Caltrans compendium of underwater sound data from pile driving – 2014 update

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ABSTRACT

In 2009 the California Department of Transportation (Caltrans) published Technical Guidance for Assessment and Mitigation of Hydroacoustic Effects of Pile Driving on Fish (1). The purpose of the technical manual is to provide Caltrans engineers and biologists, and consultants with guidance related to the environmental permitting of pile driving projects in or near water. Appendix I – Compendium of Pile Driving Sound Data provides a summary of measured underwater sound levels for a variety of pile driving situations. The Compendium originally summarized and reported data from 36 projects between years 2000 – 2006. The Compendium was updated in 2012 with addition of 21 projects and updated again in 2014 with the addition of new data from 12 projects. The projects added in 2012 and 2014 included various types of pile driving for coastal and river bridges, harbors and wharfs, additional construction of the San Francisco – Oakland Bay Bridge, and a major structure over water being built for the US Navy. This paper highlights several interesting projects and updates analyses of the data base.

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1. INTRODUCTION

The 2014 Compendium update will provide information on sound levels measured underwater during pile driving in the states of California, Oregon, Washington, Alaska, Hawaii, Idaho, and Nebraska, USA. The document is an empirical database to assist in predicting underwater sound levels from marine pile driving projects and determining the effectiveness of measures used to reduce the sound level. Descriptions and data are provided for major and minor projects with a variety of different pile and hammer types that were completed within the last 14 years beginning with the Pile Installation Demonstration Project for the San Francisco-Oakland Bay Bridge in December 2000. The Compendium originally summarized and reported data from 36 projects between years 2000 – 2006. The Compendium was updated in 2012 with the addition of 21 projects and updated again in 2014 with the addition of new data from 12 projects. The projects added in 2012 and 2014 included various types of pile driving for coastal and river bridges, harbors and wharfs, additional construction of the San Francisco – Oakland Bay Bridge, and a major structure over water being built for the US Navy. All monitoring projects included in the Compendium were completed by Illingworth & Rodkin, Inc.

The nearly 70 projects described in the Compendium provide information on a wide variety of conditions that affect sound levels in the water in the vicinity of pile driving. These data can be very useful to engineers and scientists who are responsible for predicting the effects of pile driving on biological resources. The Compendium was written to address potential impacts on fish, but the data are also applicable to the assessment of potential effects upon other biological resources such as marine mammals, diving birds, and turtles. The data demonstrate that, in addition to the obvious factors expected to affect sound levels such as hammer size and pile type, other factors such as water depth, geotechnical conditions, and topography cause significant variations in sound levels generated by pile driving and the potential effectiveness of control measures. Guidance is provided on how to use

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the data in the Compendium to best estimate sound levels and the noise reduction that may be achievable through the use of various control measures for the set of conditions specific to a particular project.

2. COMPENDIUM OVERVIEW

2.1 Organization

The Compendium is generally organized by pile type and hammer type (either impact or vibratory). Large and complex projects that include a variety of pile types and hammer types are discussed in separate chapters. The 2014 Compendium update will include a summary chapter; chapters addressing various pile types including steel pipe, cast-in-steel shell (CISS), steel H-type, concrete, steel sheet, and timber; and, several chapters devoted to major multi-year projects that typically included a variety of pile types and driving hammers including the San Francisco – Oakland Bay Bridge begun in 2000 and now in the demolition phase of the old bridge, the Benicia – Martinez Bridge, and the Richmond – San Rafael Bridge seismic strengthening project.

The Summary provides an analysis of the data including representative data for various pile types during vibratory and impact pile driving. The data and relevant conditions from each monitoring project are then summarized. The discussion for each project includes a description of the conditions at the site, the pile type and size, the hammer type, the description of the attenuation system if one was used, measurement locations, and measurement results. During the early monitoring projects the criteria included “Peak” and “RMS” sound levels, so these data were measured and reported. Frequency spectra and pressure-time histories for the pile strikes were also measured and reported for most projects included in the Compendium. Beginning in 2002-2003 the Sound Exposure Level (SEL) for individual pile strikes and subsequently the cumulative SEL for the driving of each pile and the driving of piles during each day were calculated as the various criteria addressing the effects were refined.

2.2 Summary of Impact and Vibratory Pile Driving Data

Data from many of the projects that are described in the Compendium are summarized in Table 2.2.1 for impact hammers and Table 2.2.2 for vibratory installation. Not included in these tables are sound levels associated with use of attenuation systems or use of a drop hammer. Results from these projects were highly variable and cannot be summarized into one level for a certain type of pile. These tables summarize results from un-attenuated pile driving at positions close to the pile. Information includes the pile type, pile size, water depth, and measured peak, root mean square (RMS), and sound exposure level (SEL) where available. The peak pressure is the level based on the absolute value of the largest positive or negative pressure associated with the pulse. The RMS level for impact driving is calculated using the portion of the pulse containing 90 percent of the energy, ignoring the 5 percent contained in the initial and final segments. For vibratory driving the RMS level is the average over the period of the driving time. The Compendium provides additional more extensive summary tables to assist the user. Table 2.2.3 is a portion of one project summary table from the Compendium for pile driving activities that did not use attenuation systems. These data can be used as a ready reference and for comparative purposes when screening a proposed project. In practice the Compendium is most helpful when one digs deeper and mines the projects with similar conditions for the most representative data.

2.3 Example Project – Tongue Point Facility Pier Repairs, Astoria, Oregon

Each pile driving project included in the Compendium is described in a summary report. The following summary report for the Tongue Point Facility Pier Repairs is a representative example:

Ten piles were monitored over a two-day period at the Point Pier in Astoria, Oregon under the terms of the Underwater Noise Monitoring Plan. The hydroacoustic monitoring was conducted for pile driving with a D-46-42 Diesel impact hammer installing 24” steel shell piles through the existing pier. A multi-level bubble ring was used to reduce the sound pressure from the pile driving. The hydroacoustic data with and without bubble rings operating are primarily reported for individual pulses as peak sound pressure level (SPL), Root Mean Square (RMS) impulse sound pressure level, and the sound exposure level (SEL); and the accumulated SEL is reported for the driving events.

Table 2.2.1 - Summary of near-source (10 m) un-attenuated sound levels for pile driving using an impact hammer

Pile Type and Approximate Size	Relative Water Depth	Average Sound Level Measured (dB)[1]		
		Peak	RMS	SEL
0.30 m (12 in) steel H-type – thin	<5 m	190	175	160
0.30 m (12 in) steel H-type – thick	~5 m	200	183	170
0.36 m (14 in) steel H type - thick	±6 m	208	--	177
0.61 m (24 in) AZ steel sheet	~15 m	205	190	180
0.33 m (13 in) plastic pile	10 m	177	153	--
0.30 m (12 in) concrete pile	Land based	176	--	146
0.46 m (18 in) concrete pile	<3 m	185	166	155
0.61 m (24 in) concrete pile	~5 m	185	170	160
0.61 m (24 in concrete pile	~15 m	188	176	166
0.30 m (12 in) steel pipe pile	<5 m	192	177	--
0.36 m (14 in) steel pipe pile	~15 m	200	184	174
0.41 m (16 in) steel pipe pile	3 m	182	--	158
0.51 m (20 in) steel pipe pile	± 3 m	204	161	--
0.61 m (24 in) steel pipe pile	~15 m	207	194	178
0.61 m (24 in) steel pipe pile	~5 m	203	190	177
0.76 m (30 in) steel pipe pile	± 3 m	210	190	177
0.91 m (36 in) steel pipe pile	<5 m	208	190	180
0.91 m (36 in) steel pipe pile	~10 m	210	193	183
1.52 m (60 in) steel CISS pile[2]	<5 m	210	195	185
1.68 m (66 in) steel pipe pile [3]	Land Based	197[3]	--	173[3]
1.83 m (72 in) steel pipe pile	Land Based	204	--	175
2.21 m (87 in) steel pipe pile[4]	Land Based	194[4]	--	160[4]
2.44 m (96 in) steel CISS pile	~10 m	220	205	195

Notes:

[1] Reference for Peak and RMS is 1 μPa. Reference for SEL is 1 μPa^2-sec.

[2] CISS - Cast-in-steel shell

[3] Measured 17 meters from pile

[4] Measured 35 meters from pile

Table 2.2.2 - Summary of near-source (10 m) un-attenuated sound pressure levels for in-water pile installation using a vibratory driver/extractor

Pile Type and Approximate Size	Relative Water Depth	Average Sound Level Measured (dB)[1] Peak	RMS	SEL
0.30 m (12 in) steel H-type	<5 m	165	150	150
0.30 m (12 in) steel pipe pile	<5 m	171	155	155
0.91 m (36 in) steel pipe pile	~5 m	180	170	170
0.61 m (24 in) AZ steel sheet	~15 meters	175	160	160
0.61 m (24 in) AZ steel sheet	~15 meters	182	165	165
0.91 m (36 in) steel pipe pile	~5 meters	185	175	175
1.83 m (72 in) steel pipe pile	~5 meters	183	170	170
1.83 m (72 in) steel pipe pile	~5 meters	195	180	180

Notes:

[1] Reference for Peak and RMS is 1 μPa. Reference for SEL is 1 μPa^2-sec.

Table 2.2.3 – Excerpt from expanded project summary table

Project	Water Depth	Distance	Average Sound Level (dB)[1] Peak	RMS	SEL	Attenuation Rate with Distance[6]
Tongue Point Pier, Astoria, OR[2]	± 4 m	10 m	205	188	173	23Log
0.61 m (24 in) steel pipe pile - D46		20 m	198	180	162	
SR 520 Test Piles, Seattle, WA[3]	3 – 7 m	10 m	196	185	172	15Log
0.76 m (30 in) steel pipe pile		200 m	177	161	146	10m to 200m
		500 m	160	145	135	20Log
						10m to 500m
Russian River Bridge, Ukiah, CA[4]	On-Land	17 m	197	185	173	17Log
1.68 m (66 in) steel pipe pile - D132		110 m	183	168	157	
Parson Slough, Monterey, CA[5]	4 m	10 m	200	178	166	30Log - Peak
Steel H-piles – APE19-42		20 m	190	174	162	15Log - SEL

Notes:

[1] Reference for Peak and RMS is 1 μPa. Reference for SEL is 1 μPa^2-sec.

[2] Permanent piles driven through holes in the existing pier. Measurements were part of a test of the effectiveness of a bubble ring system.

[3] Test pile project, pile driven in soft substrate.

[4] Permanent piles driven on land, the Russian River depth was less than 1 meter.

[5] Small diesel hammer in deep water.

[6] Calculated from the data values. Not valid within 10 m of pile.

Figure 2.3.1 - One level of the multi-stage bubble ring

Figure 2.3.2 – Deployment of the bubble rings

All piles were measured at 10 meters at the mid-water depth and three piles were additionally measured at 20 meters also at the mid-water depth. The underwater sound was measured continuously throughout the duration of the drive. The effectiveness of the bubble ring was tested by turning the bubble rings off for short intervals at the beginning of the drive, part way through the drive, and near the end of the drive. Table 2.3.1 shows a summary of the data collected in terms of the peak SPL, RMS and the single-strike SEL.

With the bubble rings turned off the average Peak SPL was 197 dB re: 1µPa and ranged from 189 dB to 207 dB. The average single strike SEL was 168 dB re: $1uPa^2$-sec and the levels ranged from 160 dB to 175 dB. The average RMS_{imp} was 182 dB re: 1µPa and the levels ranged from 178 dB to 189 dB. With the bubble rings turned on the average Peak SPL was 183 dB re: 1µPa and ranged from 172 dB to 189 dB. The average single strike SEL was 156 re: $1uPa^2$-sec and the levels ranged from 151 dB to 160 dB. The average RMS_{imp} was 167 dB re: 1µPa and the levels ranged from 159 dB to 172 dB. The average Accumulated SEL measured, including the bubble on/off tests was 189 re: $1uPa^2$-sec and the levels ranged from 180 dB to 193 dB. The average calculated Accumulated SEL, not including the bubble ring off portion of the tests, was 182 dB re:$1µPa^2$-sec and ranged from 177 dB to 184 dB.

During driving time when the bubble rings were turned off the impulses were characterized by higher peak levels and a faster rise times that translated into higher frequency sound energy content. When the bubble ring was used the average reduction in peak SPL was 14 dB and the reductions ranged from 5 dB to 22 dB. While the levels were reduced throughout the frequency range the 100 to 500 Hz range is where the greatest reduction occurred with the use of the bubble rings.

Analyses of pulses recorded at 10 meters with the bubble rings on and off are shown in Figure 2.3.3. The bubble rings off pulse had considerable high frequency content that was effectively attenuated with the bubble ring on. The bubble ring provided about 19 dB of attenuation of the peak pressure. The typical SEL per strike was 176 dB without the bubble ring and 160 dB with the bubble ring.

A test of the effect of the power settings for the hammer was conducted on pile 5 with the bubble ring system on. The power setting was started out at 1 and was increased by one every couple of minutes until it reached the highest setting of 4. The average peak noise levels went up by 4 dB from power setting one to power setting two. After the initial increase the average peak noise levels did not increase with the increase in power.

Table 2.3.1 - Summary of sound levels measured at 10 meters during driving of 24-inch steel shell piles

Pile #	Peak (dB)[1]		RMS (dB)[1]		SEL (dB)[1]		Average Reduction
	Maximum	Average	Maximum	Average	Maximum	Average	
Attenuated – With Bubble Rings							
1	197	196	183	181	171	169	14
2	206	202	186	183	175	171	19
3	193	193	178	178	168	168	10
4	196	195	186	184	167	167	10
5	ND[1]	ND	ND	ND	ND	ND	ND
6	ND	ND	ND	ND	ND	ND	ND
7	190	190	ND	ND	161	161	12
8	205	204	189	188	174	173	17
9	199	196	ND	ND	171	170	13
10	199	197	182	181	170	169	11
Un-attenuated – Without Bubble Rings							
1	188	182	172	166	161	155	14
2	183	180	175	164	159	155	19
3	190	186	170	168	160	157	10
4	189	189	174	168	160	158	10
5	187	184	169	167	157	156	ND
6	185	181	168	165	157	153	ND
7	178	175	165	161	153	151	12
8	190	187	174	169	161	159	17
9	187	185	171	169	159	156	13
10	188	186	171	172	159	157	11

Notes:

[1] Reference for Peak and RMS is 1 μPa. Reference for SEL is 1 μPa^2-sec.

[2] ND – No Data

Table 2.3.2 - Summary of sound levels measured at 20 meters during driving of 24-inch steel shell piles

Pile #	Peak (dB)[1]		RMS (dB)[1]		SEL (dB)[1]		Average Reduction
	Maximum	Average	Maximum	Average	Maximum	Average	
Attenuated – With Bubble Rings							
6	171	167	ND[2]	ND	147	145	--
7	173	167	ND	ND	144	141	20
10	172	171	155	154	142	141	12
Un-attenuated – Without Bubble Rings							
6	ND	ND	ND	ND	ND	ND	--
7	191	188	ND	ND	163	161	20
10	192	182	170	166	157	153	12

Notes:

[1] Reference for Peak and RMS is 1 µPa. Reference for SEL is 1 μPa^2-sec.

[2] ND – No Data

Table 2.3.3 - Average sound levels with various power settings on impact hammer (bubble rings on)

Power Setting/ Energy Rating	Peak (dB)[1]	RMS (dB)[1]	SEL (dB)[1]
1st / 55,932 ft-lbs	180	164	152
2nd / 75,646 ft-lbs	185	168	155
3rd / 95,130 ft-lbs	186	169	156
4th / 114,615 ft-lbs	185	168	156

Notes:

[1]Reference for Peak and RMS is 1 µPa. Reference for SEL is 1 μPa^2-sec.

Tongue Point Dock Repair - Comparison of Bubble Rings Off and ON - @ Pile 8 11/18/08

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

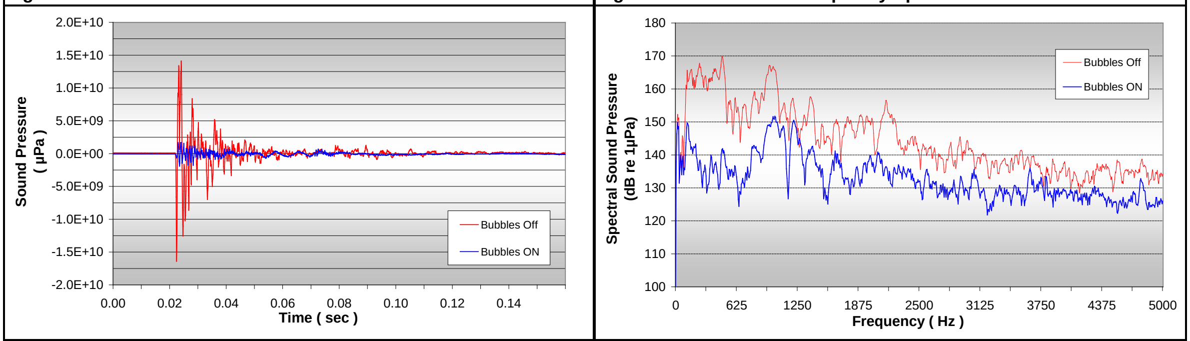

Figure c. Accumulation of Sound Energy

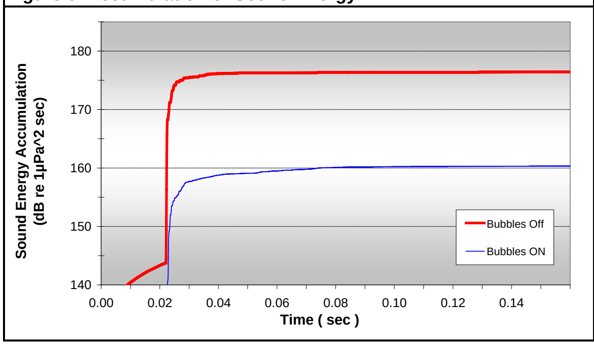

Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels

	Peak	RMS90%*	SEL
Bubbles Off	204	193	176
Bubbles On	185	172	160

Typical Sound Pressure / Energy Levels Throughout Drive

	Peak	SEL
	Off / On	Off / On
Reported Average	205 / 187	174 / 159
Reported Maximum	207 / 190	177 / 162

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

Figure 2.3.3 - Representative signal analyses for un-attenuated and attenuated piles

3. APPLICATION IN BIOLOGICAL ASSESSMENTS

Data in the Compendium are useful when evaluating the potential adverse effects of underwater sound resulting from a proposed marine pile driving project upon biological resources. The sound field in the water results primarily from both direct sound transmission from the pile and sound radiated from the sea or river bottom. The relative contributions depend upon water depth, whether or not attenuation systems are used (and their effectiveness), and geotechnical conditions affecting the pile resistance and propagation characteristics beneath the bottom. The data in the Compendium have proven to provide a solid basis for empirical modeling for the purpose of biological assessments.

There are several steps necessary to make a reasonable prediction of pile driving noise from the data in the Compendium. First, find examples of projects with similar pile types and sizes. Then select the appropriate hammer type, either impact or vibratory. Sometimes this information is not known, so assumptions that lead to credible worst case conditions must be made. Frequently a combination of pile driving methods is used, where the pile is vibrated in and then “proofed” with an impact hammer to confirm that the specified resistance has been achieved. The next step is to identify projects that have similar settings, for example a project where piles are driven in a bay or a river. Many projects include piles driven in the water and on land near the shore, and both can result in significant sound levels in the water. The other critical element is the prediction of the performance of the attenuation system. The attenuation provided by a bubble curtain or other system only affects the direct contribution radiated from the pile. Measurements of pile driving on land near shore and in fully de-watered coffer dams demonstrate that the ground-borne component of the pulse results in high sound levels in the water. So caution must be used when evaluating the benefits of proposed attenuation systems, particularly for piles driven in shallow water near shore.

One can confidently use the data in the Compendium to predict underwater sound levels from a proposed project when these factors are properly considered. As more well documented data becomes available the accuracy of empirical and theoretical models will further improve.

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