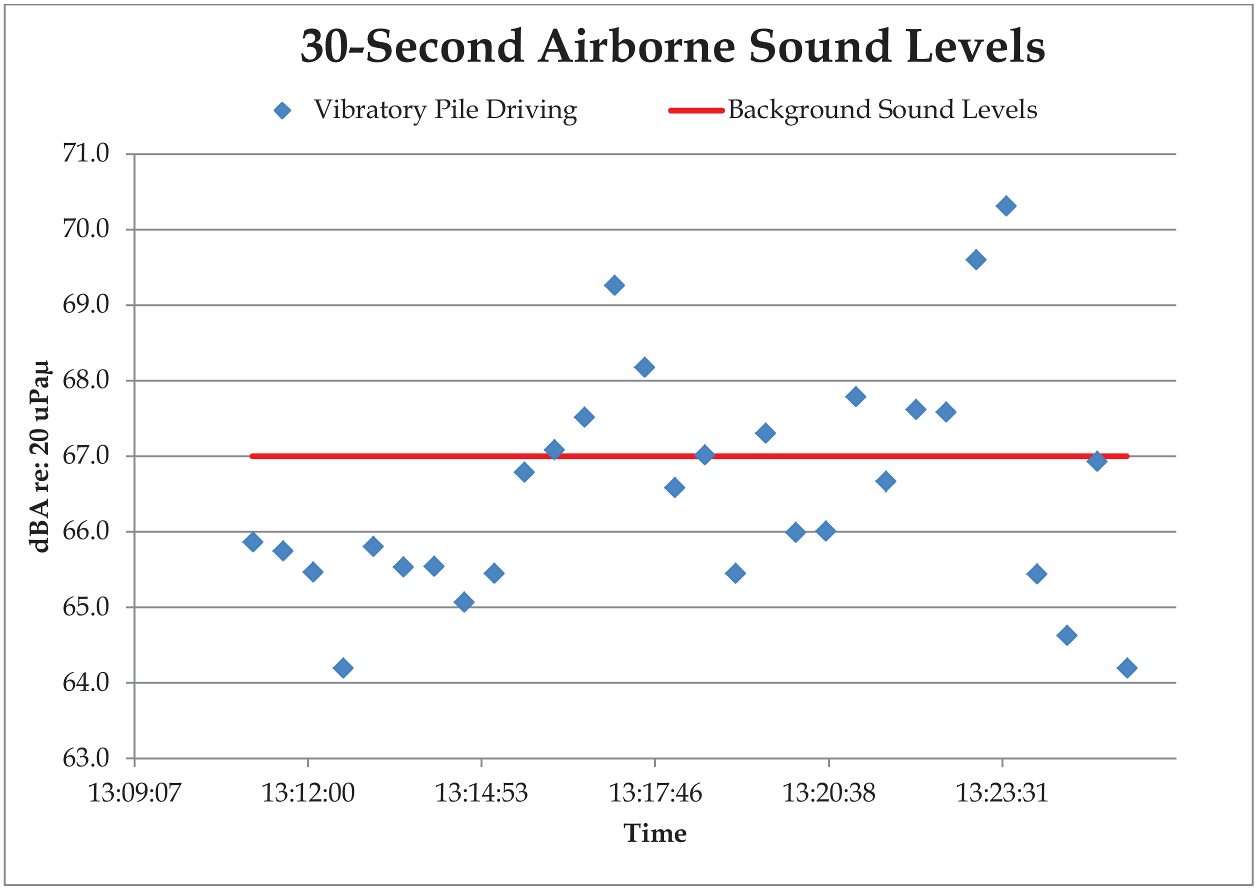


Figure 11: Time history of vibratory pile driving measurements at 91 meters relative to background sound levels.

The 1/3rd octave band frequencies for vibratory driving were averaged for each 30-second measurement and plotted in Figure 12. The plot shows the dominant frequency at approximately 800 Hz which is slightly higher than typical vibratory driving frequencies which are between 25 and 63 Hz. This is probably due to the influence of SR 520 traffic as mentioned above which typically has a dominant frequency between 800 Hz and 1000 Hz. These results are typical of the other piles measured.

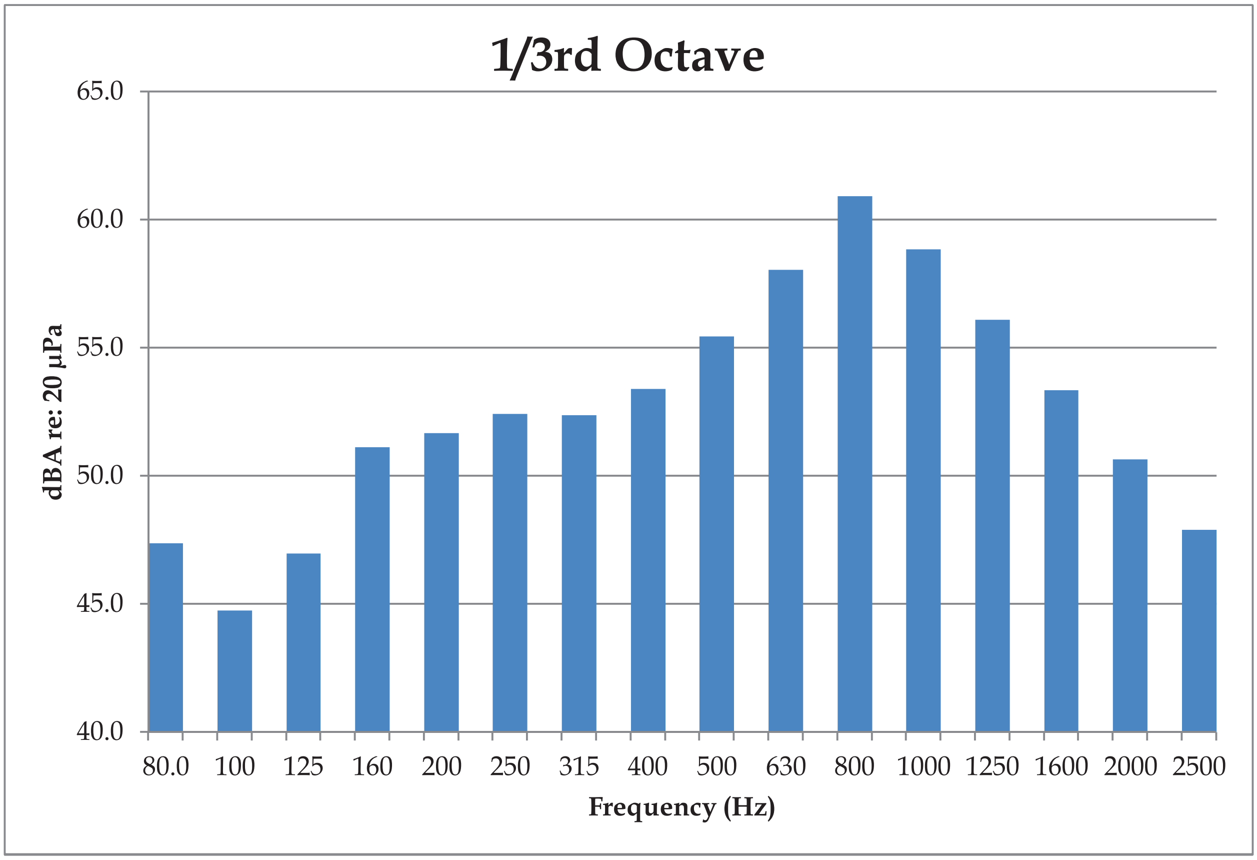


Figure 12: Average 1/3rd octave band frequencies (L_{Aeq}) for vibratory driving.

CONCLUSIONS

A total of 28, 24-30-inch steel piles were monitored for the construction of the SR 520 West Connection Bridge project. The underwater sound levels analyzed, produced the following results.

- Peak underwater attenuated sound levels at 10 meters varied in a range between 178 dB_{Peak} and 202 dB_{Peak}.
- The measured $RMS_{90\%}$ levels of the 10 meter measurements ranged between 168 dB_{RMS} and 185 dB_{RMS}.
- Cumulative Sound Exposure Levels (cSEL) for all piles driven on a particular day at 10 meters all exceeded the 187 dB_{SEL} threshold except for on 1/14/14 at 10 meters and for the last day on 3/2/14 at the 3H location. The daily cSEL values ranged between 187 dB_{SEL} and 200 dB_{SEL} at 10 meters.
- The distance measured from the 3H location to the 187 dB_{peak} threshold ranged between 10 feet and 300 feet.

Six 24-inch piles were monitored for airborne sound levels during impact driving. The measurements produced the following results.

Impact Driving

- L_{Aeq} sound levels were measured to between 109 and 110 dB between 14 meters and 27 meters.
- L_{max} levels ranged between 97 and 98 dB between 14 meters and 27 meters.
- Impact driving sound levels are all below the SMC for daytime impulsive levels.

Vibratory Driving

- L_{Aeq} sound levels were measured to between 64 and 67 dB and were partially or totally masked by traffic sounds from SR 520.
- L_{max} levels ranged between 70 and 84 dB.
- Vibratory driving sound levels are all below the SMC for maximum daytime sound levels.