Compendium of Pile Driving Sound Data

Prepared for:
The California Department of Transportation
1120 N Street
Sacramento, CA 94274
Contact: Suzanne Theiss

Prepare by:
Illinworth & Rodkin
505 Petaluma Blvd. South
Petaluma, CA 94952
Contact: James Reyff

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I.1 Introduction

This appendix provides information on sound pressures resulting from pile driving measured throughout Northern California. The information provides an empirical database to assist in predicting underwater sound levels from marine pile driving projects and determining the effectiveness of measures used to control the noise. This compendium includes information on major and minor projects with a variety of different pile and hammer types that were completed within the last 6-1/2 years and were completed since work began on the pile installation demonstration project for the San Francisco-Oakland Bay Bridge in December 2000. The document is set up in sections or, more properly, chapters which are self-contained in terms of the figure and table numbering and references. Chapters on additional pile types are expected as more projects are completed and data become available.

This appendix includes the following sections:

- Summary – provides an overview of data contained within the compendium;
- Steel Pipe or CISS Piles – provide the results of monitoring the installation of steel pipe or cast-in- steel shell (CISS) piles on numerous projects utilizing various construction methods throughout Northern California.
- Steel H-Type Piles – provides limited available data on the installation of steel H-type piles.
- Concrete Piles – provides data on the installation of concrete piles typically used for wharf construction such as berth construction at Ports.
- Steel Sheet Piles – provides some information on steel sheet piles used to construct walls and cofferdams in marine environments.
- Timber Piles – provides very limited data on timber piles; these piles are not commonly used in Northern California.
- New Benicia-Martinez Bridge Project – provides extensive data accumulated during the pile driving required for the Benicia-Martinez Bridge including extensive work documenting the effectiveness of attenuation systems.
- San Francisco-Oakland Bay Bridge East Span Replacement Project – provides a comprehensive summary of the initiating project for concern regarding these impacts in California. Data are presented for the Initial Pile Installation Demonstration Project, the re-striking of these piles a year later, and numerous measurements conducted throughout the Bay under different conditions during driving of production piles.
- Richmond-San Rafael Bridge Project – provides data on a wide variety of steel pile sizes ranging from 12-inch to 150-inch in diameter using several different types and methods of pile driving hammers.
- Humboldt Bay Bridges Project – provides data for the driving of CISS piles as part of a seismic retrofit project. This also includes testing of attenuation systems for the project.

I.2 Summary

Generally, as one would intuitively expect, sound pressures from marine pile driving depend upon the size of the pile and the size of the hammer. There are, however, other factors that can cause large variations in measured sound pressures at a particular project site or from project site to project site. These factors include water depth, tidal conditions or currents if sound attenuation systems are used, and geotechnical conditions that determine how difficult it is to drive the pile.

Data from many of the projects that are described in the subsequent chapters are summarized in Table 1.2-1 for continuous impact hammers and Table I.2-2 for vibratory installation. Not included in these tables are sound levels associated with use of attenuation systems or when a drop hammer was used. Results from these projects were highly variable and cannot be summarized into one level for a certain type of pile. Table I.2-3 summarizes all pile driving sounds reported in this compendium that did not use attenuation systems. These tables summarize results from unattenuated pile driving at positions close to the pile. Information includes the pile type, pile size, location of the project, water depth, distance from the pile where the data were collected, measured peak RMS and sound exposure level were available, an approximation of the attenuation rate, comments and photos where available. These data can be used as a ready reference and for comparative purposes when screening a project. The reader is encouraged to read the appropriate chapter to find more acoustical information on a specific type of pile.

Table 1.2-1 Summary of Near-Source (10-Meter) Unattenuated Sound Pressures for In-Water Pile Driving using an Impact Hammer

Pile Type and Approximate Size	Relative Water Depth	Average Sound Pressure Measured in dB		
		Peak	RMS	SEL
0.30 meter (12-inch) Steel H-type - Thin	<5 meters	190	175	160
0.30 meter (12-inch) Steel H-type - Thick	~5 meters	195	183	170
0.6 meter (24-inch) AZ Steel Sheet	~15 meters	205	190	180
0.61 meter (24 inch) Concrete Pile	~5 meters	185	170	160
0.61 meter (24 inch) Concrete Pile	~15 meters	188	176	166
0.30 meter (12-inch) Steel Pipe Pile	<5 meters	192	177	--
0.36 meter (14 inch) Steel Pipe Pile	~15 meters	200	184	174
0.61 meter (24 inch) Steel Pipe Pile	~15 meters	207	194	178
0.61 meter (24 inch) Steel Pipe Pile	~5 meters	203	190	177
1 meter (36-inch) Steel Pipe Pile	<5 meters	208	190	180
1 meter (36-inch) Steel Pipe Pile	~10 meters	210	193	183
1.5 meter (60 inch) Steel CISS	<5 meters	210	195	185
2.4 meter (96 inch) Steel CISS	~10 meters	220	205	195

Table 1.2-2 Summary of Near-Source (10-Meter) Unattenuated Sound Pressures for In-Water Pile Installation using a Vibratory Driver/Extractor

Pile Type and Approximate Size	Relative Water Depth	Average Sound Pressure Measured in dB		
		Peak	RMS*	SEL**
0.30 meter (12-inch) Steel H-type	<5 meters	165	150	150
0.30 meter (12-inch) Steel Pipe Pile	<5 meters	171	155	155

1 meter (36-inch) Steel Pipe Pile - Typical	~5 meters	180	170	170
0.6 meter (24-inch) AZ Steel Sheet - Typical	~15 meters	175	160	160
0.6 meter (24-inch) AZ Steel Sheet - Loudest	~15 meters	182	165	165
1 meter (36-inch) Steel Pipe Pile - Loudest	~5 meters	185	175	175
1.8 meter (72-inch) Steel Pipe Pile - typical	~5 meters	183	170	170
1.8 meter (72-inch) Steel Pipe Pile - Loudest	~5 meters	195	180	180

* Impulse level (35 millisecond average)
**SEL for 1 second of continuous driving

Table I.2-3 Summary of Unattenuated Sound Measurements for Marine Pile Driving (Part 1 of 4)

Pile Type	Size or Diameter	Project	Location	Hammer Type	Water Depth	Measured Sound Levels: Distance	Peak	RMS	SEL	Distance Attenuation Rate[1]	Comments
Steel Pipe	12-inch	Sausalito Dock	Sausalito, CA - Richardson Bay	Drop	2m	10m	177	165	152		Piles driven using 3,000 pound drop hammer that included a cushion block. Cusion block consisted of wood. Drop heights ranged 5-8 ft
				(3,000 lb)		20m	170	156	NA	>5dB at 20m	
Steel Pipe	12-inch	Point Isabel Foundation Repair	El Cerrito, CA - San Francisco Bay	Diesel Impact	1-2m	10m	192	177	NA		Piles driven using small diesel impact hammer. Piles installe in shallow water near land.
Steel Pipe	13-inch	Mad River Slough Pipeline	Mad River Sough, Arcata, CA	Drop Hammer	5m	10m	185	170	NA		Piles driven in tidal river sloough. Piles were first vibrated, then driven with a drop hammer.
				Vibratory Hammer	5m	10m	171	155	155		
Steel Pipe	14-inch	Richmond-San Rafael Bridge, CALTRANS	San Rafael, CA - San Francisco Bay	Diesel Impact	>15m	20m	196	180	170		Piles driven in fairly deep waters as part of siesmic retrofit work for the Richmond-San Rafael Bridge. Very short driving periods in deep water next to bridge piers
				(Delmag D19-42)		30m	190	180	NA		
						40m	191	178	165		
						50m	189	175	NA	~5 dB at 25-50m	
						195m	172	159	NA		
Steel Pipe	20-inch	Stockton WWTP Pipeline	Stockton, CA - San Joaquin River	Diesel Impact	3-4m	10m	208	187	176		Piles driven in San Joaquin River, where water depth was shallow. Piles were also driven on land next to the river.
				(Delmag D19-42)		20m	201	184	173	3-5 dB at 20m	
					Land-based	10m	198	183	171		
						20m	188	172	163	8-10 dB at 20m	
Steel Pipe	24-inch	Rodeo Dock Repair	Rodeo, CA - San Francisco Bay, CA	Diesel Impact	~5m	10m	203	189	178		Dock repair in San Francisco Bay
				(Delmag D36-32)		50m	191	178	167	>10 dB at 10-50m	
Steel Pipe	24-inch Battered	Amorco Wharf Repair	Martinez, CA - Carquinez Straits	Diesel Impact	>12m	10m	205	190	175		Construction of new dolphins for oil tanker wharf in Benicia Straits
	24-inch Vertical				>12m	10m	207	194	178		
Steel Pipe	24-inch	Russian River Geyserville Temprorary Trestle Piles CALTRANS	Geyserville - Russian River, CA	Diesel Impact	Land-based	15m	197	185	173		Emergency bridge repair for the Russian River during rainy season when river was near flood stage. These were temporary trestle piles driven on land adjacent to water through saturated soils.
				(Delmag D46-32)		35m	186	174	163	~10 dB 15-35m	
						70m	175	163	NA	~10 dB 35-70m	
Steel Pipe	30-inch	Richmond-San Rafael Bridge, CALTRANS	San Rafael, CA - San Francisco Bay	Diesel Impact	4-5m	10m	205	190	NA		Temproary trestle piles driven in relatively shallow waters along the westerno portion of the Richmond-San Rafael Bridge
				(Delmag D62-22)		20m	200	185	NA	5 dB at 10-20m	
						30m	199	181	170		
						40m	194	178	NA	5-7 dB at 20-40m	
						60m	195	169	NA		
CISS Steel Pipe	36-inch	Humboldt Bay Bridges, CALTRANS	Eureka, CA - Humboldt bay	Diesel Impact	10m	10m	210	193	183		Permanent piles driven next to bridge piers. Measurements part of a test that involved short driving periods with pile well setup.
				(Delmag D36-32)		50m	198	182	NA		
Steel Pipe	40-inch	Alameda Bay Ship & Yacht	Alameda	Diesel Impact (Delmag D80)	13m	10m	208	195	180		Pile driven at Alameda Estuary at a ship and yacht dock.
CISS Steel Pipe	48-inch	Russian River Geyserville Temprorary Trestle Piles CALTRANS	Geyserville - Russian River, CA	Diesel Impact	Land-based	10m	198	185	175		Permanent 48-inch piles used to support new bridge over Russian River. Piles driven next to river during low flow conditons in the narrow river. Water depth was 2m at the deepest channel of the river, which was only 15 meters wide. Levels variede considerablly durign driving event. The levels shown are representative of the louder driving periods.
				(Delmag D100-13)		20m	199	187	172	0 dB 10-20m	
						50m	190	177	164	10 dB 20-40m	

Source: Illingworth Rodkin, Inc. (Ver. 9/27/2007)

Table I.2-3 Summary of Unattenuated Sound Measurements for Marine Pile Driving (Part 2 of 4)

Pile Type	Size or Diameter	Project	Location	Hammer Type	Water Depth	Measured Sound Levels: Distance	Peak	RMS	SEL	Distance Attenuation Rate[1]	Comments
CISS Steel Pipe	48-inch	Russian River Geyserville Permanent Piles	Geyserville - Russian River, CA	Diesel Impact (Delmag D100-13)	2m	10m	205	195	185		Permanent 48-inch piles used to support new bridge over Russian River. Piles driven in water during low flow conditons in the narrow river. Water depth was 2m at the deepest channel of the river, which was only 15 meters wide. Levels variede considerablly durign driving event. The levels shown are representative of the louder driving periods.
						20m	202	190	180	3-5 dB at 10-20m	
						45m	195	185	175	~5 dB at 20 to 40m	
						65m	185	175	NA	~10 dB at 45-65m	
CIDH Steel Pipe	66-inch	Richmond-San Rafael Bridge, CALTRANS	San Rafael, CA - San Francisco Bay	Diesel Impact (Delmag D62 or D100)	4m	4m	219	202	NA		CIDH piles driven through temporary trestle constructed using 30-inch piles. Piles driven in fairly shallow water along the westerno portion of the Richmond-San Rafael Bridge.
						10m	210	195	NA	5 dB at 10-20m	
						20m	205	189	NA		
						30m	203	185	173		
						40m	198	180	NA	>5 dB at 20-40m	
						60m	187	169	158		
						80m	187	170	NA	~10 dB at 20-40m	
CISS Steel Pipe	96-inch	Benicia-Martinez Bridge, CALTRANS	Benicia, CA - Carquinez Straits	Hydraulic Impact (Menck MHU500T)		5m	227	215	201		Numerous measurements made during unattenuated driving of permanent CISS piles for the new Benicia-Martinez Bridge foundations. The levels shown were interpolated from a graph of unattenuated levels that matched well with the extensive measurements by both I&R and Greeneridge Sciences.
						10m	220	205	194		
						20m	214	203	190		
						50m	210	196	184		
						100m	204	192	180		
						500m	188	174	164	*16 Log (Dist)*	
						1000m	180	165	155		
Steel Pipe	96-inch	SFOBB 2000 PIDP, CALTRANS	Oakland, CA - San Francisco Bay	Hydraulic Impact (Menck MHU1700T)	~10m	100m	207	195	183		Indicator piles driven as a test program for the San Francisco-Oakland Bay Bridge East Span Replacement Project known as the PIDP. Measurements made when the 4th or last portion of pile driving weas conducted.
						200m	201	189	178	*20 Log (Dist)*	
						360m	191	179	168	*29 Log (Dist)*	
CISS Steel Pipe	96-inch	SFOBB 2002 PIDP Restrike, CALTRANS	Oakland, CA - San Francisco Bay	Hydraulic Impact (Menck MHU1700T)	~10m	65m	210	195	NA		This was a restrike of the PIDP (indicator) piles for the San Francisco-Oakland Bay Bridge East Span Replacement Project, as described above. Piles were restruck after two years.
						100m	198-208	184-195	NA	>12 dB at 50 - 100m	
						450m	190-198	175-185	NA	or ~*20 Log(Dist)*	
CISS Steel Pipe	96-inch	SFOBB Skyway Construction, CALTRANS	Oakland, CA - San Francisco Bay	Hydraulic Impact (Menck MHU1700T)	Dewatered Cofferdam ~5-8m	50m	185-190	165-180	NA		Production piles driven in a dewatered cofferdam, where surrounding waters were 5 to 8 meters deep. Sound levels varied considerablly with direction and distance. These measurements represent the loudest portion of the pile driving, when the last portion of the pile was driven.
						100m	185-205	175-190	NA		
						500m	170-185	160-175	NA	Variable	
						1000m	160-170	~155	NA	about *15 Log(Dist)*	
CISS Steel Pipe	96-inch	SFOBB Skyway Construction, CALTRANS	Oakland, CA - San Francisco Bay	Hydraulic Impact (Menck MHU1700T)	8-12m	25m	213	197	188		Production piles driven in water when bubble curtain was not in use due to air bubble curtain testing for fish cage studies. Sound levels varied considerablly with direction and distance. These measurements represent the loudest portion of the pile driving, when the last portion of the pile was driven.
						50m	213	200	187		
						100m	197-204	186-192	174-180	>12 dB at 50 - 100m	
						400m	186	175	165	or ~*20 Log(Dist)*	

Source: Illingworth Rodkin, Inc. (Ver. 9/27/2007)

Table I.2-3 Summary of Unattenuated Sound Measurements for Marine Pile Driving (Part 3 of 4)

Pile Type	Size or Diameter	Project	Location	Hammer Type	Water Depth	Distance	Measured Sound Levels: Peak	RMS	SEL	Distance Attenuation Rate[1]	Comments
CISS Steel Pipe	126-inch	Richmond-San Rafael Bridge, CALTRANS	San Rafael, CA - San Francisco Bay	Hydraulic Impact	>15m	10m	218-208	206-197			Piles driven below water to mud line using an IHC Hydraulic hammer imparting energy up to 358 kJ. Piles were driven for siesmic upgrade work for the Richmond-San Rafael Bridge.
				Submersible IHC		55m	200	190			
						100m	195	185	170	5 dB at 55-100m	
						230m	190	177	165		
CISS Steel Pipe	150 and 166-inch	Richmond-San Rafael Bridge, CALTRANS	San Rafael, CA - San Francisco Bay		>15m	20m	215-208	206-197	NA		Same as above, but for 150- and 166-inch piles for the Richmond-San Rafael Bridge
						50m	205	192	NA	5-10 dB at 20-50m	
						95m	194	181	NA		
						160m	191	175	NA		
						235m	192	178	NA	2-3 dB at 95-235m	
						~1000m	169	157	NA		
Steel H Pile	~12-inch	Noyo River Bridge	Fort Bragg, CA -	Diesel Impact	2m	30m	179	165	NA		Temporary trestle piles. Piles driven using small diesel impact hammer. Piles installed in shallow water.
						55m	178	164	NA	<5 dB at 30-56m	
						85m	165	150	NA	>5 dB at 56-90m	
					5m	70m	168	156	NA		Same as above, but these piles were driven in deeper water adjacent to the navigational channel.
						90m	170	158	NA		
					Land	25m	174	159	NA		Piles driven using small diesel impact hammer. Piles installed on land next to 2m deep water.
						35m	169	158	NA		
						95m	157	145	NA		
Steel H Pile	10-inch	San Rafael Canal	San Rafeal, CA -	Diesel Impact	2m	10m	190	175	NA		Piles driven using small diesel impact hammer. Piles installed close to slough shore in very shallow water.
						20m	170	160	NA	>10 dB at 20m	
				Vibratory Hammer	2m	10m	161	147	NA		
						20m	152	137	NA	10 dB at 20m	
Steel H Pile	15-inch thin, battered	Ballena Isle Marina	Alameda, CA - San Francisco Bay	Diesel Impact	2-3m	10m	190	165	155		Piles driven using small diesel impact hammer. Piles installed close to slough shore. Piles were battered.
	15-inch thick vertical				2-3m	10m	195	180	170		Same as above, but thick-walled vertical piles.
Steel H Pile	15-inch thick vertical	Ballena Isle Marina	Platte River, Nebraska	Diesel Impact	Dewatered Cofferdam	10m	172	160	147		Piles driven in dewatered cofferdam adjacent to Platte River, which is very shallow - about 2 meters deep.
						25m	177	165	148		
Concrete	16-inch Square	Pier 2, Concord NWS	Concord, CA - Carquinez Straits	Drop Steam-powered	10m	10m	184	173	NA		Piles driven using steam powered drop hammer that included a cushion block. Hammer energies were 48,000 to 60,000 ft-lbs.
Concrete	24-inch Square	Pier 40 Berth Construction	San Francisco, CA - San Francisco Bay	Diesel Impact	3-4m	10m	185	173	--		Piles driven using small diesel impact hammer. Piles installed in shallow water with dense sand layer. Water jetting and cushion block used. Lower hammer energy used to reduce sound pressures.
						20m	178	165	--		
Concrete	24-inch Octagonal	Berth 22 Reconstruction, Port of Oakland	Oakland, CA - San Francisco Bay	Diesel Impact (Delmag D62-22)	10-15m	10m	188	176	166		Piles installed using D62-22 Delmag Impact hammer with cushion block. Hammer energies up to 165,000 ft-lbs (224 kilo joules). Fish exposure study conducted during measurements.
						100m	174	163	152	*13Log(Dist)*	

Source: Illingworth Rodkin, Inc. (Ver. 9/27/2007)

Table I.2-3 Summary of Unattenuated Sound Measurements for Marine Pile Driving (Part 4 of 4)

Pile Type	Size or Diameter	Project	Location	Hammer Type	Water Depth	Measured Sound Levels: Distance	Peak	RMS	SEL	Distance Attenuation Rate[1]	Comments
Concrete	24-inch Octagonal	Berth 22 Reconstruction, Port of Oakland	Oakland, CA - San Francisco Bay	Diesel Impact	Land	10m	192	181	174		Piles installed at edge of water for wharf construction as described above.
						20m	187	176	168	5 dB at 10 to 20m	
						35m	184	171	--		
						85m	173	161	--	>5 dB at 35 to 85m	
Concrete	24-inch Octagonal	Berth 32 Reconstruction, Port of Oakland DUTRA	Oakland, CA - San Francisco Bay	Diesel Impact (Delmag D62-22)	~7-8m	10m	185	173	163		Piles installed in-water for wharf construction.
Concrete	24-inch Octagonal	Berth 32 Reconstruction, Port of Oakland MANSON	Oakland, CA - San Francisco Bay	Diesel Impact (Delmag D62-22)	8m	10m	184	174	165		Piles installed for wharf construction, similar to above. Unattenuated measurements made briefly at end of drive.
Concrete	24-inch Octagonal	Berth 23, Port of Oakland (Vortex)	Benicia, CA - Carquinez Straits	Diesel Impact (Delmag D62-22)	4m	10m	185	172	NA		Piles installed as part of wharf reconstruction, where moderate tidal currents were present. Levels briefly reached 192 dB peak and 172 dB RMS at 10 meters (unattenuated) for most driving events.
						20m	180	170	NA		
AZ Steel Sheet	24-inch AZ	Berth 23, Port of Oakland (Vortex)	Oakland, CA - San Francisco Bay	Diesel Impact	15m	5m	209	195	NA		Sheet piles installed to construct underwater sea wall for deep port to accommodate large vessels. Poiles first vibrated into place. A follower was attached to impact hammer that extended to sea bottom, so piles could be driven to tip elevation near mud line.
						10m	205	189	179		
						20m	205	186	175		
						40m	188	173	NA		
				Vibratory	15m	10m	177	163	162		
						20m	166	NA	NA		
AZ Steel Sheet	24-inch AZ	Berth 30, Port of Oakland	Oakland, CA - San Francisco Bay	Vibratory	15m	10m	175	162	162		Tested method to vibrate piles to tip elevation rather than use impact hammer. Follower used with vibratory driver/extractor.
AZ Steel Sheet	24-inch AZ	Berth 35/37, Port of Oakland (Dutra)	Oakland, CA - San Francisco Bay	Vibratory (APE 600B Super Kong)	15m	10m	177	163	163		Vibratory installation of sheet piles for deep water berth, as described above. Some driving events had sound levels exceed 185 dB peak and 165 dB SEL for very short periods.
Timber	12-14 inch	Ballena Bay	Alameda, CA - San Francisco Bay	Drop (3,000 lb)	2-4m	10m	180	170	160		Piles driven using 3,000 pound drop hammer that included a cushion block. Cusion block consisted of rubber matting, plastic and wood. Drop heights ranged 5-15 ft
						20m	170	160	NA	>5dB at 20m	

Source: Illingworth Rodkin, Inc. (Ver. 9/27/2007)

I.3 Steel Pipe or CISS Piles

This chapter describes results for various projects that involved the installation of steel pipe piles or cast in steel shell piles. Most of these projects were small and some only involved the measurements when one or two piles were driven. Some projects used various attenuation systems, while others did not. Where available, measurement results for vibratory pile installation are included. The projects are described in chronological order.

I.3.1 12-Inch Diameter Steel Piles in Shallow Water, El Cerrito, CA

Two steel shell piles were driven in the San Francisco Bay near El Cerrito, California in October 2002[1]. The purpose of the project was to repair a building foundation. The piles had a diameter of 0.3 meters or 12 inches and were driven using an impact pile-driving hammer. Underwater sound levels were measured during the driving of two piles. The first pile (center pile) was located approximately 7meters from dry land in 2 meter deep water. The second pile (east pile) was near shore where the water depth was about 1 meter. Underwater sound levels were measured at a depth of 2 meters, where the water was 3 meters deep. The distance from the hydrophone to the pile being driven was approximately 10 meters. The typical peak levels for the center pile were 190 to 192 dB peak and the RMS-impulse sound pressure levels were typically 175 to 177 dB RMS. The East Pile, which was driven in very shallow water, resulted in peak sound pressures of about 185-188 dB and RMS sound pressure levels of 170-173 dB. The duration of continuous driving for each pile was approximately 5 minutes. The driving event was preceded by about 1 to 2 minutes of occasional pile strikes that had sound pressures that were about 5 dB lower. An underwater noise attenuation system was not employed on this project. Measured sound pressure data are summarized in Table I.3-1.

Table I.3-1 Summary of Sound Pressures Measured for the Driving of 12-inch Steel Shell Piles – El Cerrito

Pile	Conditions	Sound Pressure Levels in dB Measured at 10 Meters		
		Peak	RMS	SEL
Center	Unattenuated – Diesel Impact Hammer	192	177	--
East	Unattenuated – Diesel Impact Hammer	188	172	--

Analysis of signal recordings, not shown, indicate that the pulse durations were about 60 msec with most energy contained within the first 30 msec. Acoustical energy was concentrated in the frequency region between 250 Hz and 1,000 Hz. SEL Levels were not measured or calculated for this project.

I.3.2 60-inch CISS Piles - Noyo River Bridge Replacement, Fort Bragg, CA

In October 2002, permanent 1.5-meter (60 inch) diameter CISS piles were driven as part of the Noyo River Bridge Replacement project in Fort Bragg, CA[2]. Temporary H-type piles were also driven for this project, but are discussed in a different chapter. The CISS piles are part of the south pier supporting the new bridge. The piles were driven within a water-filled cofferdam, near shore in about 1.5-meter deep water (see Figure I.3-1). Underwater sound monitoring was conducted for the sole purpose of identifying safety zones for marine mammals (seals) that inhabit the area. Measurements were made across the main channel of the harbor at positions ranging from 12 meters to 150 meters from the piles.

Figure I.3-1 CISS piles driven for the Noyo River Bridge Replacement Project

Results of the measurements made on October 25, 2002 are summarized in Table I.3-2. Sound pressure levels dropped off at a rate of about 7 dB per doubling of distance out to 80 meters and then dropped off at a much faster rate out to 125 meters. Water depth was generally very shallow, less than 2 meters. The fairly narrow navigation channel depth was about 3 to 5 meters deep at the time of the measurements (depth varies with tide). Because measurements were only conducted to identify the extent of the marine mammal safety zone, which was based on RMS sound pressure level measurements, detailed analysis of acoustic signals was not performed. Therefore, SEL levels are not available.

Table I.3-2 Summary of Sound Pressures Measured for the Driving of 60-inch CISS Piles – Noyo Bridge Replacement – Fort Bragg, CA

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
Cofferdam – in water	Unattenuated – Impact Hammer at 10m	207	192	--
	Unattenuated – Impact Hammer at 50m	190	175	--
	Unattenuated – Impact Hammer at 80m	187	171	--
	Unattenuated – Impact Hammer at 125m	175	160	--

I.3.3 12-Inch Diameter Steel Piles in Shallow Water Using Drop Hammer Sausalito, CA

Two small diameter steel pipe piles were driven in March 2003 in Sausalito, California[3]. The purpose of the project was to secure marina docks at Galilee Marina. The pile-driving hammer used was a 3,000-pound drop hammer. Measurements were made primarily at 10 meters from the pile with supplementary measurements at 20 meters. The water depth was about 2 meters, so the hydrophones were positioned at 1-meter water depth. Measured sound pressure data are summarized in Table I.37-3. At 10 meters, the average peak pressure was 175 dB and most strikes were 178 dB or lower. The 20-m distant results were consistently 5 dB lower and the highest level measured was 175 dB peak. Underwater sound level varied as drop height was not precisely controlled. Hammer drops of 1.5 to 2.5 meters (5 to 8 feet) yielded peak pressures that ranged from 170 to 178 dB at the 10-meter position. For one particularly high drop (3 meters or 10 feet), the peak pressure level was 181 dB. The duration of driving for each pile was approximately 10 minutes with sporadic hammer strikes. Each pile required about 30 strikes to install. Although not reported, measurements made at 20 meters were observed to be 5-dB lower. An underwater noise attenuation system was not employed on this project.

Table I.3-3 Summary of Sound Pressures Measured for the Driving of 12-inch Steel Shell Piles – Galilee Marina , Sausalito

Pile	Conditions	Sound Pressure Levels in dB Measured at 10 Meters		
		Peak	RMS	SEL
1 & 2	Unattenuated – Drop Impact Hammer	175	165	152

The representative signal analysis (see Figure I.3-2) describes the relatively high frequency content of the pulse. Most acoustical energy was contained within about 250 to 2000 Hz. The peak sound pressure occurred about 20 milliseconds into the 75-msec event. As a result, the rate sound energy was accumulated was relatively slow. The SEL for these typical strikes was 152 dB.

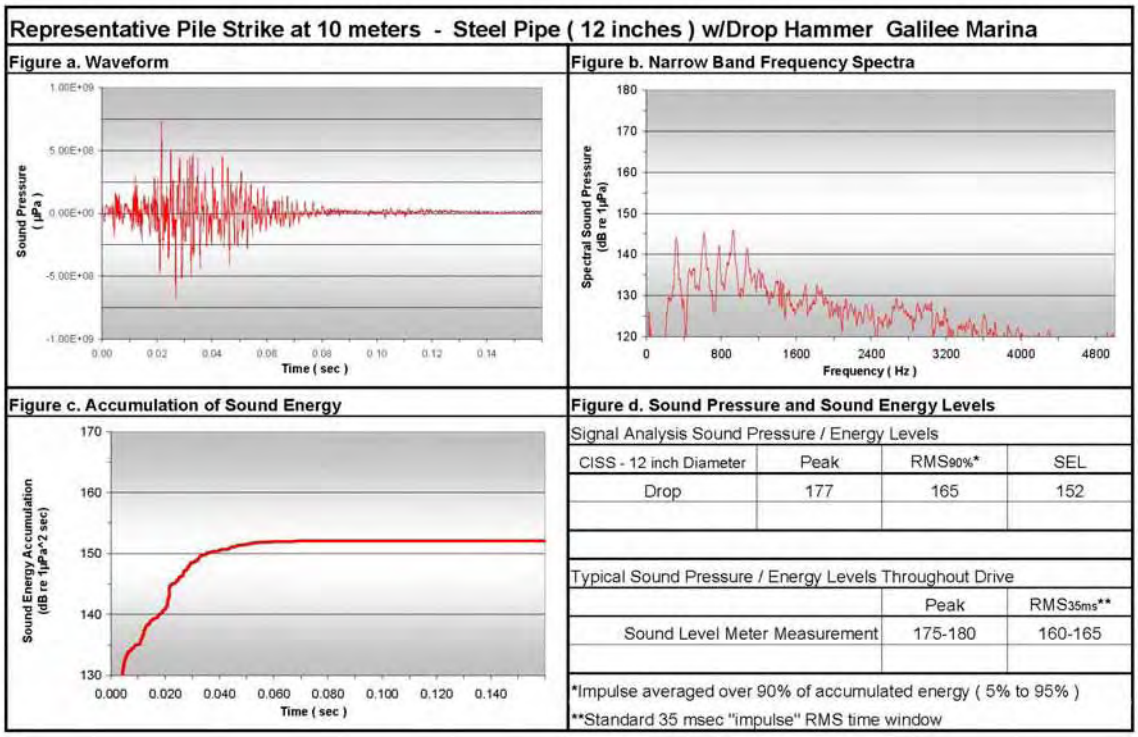

Figure I.3-2 Representative Signal Analysis for Galilee Dock Construction

I.3.4 13 inch Diameter Piles for the Mad River Slough Pipeline Construction - Arcata, CA

Three steel pipe piles were driven in July 2003 at the Mad River Slough near Arcata, CA[4]. The purpose of the project was to retrofit a water pipeline. Steel pipe piles with a diameter of 0.3 meters (actually 13 inches) were first installed with a vibratory driver/extractor. The installation was completed with a drop impact hammer. A confined air bubble curtain system was used to attenuate sounds during use of the drop hammer. The water depth was about 5.5 meters (18 feet) for the first pair of piles, and about 4.5 meters (15 feet) for the second pair. Measurement depth was 3 meters (10 feet). Underwater sound measurements were made at 10 meters from the first pile pair, and at 10m and 20m for the second pair.

Measured sound pressure levels are summarized in Table I.3-4. Signal analysis of individual pile strikes was not performed, and therefore, SEL data for this installation is not available.

Figure I.3-3 13-inch Steel Pipe Pile Installation with Confined Air Bubble Curtain System

Vibratory Installation

At 10 meters, average peak sound pressures were 171 dB for all three piles. However, peak pressures varied by 10 dB and some peak pressures approached 180 dB. Average RMS-impulse sound pressure levels were 155 dB. At 20 meters, the average peak and RMS sound pressures were 168 and 150 dB respectively (about 5 dB lower).

Drop Hammer Impacts

At 10 meters, the average peak sound pressure was about 185 dB. Maximum peak pressures for each drive were slightly higher, although one strike was 192 dB. The average and maximum RMS sound pressure was 167 and 174 dB respectively. At 20m, the average peak and RMS sound pressures were 177 and 161 dB respectively. The rate of attenuation from 10 to 20 meters was about 8 dB. Driving periods were about 1 minute, where only about 10 hammer strikes were required to drive a pile. Since the confined air bubble curtain system was used throughout the project, it was not possible to measure the reduction in sound pressure that resulted.

Table I.3-4 Summary of Sound Pressures Measured for the Driving of 13-inch Steel Shell Piles – Mad River Slough

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
1	Unattenuated - Vibratory Hammer at 10 meters	171	155	NA
1	Attenuated - Drop hammer at 10 meters	185	166	NA
2	Unattenuated – Vibratory Hammer at 10 meters	171	154	NA
2	Attenuated - Drop hammer at 10 meters	183	167	NA
3	Unattenuated - Vibratory Hammer at 10 meters	171	156	NA
3	Unattenuated - Vibratory Hammer at 10 meters	168	150	NA
3	Attenuated - Drop hammer at 10 meters	186	169	NA
3	Attenuated - Drop hammer at 10 meters	177	161	NA

I.3.5 72 Inch Pile Vibratory Installation at the Richmond Inner Harbor, Richmond, CA

In November 2003, a 1.8-meter (72-inch) diameter steel pipe pile was installed in the Richmond Inner Harbor in Richmond, CA[5]. The pile was installed at the Castrol Oil facility dock as a breasting dolphin for large ships. The pile was installed using a vibratory driver/extractor to avoid significant underwater noise impacts. Pile installation occurred on three separate days due to unanticipated construction problems. The first two days of pile installation involved the use of a APE Model 400B Vibratory Driver/Extractor (King Kong Driver). The pile could not be installed to the specified depth using the King Kong Driver, so the larger Super Kong Driver (Model 600) was used on the third day. Figures I.3-4a and I.3-4b show the APE King Kong Driver in use.

Figure I.3-4a Pile installation using the APE Model "King Kong" Vibratory Driver/Extractor

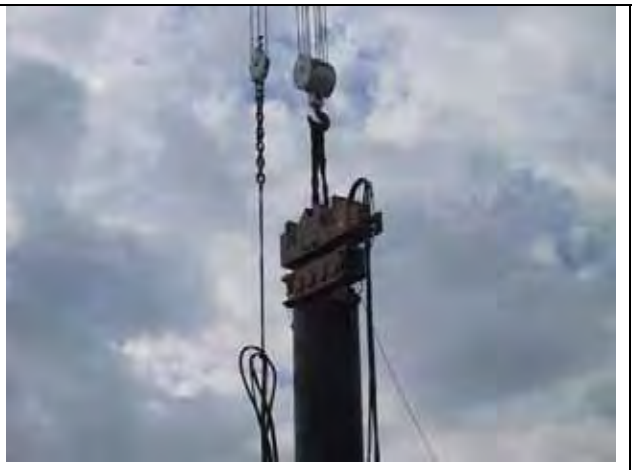

Figure I.3-4b Close-up of Figure I.3-4a

The large pile did not move much after the initial installation using the King Kong vibratory driver. Several hours of data were captured using this driver. For the most part, peak sound pressure levels were about 175 to 185 dB the first day and 185 to 195 dB the second day, with an absolute maximum level of 205 dB. The large variation may have had to do with the coupling of the driver to the pile and whether the pile was being driven or extracted at that time. In an attempt to achieve further penetration, the pile would be slightly extracted and then driven again. The larger "Super Kong" driver was not much more successful installing the pile and produced consistent peak sound pressures of about 180-182 dB, with an absolute maximum peak pressure of 184 dB. Measurements were also made at 20m and 30m, which indicated that peak sound pressures dropped off at a rate of about 7 dB per doubling of distance. Results are summarized in Table I.3-5. The SEL is reported for a 1-second period, which is nearly equivalent to the RMS-impulse level since the sounds are nearly continuous. Keep in mind the SEL is an event descriptor, so the selection of a 1 second timer period is somewhat arbitrary.

Table I.3-5 Summary of Sound Pressures Measured for the Vibratory Installation of 72-inch Steel Shell Piles – Richmond, CA

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL ($_{1sec}$)
Day 1	Vibratory Hammer at 10 meters	183	170	170
--	Vibratory Hammer at 20 meters	176	164	164

--	Vibratory Hammer at 30 meters	172	160	160
Day 2 Loudest	Vibratory Hammer at 10 meters	195	180	180
Day 2 Typical	Vibratory Hammer at 10 meters	189	176	176
Day 3	Vibratory Hammer at 10 meters	181	167	167
--	Vibratory Hammer at 20 meters	174	163	163

Signal analysis of sounds measured at 10 meters for the first day of vibratory installation are shown in Figure I.3-5. The RMS levels reported in Table I.3-5 are sound pressure levels measured using the impulse setting of the sound level meter (35-milllisecond rise time). Analysis of the acoustical signals from this vibratory installation indicate that pulses of about 25 msec occurred every 50 to 60 msec; therefore, the RMS measured with the "impulse" setting may not properly measure the RMS over the pulse. However, the sound from this hammer was perceived as continuous. Furthermore, the pulse from vibratory pile installation has not been defined. If one were to use the imbedded pulse (25 msec long) as the pulse, then the RMS should be measured over about 20 to 25 msec. This would yield a higher level than the RMS measured with the impulse setting (as shown in Figure I.3-6). Most of the acoustic content was below 600 Hz. The shape of the spectra changed considerably during the driving period. The SEL was computed for one second, since the sounds are continuous and accumulate over the entire second when the event is occurring.

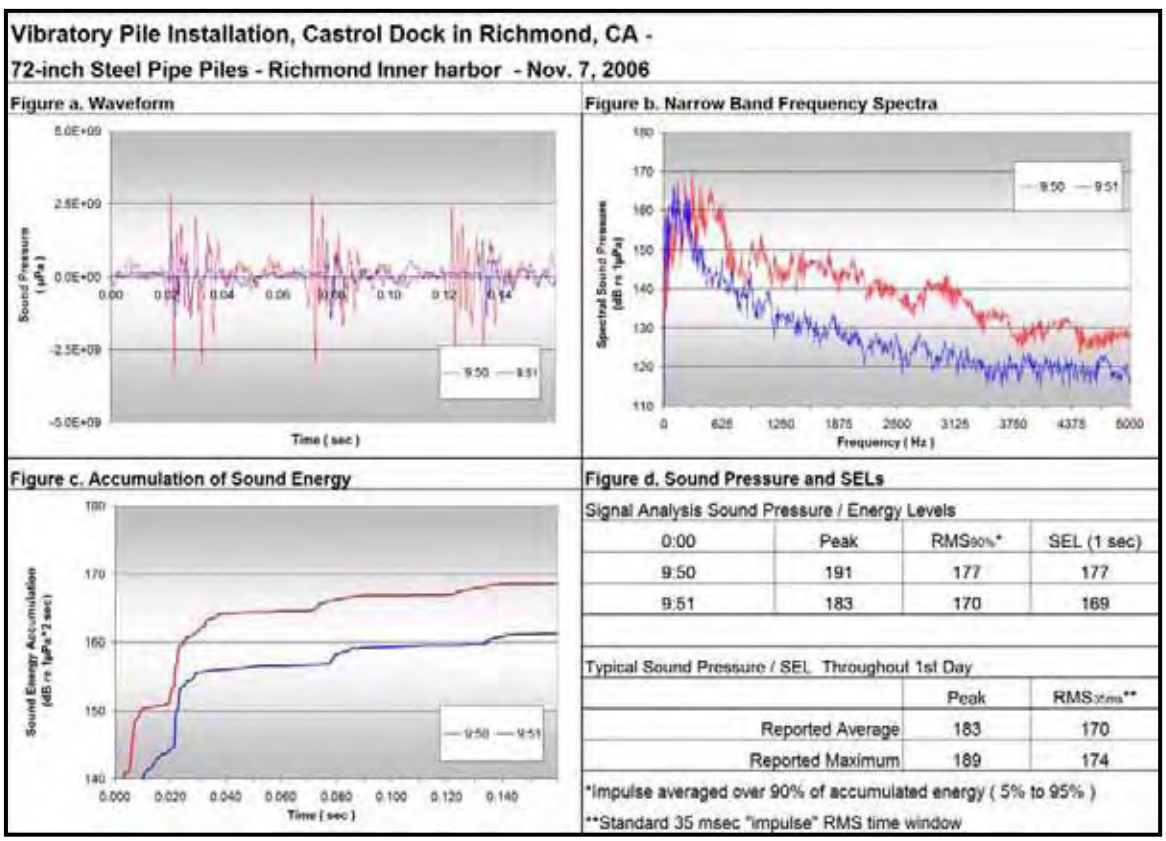

Figure I.3-5 Representative signal analysis for vibratory pile installation at Richmond, CA

I.3.6 24 Inch Piles Installed at Rodeo Dock, Rodeo, CA

Measurements were made for two 0.6-meter (24-inch) diameter steel pipe piles driven in October 2004 at the Conoco/Phillips dock in Rodeo, California[6]. The Rodeo dock is located in the northern San Francisco Bay. The purpose of the project was to reinforce the oil tanker docking pier. Piles were driven using a diesel powered impact hammer. Measurements were made at distances of 10 meters and 50 meters (33 and 165 feet) from the pile and at a depth of 3 meters (10 feet). The water depth was greater than 5 meters (15 feet). Attenuation systems were not used.

Table I.3-6 summarizes the underwater sound measurements. At 10 meters, peak sound pressures were 202-203 dB. The RMS sound pressure levels were 188-189 dB. At 50m, peak sound pressures were 190 dB and RMS sound pressure levels were 178 dB. The duration of the first pile drive was 25 minutes, and the second was 6 minutes.

Analysis of pulses recorded at 10 meters and 50 meters are shown in Figure I.3-7. The 10-meter pulse had considerable high frequency content that was effectively attenuated with distance. An attenuation rate of 5 dB per doubling of distance was measured. The typical SEL per strike was 177 dB at 10m and 167 dB at 50m.

Table I.3-6 Summary of Sound Pressures Measured for the Driving of 24-inch Steel Pipe Piles – Conoco/Phillips Rodeo Dock

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
1	Unattenuated – Impact Hammer at 10 meters	202	188	177
2	Unattenuated – Impact Hammer at 10 meters	203	189	178
1	Unattenuated – Impact Hammer at 50 meters	191	178	167
2	Unattenuated – Impact Hammer at 50 meters	189	178	166

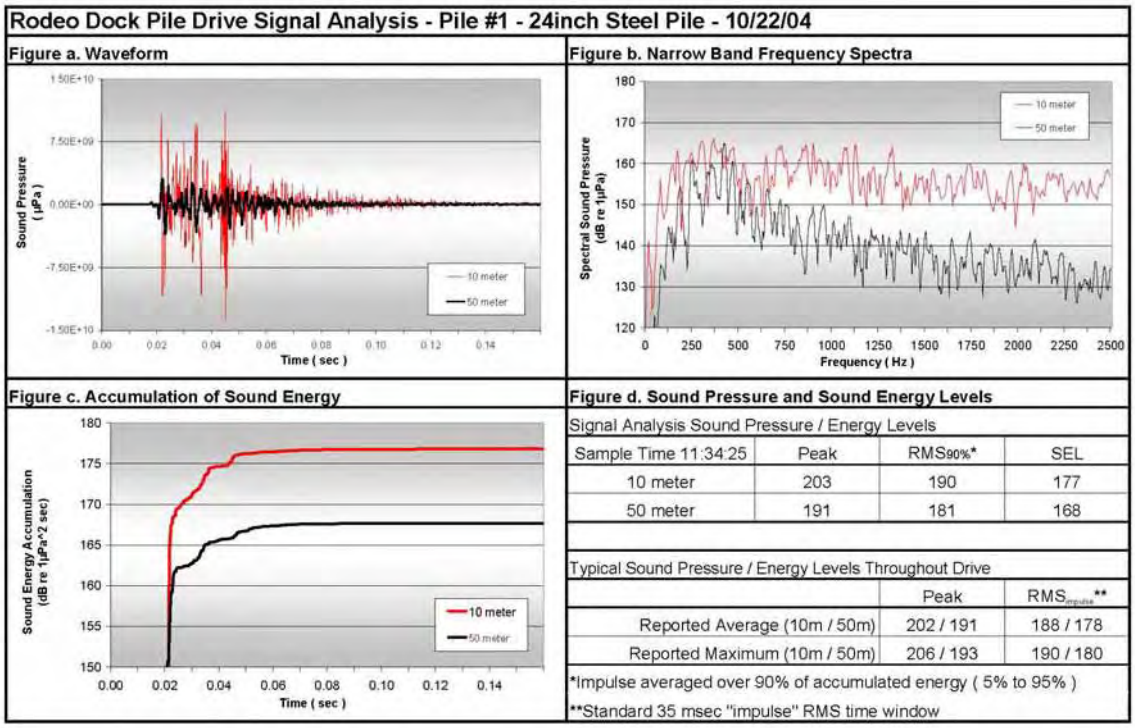

Figure I.3-6 Representative signal analysis for Rodeo Dock near San Pablo - unattenuated

I.3.7 20 and 36 inch Piles for a Wastewater Treatment Plant Utility Crossing, Stockton, CA

A utility river crossing project for the Stockton Wastewater Treatment Plant required pile driving in the San Joaquin River, in Stockton, CA[7]. The purpose of the project was to construct a pipeline utility that crossed the San Joaquin River. This project included two types of steel pipe piles: 0.5-meter (20-inch) diameter piles for a temporary trestle and 0.9-meter (36-inch) diameter CISS piles for the foundation of the utility bridge. The 20-inch piles were installed with a diesel impact hammer. The 36-inch piles were initially installed using a vibratory driver/extractor to set the piles and a diesel impact hammer was used to drive the piles to final depth. Piles were driven both on the shore and in the water (see Figures I.3-7a and I.3-7b).

A confined air bubble curtain system was used on most of the piles driven in water (see Figure I.3-8). The isolation casing used for this attenuation system consisted of a section of 1.5-meter (60-inch) diameter corrugated steel pipe that extended to the bottom of the river. A section of pipe formed into a ring was attached about two feet from the bottom of the casing. Measurements were made at both 10m and 20m from the piles and 1m from the bottom of the channel since the channel was less than 4m in depth.

Figure I.3-7a Driving 20in. Piles near shore

Figure I.3-7b Driving 36in. pile with attenuation

Figure I.3.-8 Casing for the confined air bubble curtain system

20-inch Trestle Piles Driven in Water

Measurements were made for two piles that were driven in the river with no attenuation systems on September 23, 2005. A Del-Mag Model D19-42 diesel impact hammer was used. This hammer has a maximum rated energy of 71 kiloJoules (52,362 ft-lbs). Measurements were made at 10 and 20 meters in the main river channel where water depth 3 to 4 meters.

Results are summarized in Table I.3-7 and analyses of representative signals are shown in Figure I.3-9. Unattenuated peak pressures were 207 dB at 10 meters and 200 dB at 20 meters. RMS sound pressure levels were 17 to 20 dB lower than the peak sound pressures, while the typical differences between RMS and SEL levels of about 10 dB occurred. SEL levels were 176 dB at 10 meters and 172 dB at 20 meters. The waveform depicts a typical unattenuated pile strike for a steel shell pile. Interestingly, the maximum

peak pressure occurred with the initial acoustic disturbance, resulting in a rapid accumulation of sound energy at 10 meters.

Table I.3-7 Summary of Sound Pressures Measured for the 20-inch Trestle Piles at SWWTP – In-Water, Unattenuated Piles – Stockton, CA

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
Pile 1	Unattenuated in water – Impact Hammer at 10 meters	208	187	176
Pile 1	Unattenuated in water – Impact Hammer at 20 meters	201	184	173
Pile 2	Unattenuated in water – Impact Hammer at 10 meters	206	186	175
Pile 2	Unattenuated in water – Impact Hammer at 20 meters	199	182	169

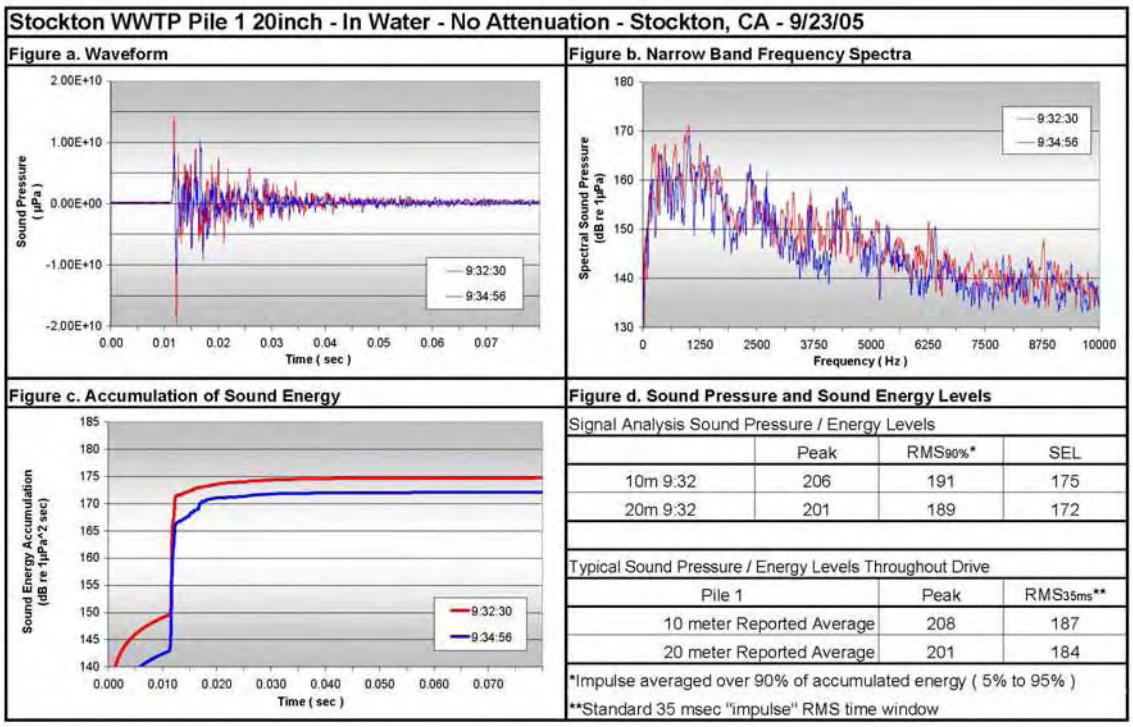

Figure I.3-9 Representative signal analysis for 20in. piles unattenuated in water

20-inch Trestle Piles Driven on Land Next to Water

Measurements were made for five 20-inch piles driven into the levee next to the river (about 0-2 meters from the water). Measurements were made at 10 meters in the main river channel for all piles. One pile was also measured at a 20-meter distance. Water depth at the measurement positions was 3 to 4 meters. The measurements were conducted on October 19, 2005.

Results are summarized in Table I.3-8. The first three piles had very consistent levels at 198 dB peak, 182 dB RMS and 171 dB SEL. The fourth and fifth piles were quieter, especially in terms of RMS and SEL. The one measurement made at 20 meters indicated a 10 dB attenuation rate.

Table I.3-8 Summary of Sound Pressures Measured for the 20-inch Trestle Piles at SWWTP – on-land next to water – Stockton, CA

Pile	Conditions	Avg. Sound Pressure Levels in dB		
		Peak	RMS	SEL
Pile 1	Land driven – Impact Hammer at 10 meters	198	183	171
Pile 2	Land driven – Impact Hammer at 10 meters	198	182	171
Pile 3	Land driven – Impact Hammer at 10 meters	198	182	NA
--	Land driven – Impact Hammer at 20 meters	188	172	163
Pile 4	Land driven – Impact Hammer at 10 meters	196	179	167
Pile 5	Land driven – Impact Hammer at 10 meters	197	179	168

The signal analysis for pulses generated by the third pile at 10 and 20 meters are shown in Figure I.3-10. These were low frequency pulses propagating through the sediment into the water with much of the acoustical content contained below 1500 Hz. The received pulses were highly attenuated since they propagated through the bottom sediments. These levels are probably the maximum attenuation one could achieve from these piles driven in this environment. Additional 20-inch diameter piles were driven in the water with attenuation systems and are discussed in the next section.

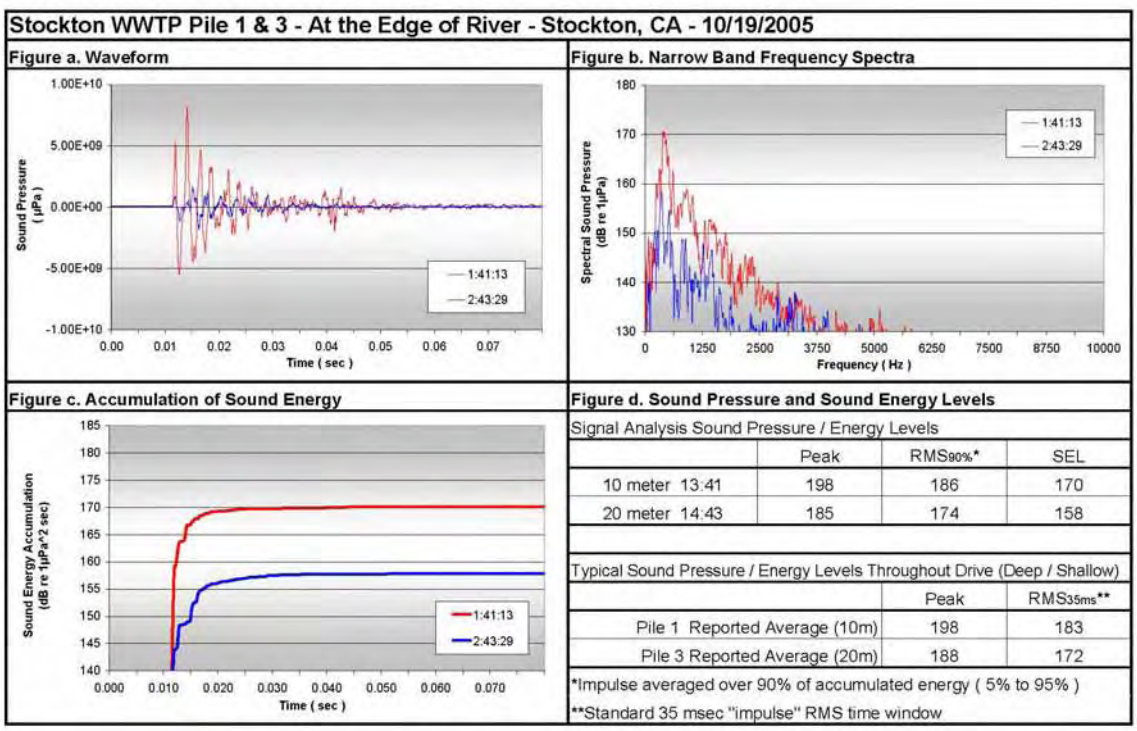

Figure I.3-10 Representative signal analysis for 20in. piles on land

20-inch Trestle Piles Driven in Water with Attenuation System

Measurements were made for three piles driven in the water with the confined air bubble curtain system. The casing prevented the current from washing the bubbles away from the pile. Measurements were made on October 25, 2005. Measurements were made at 10 meters and 20 meters in the main river channel where water depth exceeded 3 meters. Results are summarized in Table I.3-9. The attenuation

system appeared to reduce peak sound pressures by 7 to 10 dB at 10 meters and less at 20 meters. However, the reduction in RMS and SEL levels were less than 5 dB.

Table I.3-9 Summary of Sound Pressures Measured for the 20-inch Trestle Piles at SWWTP – in water with attenuation– Stockton, CA

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
Pile 1	Attenuated in water – Impact Hammer at 10 meters	201	186	175
--	Attenuated in water – Impact Hammer at 20 meters	196	182	171
Pile 2	Attenuated in water – Impact Hammer at 10 meters	198	183	175
--	Attenuated in water – Impact Hammer at 20 meters	193	178	169
Pile 3	Attenuated in water – Impact Hammer at 10 meters	197	182	171
--	Attenuated in water – Impact Hammer at 20 meters	--	--	--

The signal analysis for piles 1 and 3 are shown in Figure I.3-11. Comparison to Figure I.3-9 (untenanted conditions) shows how the attenuation system was effective at reducing higher frequency sound. This was evident in the reduction of the peak pressures; however, RMS and SEL levels were dominated by the low frequency sound content of these pulses.

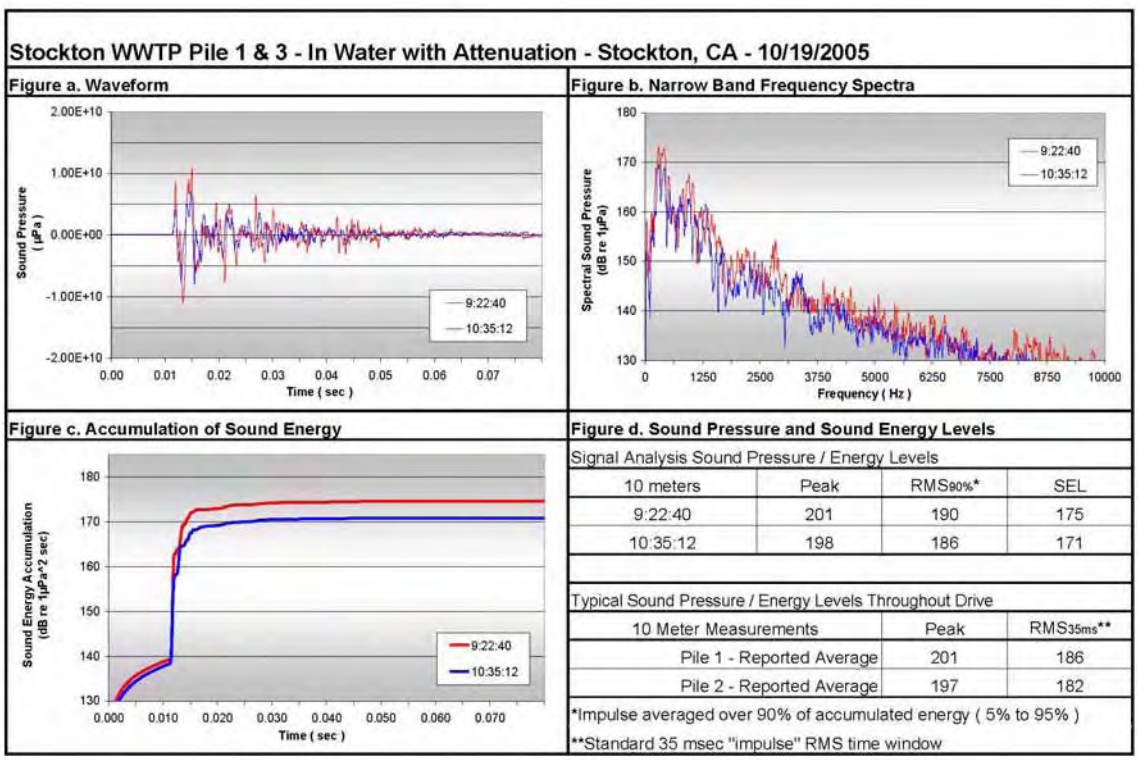

Figure I.3-61 Representative signal analysis for 20in. piles in water with attenuation

36-inch Trestle Piles Driven on Land

The 36-inch (0.9-meter) diameter piles driven into the levee for Bent 4 were measured on November 8, 2005. The piles were first installed with an ICE-66 Vibratory Hammer and then driven using a Del-Mag D46-42 diesel impact hammer. The hammer has a maximum obtainable energy of 180 kiloJoules (132,704 ft-lbs). Measurements were made in the river channel at 10 and 20 meters from the pile.

Results for both vibratory and impact installation are summarized in Table I.3-10. Signal analyses of vibratory pile installation sounds were not performed, and therefore, corresponding SEL data are only available for impact hammering. The sound pressures associated with the vibratory installation were quite low and were not of interest to this project. The impact driving on land produced levels similar, but slightly higher than the 20-inch piles that were also driven on land. However, there was very little attenuation from 10 to 20 meters with the 36-inch piles. As discussed previously, there was nearly 10 dB of attenuation with the 20-inch piles.

Table I.3-9 Summary of Sound Pressures Measured for the 36-inch Bent 4 Piles at SWWTP – on land– Stockton, CA

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
Pile 1	Vibratory Installation – Impact Hammer at 10 meters	164	155	--
--	Vibratory Installation – Impact Hammer at 20 meters	158	150	--
--	Land driven – Impact Hammer at 10 meters	201	186	173
--	Land driven – Impact Hammer at 20 meters	198	183	170
Pile 2	Vibratory Installation – Impact Hammer at 10 meters	165	157	--
--	Vibratory Installation – Impact Hammer at 20 meters	158	149	--
--	Land driven – Impact Hammer at 10 meters	199	184	174
--	Land driven – Impact Hammer at 20 meters	197	183	171

Figure I.3-12 shows the signal analyses for the 10- and 20-meter received pulses. Similar to the 20-inch piles, these pulses were highly attenuated, especially above 1000 Hz. However, the 10 and 20-meter pulses were similar, indicating little additional attenuation with distance. This is indicative of the noise source being deep within the sediment.

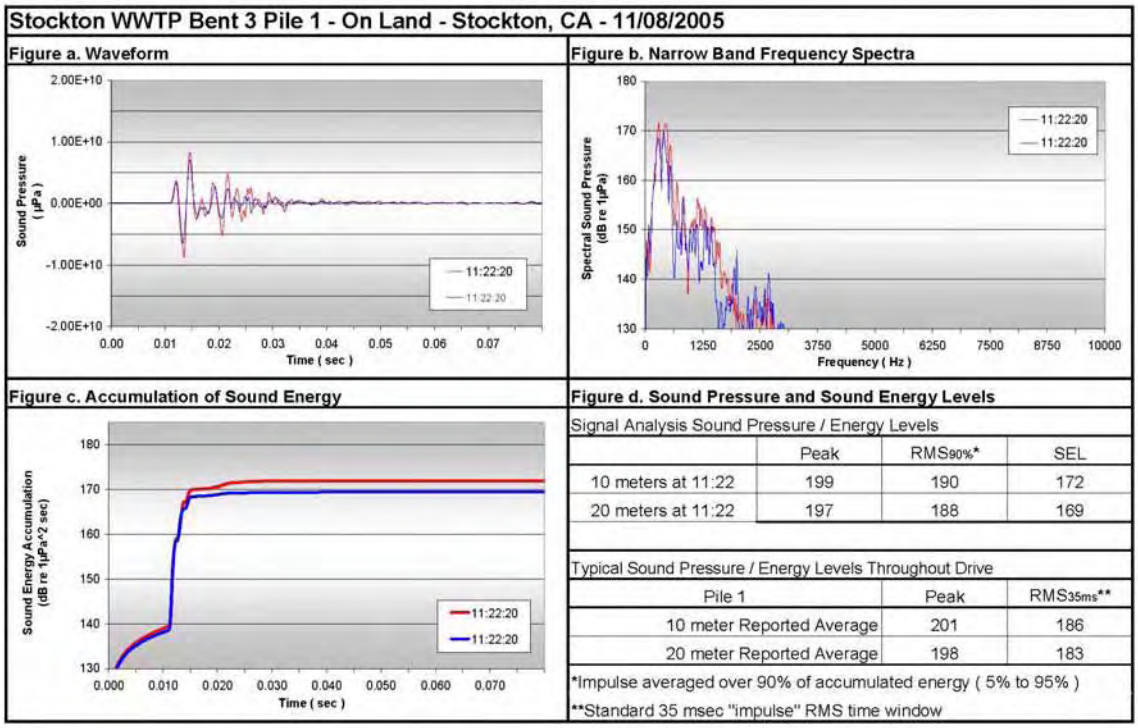

Figure I.3-12 Representative signal analysis for 36-in. Bent piles on land

36-inch Trestle Piles Driven in Water with Attenuation

The 36-inch diameter piles driven in water for Bent 3 were measured on November 8, 2005. A vibratory driver/extractor and a diesel impact hammer were used to install the piles. Measurements were made in the channel at 10 and 20 meters from the pile.

Results for both vibratory and impact installation are summarized in Table I.3-10 Vibratory installation of the piles resulted in peak sound pressures that were about 15 to 20 dB lower. Because of the different nature of the sounds, one impulsive and the other continuous, it is difficult to compare in terms of RMS. The standard RMS-impulse level (averaged over 35 msec) was about 15 dB lower when the vibratory driver was used.

Table I.3-10 Summary of Sound Pressures Measured for the 36-inch Bent 3 Piles at SWWTP – in water with attenuation– Stockton, CA

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
Pile 3	Vibratory Installation – Impact Hammer at 10 meters	180	168	--
	Vibratory Installation – Impact Hammer at 20 meters	178	166	--
	Attenuated in water – Impact Hammer at 10 meters	199	186	175
	Attenuated in water – I– Impact Hammer at 20 meters	196	182	173
Pile 4	Vibratory Installation – Impact Hammer at 10 meters	184	175	--
	Vibratory Installation – Impact Hammer at 20 meters	--	--	--
	Attenuated in water – I– Impact Hammer at 10 meters	197	185	175
	Attenuated in water – I– Impact Hammer at 20 meters	197	183	171

Signal analyses of vibratory pile installation sounds were not performed, and therefore, corresponding SEL data are only available for impact hammering. The analyses for the in-water piles are shown in Figure I.3-13. These signals are similar to those for the 36-inch piles driven on land, indicating that the attenuation system was effective at reducing the waterborne sound coming off the piles. Similar to the results for the piles driven on land, there was little difference in sound pressures levels measured at 20 meters.

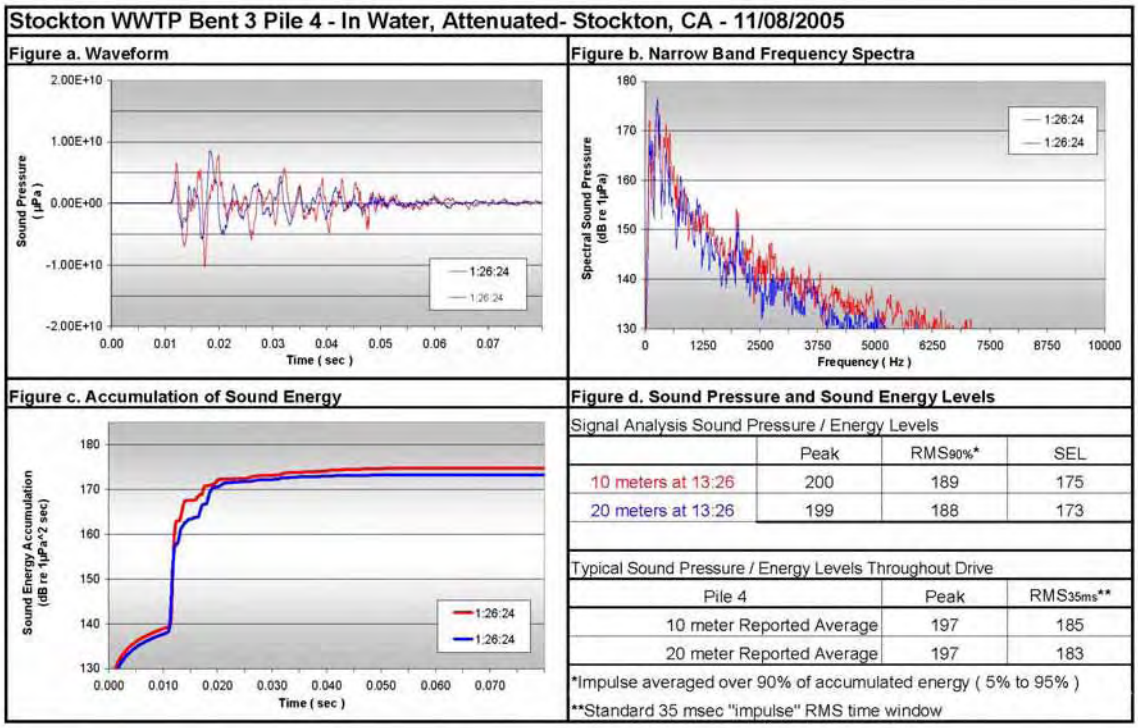

Figure I.3-73 Representative signal analysis for 36-in. Bent 3 piles in water, attenuated

I.3.8 24 Inch Breasting Dolphin Piles at Tesoro's Amorco Wharf, Martinez, CA

Pile driving was conducted to upgrade dock facilities at Tesoro's AmorcoWharf near Martinez, CA in September and October 2005[8]. Construction was performed to replace three breasting dolphins that are used to moor crude oil tankers. The project included the installation of thirty-six 0.6-meter (24-inch) diameter steel pipe piles. A set of 12 piles was installed for each dolphin. Each breasting dolphin included 6 battered piles and 6 plumb or vertical piles.

Each pile was about 100 feet long. The driving durations were between about 10 minutes and over 30 minutes. A diesel impact hammer was used to drive the piles; however, the type and size was not recorded. The hammer struck the pile about once every 1.5 seconds. The piles were driven to a specified tip elevation, unless a certain resistance was met, as determined by hammer blow counts during pile driving.

Sound measurements were conducted for all 36 piles that were driven. Water depth was about 10- to 15-meters and measurements were made at a depth of 3 meters. An air bubble curtain was used during pile driving to reduce underwater sound pressures. This system was a fire hose with

holes connected to an air compressor. Strong tidal currents were present at times, which may have reduced the effectiveness of the attenuation system. In addition, the piles were driven next to the existing concrete piles that support the wharf, complicating efforts to properly position the air bubble curtain system. Results are summarized in Table I.3-12. The levels reported are based on an average of levels measured for the 18 battered and 18 vertical (or plumb) piles that were driven for this project.

Table I.3-11 Summary of Sound Pressures Measured for the Driving of 24-inch Steel Pipe Piles – Amorco Wharf Construction – Martinez

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
Group 1 - Battered	Attenuated – Impact Hammer at 10 meters	203	185	174
Group 1 – Vertical	Attenuated – Impact Hammer at 10 meters	200	185	178
Group 2 - Battered	Attenuated – Impact Hammer at 10 meters	202	185	175
Group 2 – Vertical	Attenuated – Impact Hammer at 10 meters	200	185	173
Group 3 - Battered	Attenuated – Impact Hammer at 10 meters	200	187	178
Group 3 – Vertical	Attenuated – Impact Hammer at 10 meters	195	185	178

Pile Group #1East Breasting Dolphin

The first group of piles were driven from September 25 to 27, 2005. Drive times were longer than expected due to a hard substrate, and were as long as 30 minutes for vertical piles and over an hour for some of the battered piles. Peak sound pressures at 10 meters ranged from less than 195 dB to a maximum of 209 dB. Average peak pressures for each driving event ranged from 194 to 206 dB, indicating a wide range of bubble curtain effectiveness. RMS levels were typically 183 to 194 dB and a sample of SELs ranged from 169 to 178 dB.

Representative signal analyses for two different pile strikes are shown in Figure I.3-14. The high sound pressure levels measured in the field were indicative of poor air bubble curtain performance. As a result, the contractor made adjustments that resulted in a reduction of peak pressures by about 10 dB, and a reduction of 5 dB for RMS and SEL sound pressures. The analysis shown in Figure I.3-14 indicates that the unattenuated peak pressure was associated with high frequency sounds. This peak occurred about 10 msec into the event and appears to be the result of the pile "ringing." These piles were driven in very resistant sediments, as evidenced by the increased driving times. The beginning of the first pile is considered an almost unattenuated condition ("ABC Raised"), while the second part of the drive is considered attenuated ("ABC Lowered"). Average sound peak pressures ranged from 194 to 203 dB, indicating about 10 dB of maximum attenuation provided by the air bubble curtain system for this group of piles.

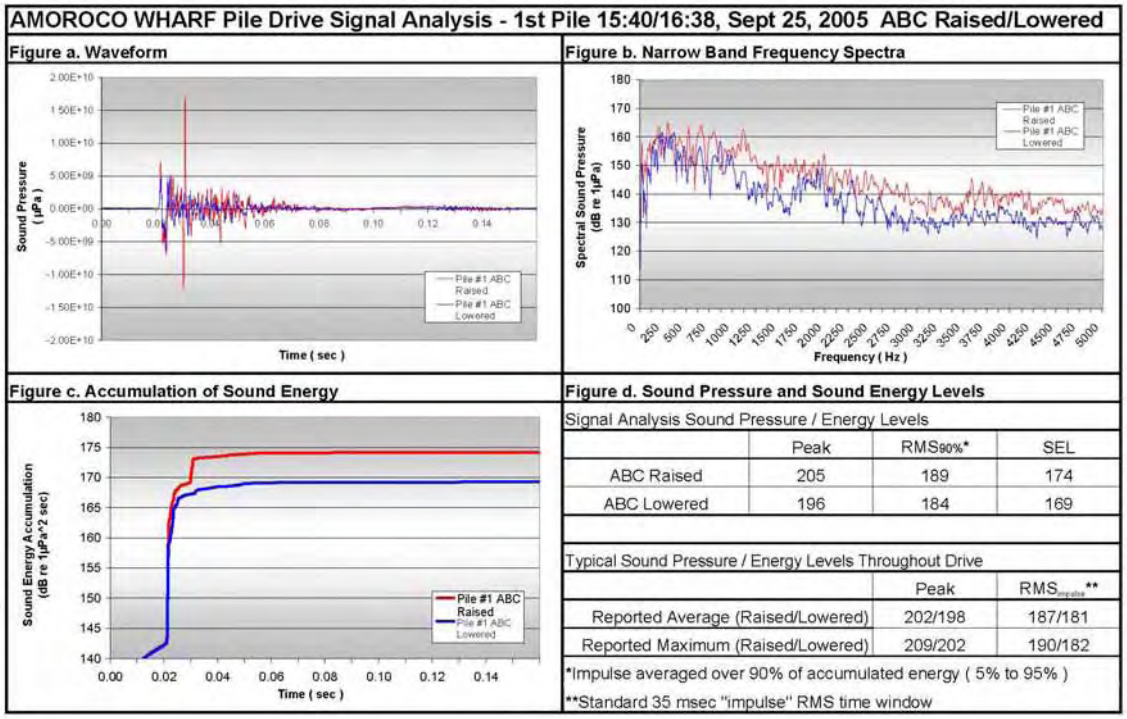

Figure I.3-84 Representative signal analysis for Amorco Wharf 24-in. piles with and with out effective air bubble curtain system

Pile Group #2

The second group of piles was driven on October 10 and 11, 2005. Drive times were considerably shorter than the first pile group, about 25 to 35 minutes for each pile. All primary measurements were made at approximately 10 meters to the south, with some additional spot measurements made at 10 meters in different directions for selected piles to assess the directionality. For battered piles, average and maximum sound pressure levels were 202 and 206 dB peak and 185 and 189 dB RMS. Typical SELs were 175 dB. There were some directionality differences. At 10meters to the west, average and maximum sound levels were 190 and 192 dB peak and 176 and 178 dB RMS. At 10 meters to the east, average and maximum sound levels were 189 and 190 dB peak and 177 and 179 dB RMS. For the vertical piles, average and maximum sound pressure levels were 200 and 205 dB peak and 185 and 190 dB RMS. Typical SEL was 173 dB. At the two alternate locations, 10m to the north and east, average and maximum sound levels were 200 and 203 dB peak and 185 and 190 dB RMS. Spot measurements at 10 meters show the sound level may differ as much as 10 dB during the driving of battered piles, depending on direction from pile. The sound levels produced by the vertically driven piles were consistent spatially.

Figure I.3-15 shows the signals for measurements made south and west of the pile. The pulse measured to the west was much more attenuated than the pulse measured to the south. There was about a 10 to 15 dB difference in sound pressure levels indicating substantial variation in air bubble curtain performance. Not only were the sound pressures lower to the west, but sound energy accumulated at a slower rate.

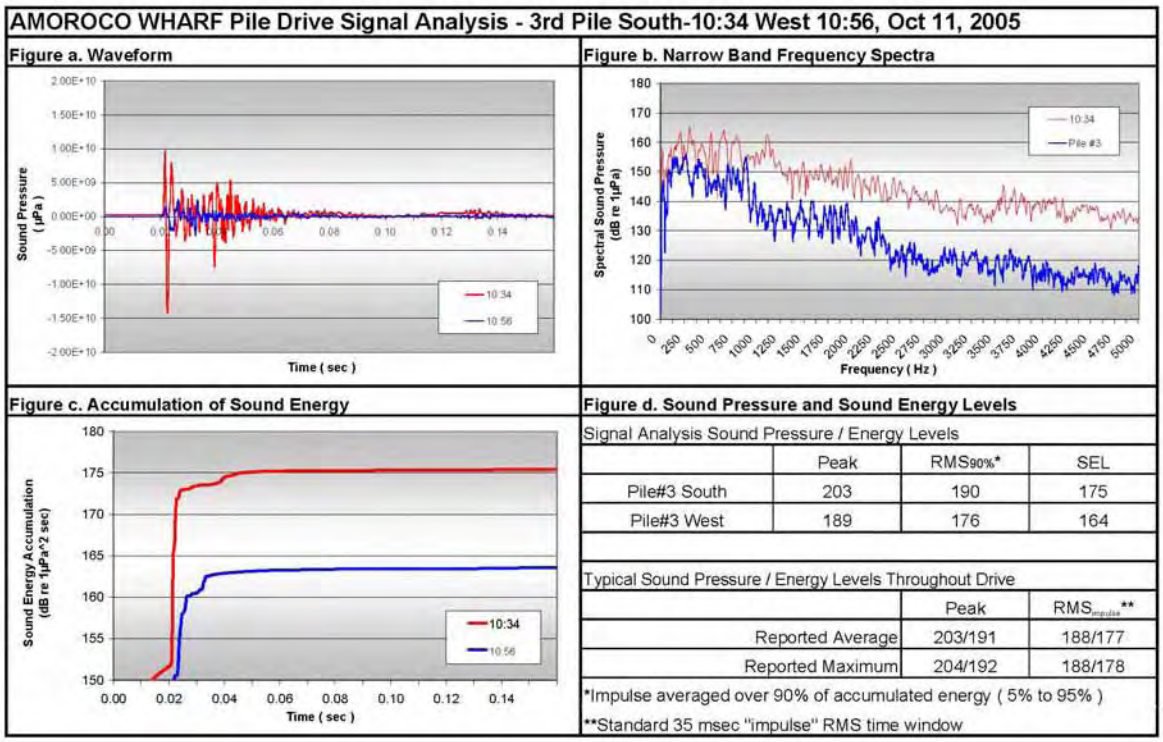

Figure I.3-95 Representative signal analysis for Amorco Wharf 24-in. directional measurements with air bubble curtain system

Pile Group #3

The third group of piles was driven on October 29 and 30. Drive times were less than the first two groups, about 10 to 15 minutes. For the driving of battered and vertical piles, average peak pressures ranged from 191 to 202 dB and the maximum for each of those drives ranged from 197 dB to 203 dB. Average RMS sound pressure levels ranged from 177 to 190 dB. SELs ranged from 164 to 178 dB. peak and 187 and 190 dB RMS respectively. SEL levels ranged from 164 to 178 dB. For the most part, driving of vertical piles resulted in lower sound pressure levels. This was likely due to better air bubble curtain performance.

Figure I.3-16 shows the signals for measurements made for two different battered piles. The pulse for Pile #1 was effectively attenuated by the air bubble curtain system. However, the pulse for Pile #5 was not very well attenuated. As with other effectively attenuated pulses, sound energy accumulated at a slower rate.

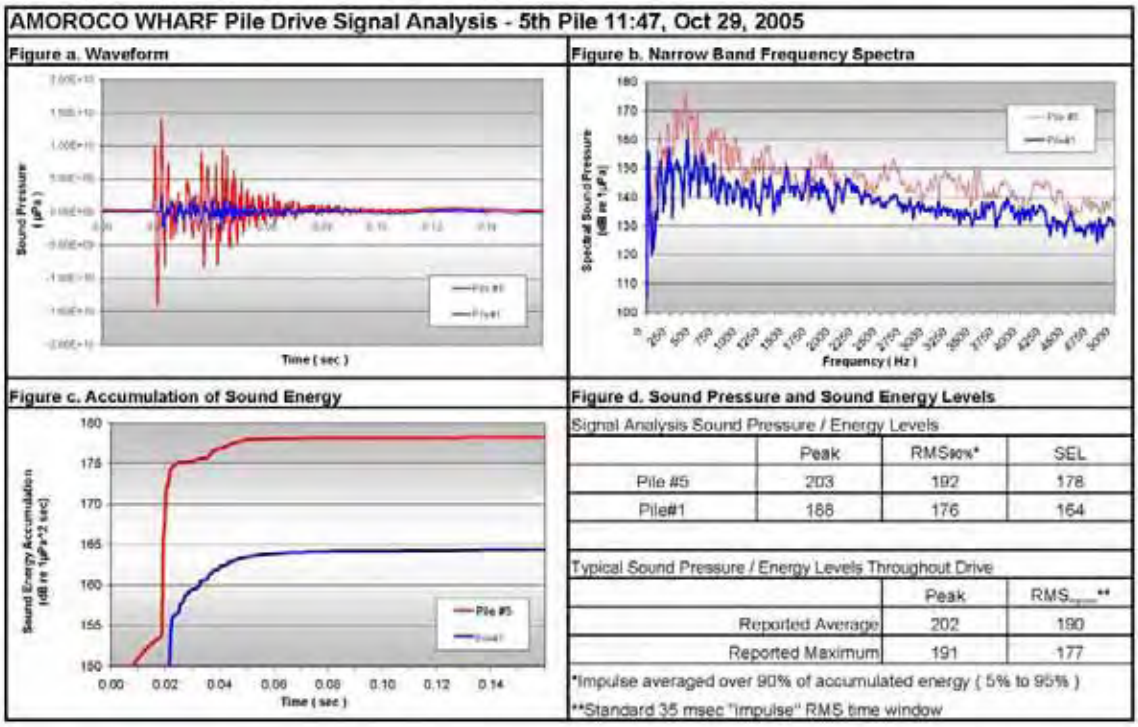

Figure I.3-16 Representative signal analysis for Amorco Wharf 24-in. showing pulse for two different battered piles with air bubble curtain system

Air Bubble Curtain System Performance

The existing wharf piers and strong currents compromised the air bubble curtain system performance at times. There were a large range of sound pressures measured throughout this project, which involved the driving of 36 piles. The first pile was poorly attenuated, because the base of the attenuation system was found to be about 5 to 6 feet above the bottom, leaving a portion of the pile exposed. That pile resulted in peak pressures of 202 dB with a maximum peak pressure of 209 dB (the highest level measured during the entire project). The RMS and SEL associated with these barely attenuated pulses were 189 and 174 dB, respectively. Most other pile driving events resulted in lower sound pressures, except for the 6th and 7th pile of the first group. Average peak pressures for some piles in the second and third groups were in the 191 to 195 dB range, 10 to 15 dB lower. The lowest RMS levels were 177 dB and the lowest SELs were 164 dB, also indicating a 15 dB range. When measurements were made at different directions simultaneously, some differences occurred, which is unusual when only 10 meters from the pile. Therefore, these were indicative of poor air bubble curtain performance in some directions. This was may have been caused by the positioning of the system, complicated by the existing piers, or current. In any event, this air bubble curtain system was capable of providing up to 15 dB of attenuation; however, lower reductions were typical.

I.3.9 24- and 48-inch Piles to Construct New Bridge Across the Russian River, Geyserville, CA

Emergency bridge replacement work was conducted in the spring and early summer of 2006 to replace the storm-damaged Geyserville Bridge that crosses the Russian River in Geyserville, CA (State Route 128)[9&10]. The river banks are almost 300 meters apart at the project location, although the main river channel is quite narrow, about 30 meters or less. The Russian River experiences large fluctuations in water flow due to heavy rainfall that occurs in the mountainous region that the river drains. Two different pile driving operations occurred on this project. A large number of 0.6-meter (24-inch) diameter steel

pipe piles were driven into the land and wetted river channel using a impact hammer to construct a temporary trestle. This trestle was used to construct the new bridge. A series of bridge piers were constructed to support the new bridge. Each pier consisted of two 1.2-meter (48-inch) diameter CISS piles. Only one pier was constructed in the wetted channel and another was constructed next to the channel. Figure I.3-17a shows construction of the temporary trestle and Figure I.3-17b shows construction of the Permanent Bridge Piers.

Figure I.3-17a Construction of the temporary trestle across the Russian River

Figure I.3-17b CISS piles driven to support new Geyserville Bridge across the Russian River

24-inch Trestle Piles

The 24-inch diameter trestle piles were driven both on land and in water during the Spring of 2006[9]. Heavy rains occurred during the beginning of this construction phase when pile driving was on land. As a result, the river was running quite high. Water depths were over 3 meters in the main channel. In addition, the entire flood plain was saturated as the river approached the flood warning stage. Piles were driven on both sides of the river in an attempt to expedite this emergency construction project. The piles on the west side began in water, while piles driven on the east side were driven on land initially and then in the water. Figures I.3-18a and I.3-18b show the pile driving operation on both sides of the river.

Figure I.3-18a Trestle pile driven on east bank. Note trestle piles extend back several hundred feet.

Figure I.3-18b Attempting to stab pile through casing (noise control) on west bank

To reduce noise, the west side pile driving was conducted through isolation casings that were dewatered and a IHC SC75 hydraulic hammer was used. This technique did not work efficiently, and therefore, a majority of the trestle piles were driven from the east side. Measurement positions during this phase of the project were determined by access to the water. The river was running quite high and swift, so hydrophones were positioned from the existing damaged bridge, using very heavy weights to fix the sensors in the water.

West Side Trestle Measurements

Table I.3-13 summarizes results of pile driving at the west side of the river where the dewatered casing was used to attenuate sound. Measurements of piles driven on the west side were infrequent. Measurements were made of only one productive driving event on April 10, 2006. However, due to heavy rain at the time, recordings were not possible for that event. That pile-driving event lasted about 6 minutes, with the pile being struck about once every second (not recorded). Peak sound pressures at 24 meters ranged from 190-195 dB throughout much of the drive. Maximum peak pressures near the end of the drive were 198 dB (2 strikes). RMS sound pressure levels were 177 to 182 dB. Signal analyses could not be performed, so SEL levels were not measured.

Table I.3-12 Summary of Sound Pressures Measured for the Driving of 24-inch Steel Pipe Piles, West Side of the Geyserville Bridge – Russian River, CA

Pile No. and Date	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
Pile 1 – 4/5/2006	Attenuated – Hydraulic Hammer at 30 meters*	186	174	NA
Pile 1 – 4/5/2006	Attenuated – Hydraulic Hammer at 90 meters*	173	164	NA
Pile 1 – 4/10/2006	Attenuated – Hydraulic Hammer at 24 meters	195	180	NA
Pile 1 – 4/25/2006	Attenuated – Hydraulic Hammer at 55 meters	<175	<165	NA

* Pile strikes were intermittent due to hammer problems, which resulted in unproductive pile driving

East Side Trestle Measurements

East side piles were driven both on land, although in saturated soils, and in the shallow river. When pile driving was conducted on land, the river was quite high because of the heavy rains that were occurring almost regularly. When pile driving reached the river channel, rains had ended and the river flow was reduced substantially. A Del Mag D46-32 impact hammer was used to drive these piles. The hammer has a maximum obtainable energy of about 180 kiloJoules (132,704 ft-lbs). Table I.3-14 summarizes results of pile driving at the east side of the river where piles were driven on land and then in the shallow water.

Table I.3-13 Summary of Sound Pressures Measured for the Driving of 24-inch Steel Pipe Piles, East Side of the Geyserville Bridge – Russian River, CA

Pile No. and Date	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
Pile 1, 3/17/2006	Land – Vibratory Driver at 65-70 meters*	<170	<155	NA
Pile 1-8, 4/5/2006	Land – Impact Hammer at 30-35 meters	186	172	~162
Pile 1-8, 4/5/2006	Land – Impact Hammer at 90-95 meters	178	164	NA
Pile 1-4, 4/10/2006	Land – Impact Hammer at 15 meters	197	185	173
Pile 1-4, 4/10/2006	Land – Impact Hammer at 35 meters	186	174	163
Pile 1-4, 4/10/2006	Land – Impact Hammer at 70 meters	175	163	NA
Pile 1, 4/25/2006	Attenuated – Impact Hammer at 27 meters	175	163	153

Pile 1-3, 4/26/2006	Attenuated – Impact Hammer at 18 meters	182	167	160
Pile 1-3, 4/26/2006	Attenuated – Impact Hammer at 34 meters	<173	<161	NA
Pile 1, 5/08/2006	Unattenuated – Impact Hammer at 10 meters	187	175	160
Pile 1, 5/08/2006	Unattenuated – Impact Hammer at 40 meters	179	166	155

* These sounds could not be heard above the noise generated by the swift river.

Prior to April, piles were mostly vibrated in place. These sounds could not be measured above the background noise of the swift flowing river (i.e., 170 dB peak and 155 dB RMS).

On April 5, 2006, piles on land were driven with an impact hammer. Although the piles were on land, the river was high and the soils were saturated. The piles driven on land took about 10 to 15 minutes to drive (being struck about once every 1.4 seconds). Sound levels started low and climbed throughout the drive. Maximum levels at 30 to 35 meters from the pile in the deep-water channel (10 meters from shore) average 186 dB peak, 172 dB RMS and about 162 dB SEL. Maximum levels were about 5 dB higher. Figure I.3-19 illustrates the low-frequency characteristics of these sounds.

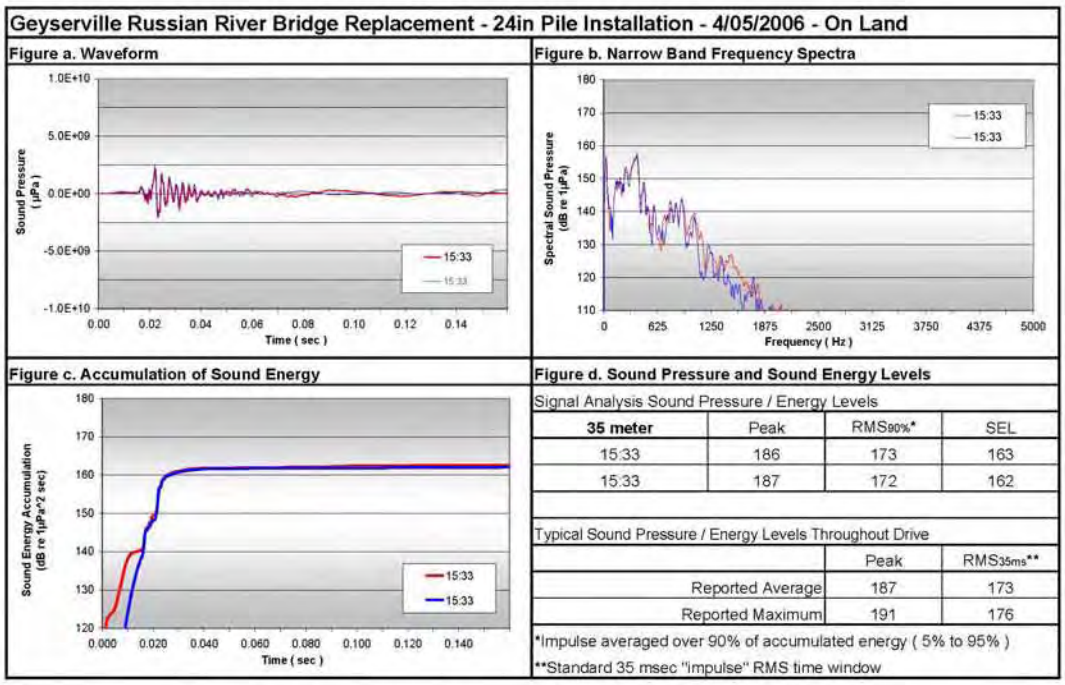

Figure I.3-19 Representative signal analysis for temporary 24-in. piles driven 35 meters away on land at the Russian River

Sound pressures were similar when the piles were driven right at the shore (April 10), which was adjacent to the deeper river channel. However, closer measurements were possible (at 15 meters). At 15 meters, peak pressures were about 197 dB, with some strikes reaching 200 dB. RMS sound pressure levels were about 185 dB and SEL levels were about 173 dB. The RMS sound pressure levels fluctuated much less than the peak levels throughout the drive. Measurements made at about 15, 30, and 70 meters indicated a drop off of sound levels in excess of 10 dB per doubling of distance from the pile. Figure I.3-20 for 15-meter measurements and Figure I.3-21 for 35-meter measurements illustrates the somewhat higher frequency content of these sounds, when compared to those from driving on April 5.

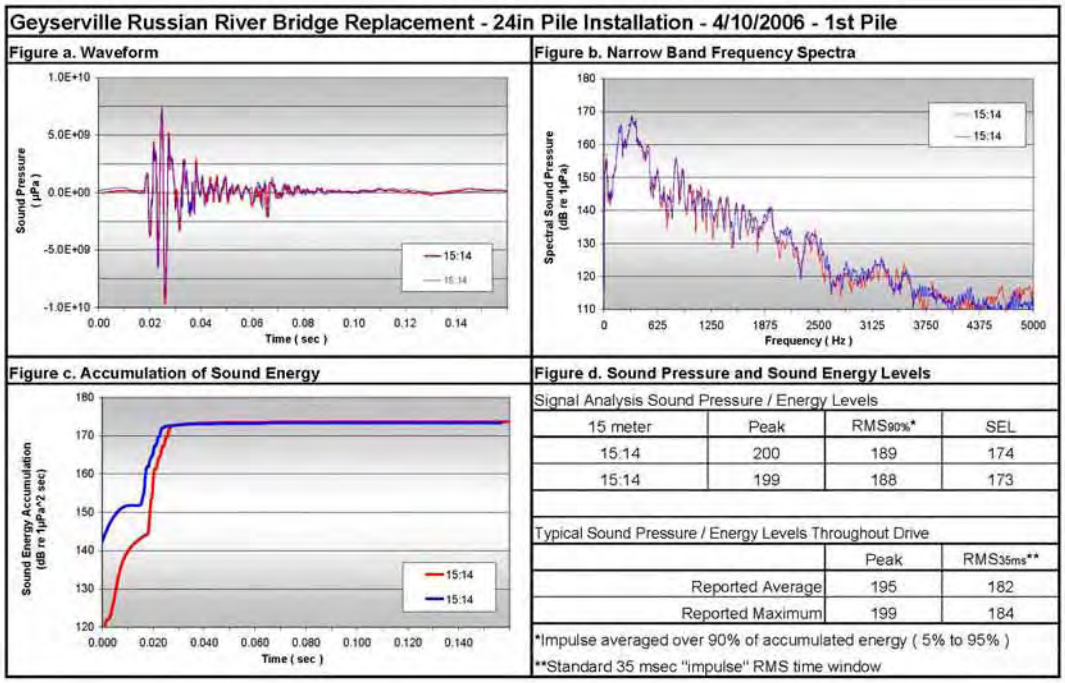

Figure I.3-20 Representative signal analysis for temporary 24-in. piles driven 15 meters away on land (at shore) at the Russian River

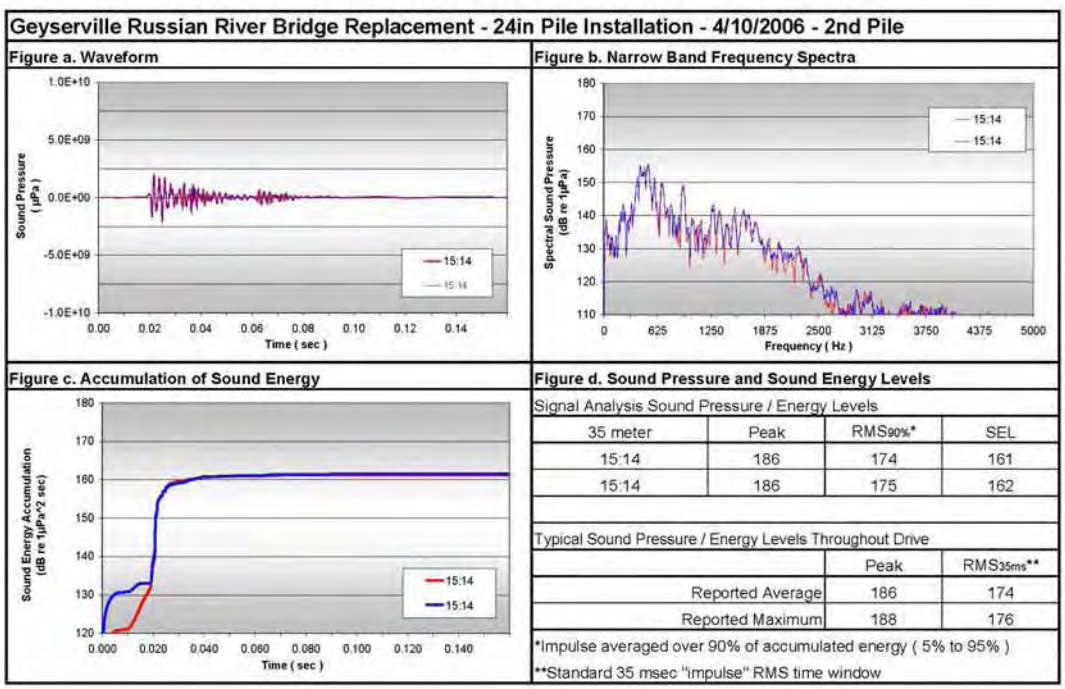

Figure I.3-21 Representative signal analysis for temporary 24-in. piles driven 15 meters away on land (at shore) at the Russian River

By April 25 and 26, the spring rains had ceased and the river flow had fallen considerably. Piles were driven in the wetted channel, but the water was not as deep. An isolation casing with an air bubble

system was used to control noise. As a result, sound pressures were much lower. An unattenuated pile driven on May 8, resulted in similar levels as the April 25 and 26 measurements. This indicated that the shallow water where measurements were made was likely the main cause for the lower levels. The swift shallow water created noise that interfered with the relatively low amplitude signal generated by pile driving on these days. Signal analyses were performed, but the analysis only indicated pulses with relatively low frequency content and peak sound pressures below 190 dB.

48-inch Trestle Piles

The permanent pier piles were stabbed using a vibratory driver/extractor and then driven using the Del Mag D100-13 with a 22,100-pound piston[10]. The hammer has a maximum obtainable energy of about 336 kiloJoules (248,00 ft-lbs). The piles were driven to a depth at which there was sufficient skin friction to support the bridge (about 150 feet). Bridge construction included 5 bents, which each included a pair of 48-inch CISS piles to support the bridge. Only one bent (i.e., Bent 5) was driven in the wetted channel. Bent 4 was driven in the dry portion of the riverbed adjacent to the wetted channel. Bents 2 and 3 were also driven in the dry riverbed, but much further from the channel. Measurements were made for portions of pile driving activities at Bents 2 through 5. Much of the monitoring focused on Bents 4 and 5. Figures I.3-22a and I.3-22b show construction of the Bridge Bents with Bents 2 through 4 in the gravel portion of the river (a) and Bent 5 in the wetted channel (b).

Figure I.3-22a Vibratory installation of a Bent 4 pile with Bent 3 and Bent 2 in the background

Figure I.3-22b Driving the top pile section of Bent 5 using a dewatered casing to reduce sound.

Each pile had a top and bottom section. The bottom section was vibrated into the substrate and then driven with an impact pile driver. Only about 5 to 7 minutes of continuous driving were needed, but there were usually breaks in the driving to make adjustments. The top section was welded on to the bottom section and then driven with the impact hammer. Bottom sections required about 45 to 60 minutes of continuous driving, but there were several breaks during the driving.

Vibratory signals were audible on the recordings, but could not be measured above the background of the river flow noise. Analyses of recorded sounds at 20 meters for Bent 4 vibratory installation indicate that peak sound pressures were below 150 dB. Table I.3-15 summarizes the measured sound pressures for impact driving of bottom pile sections at Bents 2 and 3 and top and bottom sections at Bent 4. All of these piles were driven through the dry portion of the riverbed. The closest Bent 4 pile measured, was about 2 meters from the wetted channel.

Table I.3-14 Summary of Sound Pressures Measured for the Driving of 48-inch CISS Piles, on Land at the Geyserville Bridge – Russian River, CA

Bent No. and Date	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
Bottom Pile Sections				
Bent 2 bottom, 6/12/2006	Land – Impact Driver at 20 meters	183	172	NA
	Land – Impact Driver at 60 meters	165	155	NA
Bent 3 bottom 6/12/2006	Land – Impact Driver at 33 meters	180	168	157
	Land – Impact Driver at 43 meters	179	166	NA
Bent 4 bottom 6/12/2006	Land – Impact Driver at 20 meters	192	180	165
	Land – Impact Driver at 70 meters	166	155	NA
Top Pile Sections				
Bent 4 top – 1st part 6/25/2006	Land – Impact Driver at 10 meters	198	185	174
	Land – Impact Driver at 20 meters	199	187	172
	Land – Impact Driver at 50 meters	188	174	162
Bent 4 top – 2nd part 6/25/2006	Land – Impact Driver at 10 meters	189	178	167
	Land – Impact Driver at 20 meters	190	181	167
	Land – Impact Driver at 50 meters	190	177	164

Bent 2 was a considerable distance away from the main river channel, about 55 meters. A small shallow pool of water was about 15 meters from the pile. Measurements were made in this pool at 20 meters and in the closest portion of the main river channel at 60 meters. The last one minute of driving had sound pressures that were almost 10 dB higher then the rest of the drive. At 20 meters, the peak sound pressures ranged from 180 dB to 190 dB for this last period. The RMS for that period was 70 to 180 dB. At 60 meters, highest peak sound pressures were less than 170 dB. Analyses of the signals captured for this event were not analyzed.

Bent 3 was closer to the main channel, about 25 to 30 meters from the water. Measurements were also made in a shallow pool, similar to Bent 2 measurements, but slightly further away. Sound pressures fluctuated by about 5 dB during the driving period. About three different driving periods, totaling 7 minutes were needed over a 30-minute period to install the pile section. Typical peak sound pressures were around 180 dB, with the highest level being 183 dB. RMS levels were 168 dB (maximum of 171 dB). Signal analysis were performed to measure the SEL of 157 dB.

Bent 4 was next to the main river channel. Measurements were made during installation of the north pile that was adjacent to the river channel. Both bottom and top sections of this pile were measured. The bottom section was measured at 20 meters from the pile in the main channel. Peak pressures associated with driving of the bottom section ranged from 180 to 200 dB, while RMS levels ranged from 170 to 188 dB. The SEL representative of typical pile strikes was 165 dB.

More extensive monitoring was conducted when the top section of the pile was driven. For Bent 4, measurements were made at 10, 20 and about 50 meters in the main river channel. Sound pressures varied considerably over the driving duration. About 55 to 60 minutes of pile driving were required to drive this pile over a one-hour thirty-minute period. During the first 15 minutes of driving, levels at the 10- and 20-meter positions were highest, while levels at the 50-meter position were lowest. At 10 meters, the peak pressures increased to about 200 dB during the first few minutes of driving and remained at or just below those levels for another 10 minutes. RMS levels were about 185 to 187 dB and the SEL was 174 dB.

During the second part of the driving event, sound pressure levels were lowest at the 10-meter position, slightly higher at the 20-meter position, and slightly higher at the 50meter position. During one part of the drive, levels were about 5 dB higher at 20 meters than at 10 meters. At the end of the drive, levels at 50 meters were about 2 to 3 dB higher than the 10- and 20-meter levels. At 10 and 20 meters, peak sound pressures decreased from about 195 dB to 188 dB at the end of the drive. Conversely, peak pressures at 50 meters increased from 185 to 190 dB (a maximum of 195 dB). RMS levels fluctuated much less. At 10 and 20 meters, they were mostly between 178 and 182 dB, while at 50 meters they were about 177 to 180 dB.

The piles at Bent 5 were driven through dewatered casings in the narrow channel of the river. First, the isolation casings were installed using a vibratory driver, then the bottom and top sections were driven similar to those at Bent 4. The piles were installed in 1.5-meter deep water, where the main channel was about 2 meters deep. The bottom sections required about 7 minutes to drive over the course of 1 hour for the north pile and 15 minutes for the south pile. The bottom sections required about 45 minutes of driving that occurred over a one and one-half hour periods. The hammer struck the pile about once every 1.4 seconds. All measurements made for Bent 5 were in the main channel. Measured sound pressure levels are summarized in Table I.3-16.

Table I.3-15 Summary of Sound Pressures Measured for the Driving of 48-inch CISS Piles, on Water (Bent 5) at the Geyserville Bridge – Russian River, CA

Bent No. and Date	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
Bottom Pile Sections				
Bent 5 bottom north, 6/27/2006	Water – Impact Driver at 17 meters	193	181	172
Bent 5 bottom south 6/27/2006	Water – Impact Driver at 19 meters	197	184	172
Top Pile Sections				
Bent 5 top north – 1st part 6/30/2006	Water – Impact Driver at 10 meters	199	186	175
	Water – Impact Driver at 20 meters	196	183	173
	Water – Impact Driver at 45 meters	192	182	172
	Water – Impact Driver at 75 meters	181	168	NA
Bent 5 top north – 2nd part 6/30/2006	Water – Impact Driver at 10 meters	195	183	173
	Water – Impact Driver at 20 meters	191	180	168
	Water – Impact Driver at 45 meters	194	182	171
	Water – Impact Driver at 75 meters	180	169	NA
Bent 5 top north – 3rd part 6/30/2006	Water – Impact Driver at 10 meters	188	177	165
	Water – Impact Driver at 20 meters	189	176	164
	Water – Impact Driver at 45 meters	194	182	162
	Water – Impact Driver at 75 meters	179	166	NA
Bent 5 top south – 1st part 6/30/2006	Water – Impact Driver at 10 meters	205	193	183
	Water – Impact Driver at 20 meters	202	189	180
	Water – Impact Driver at 40 meters	195	183	174
	Water – Impact Driver at 65 meters	186	174	NA
Bent 5 top south – 2nd part 6/30/2006	Water – Impact Driver at 10 meters	193	181	170
	Water – Impact Driver at 20 meters	198	186	175
	Water – Impact Driver at 40 meters	194	182	170
	Water – Impact Driver at 65 meters	182	169	NA
Bent 5 top south – 3rd part 6/30/2006	Water – Impact Driver at 10 meters	190	179	167
	Water – Impact Driver at 20 meters	191	180	167

	Water – Impact Driver at 40 meters	194	182	170
	Water – Impact Driver at 65 meters	182	170	NA

The sound levels at each position varied up to 15 dB over time, especially measurements closest to the pile. The variation of sound levels over time was similar to the Bent 4 pile. However, Bent 5 sound levels were higher. The rate of sound attenuation varied considerably over time. It is thought that as the pile was driven deeper, there was more dampening. Therefore, resulting in lower noise levels close to the pile. Positions close to the pile became shielded from noise generated from ground vibration at the pile tip, which becomes deeper with each pile strike. Peak sound pressures were over 200 dB for the first part of pile driving at 10 meters for the first pile and 10 and 20 meters for the south pile. The south pile resulted in louder sound pressures initially. Both piles had similar levels near the end of the drive. The sound drop off was essentially 0 dB from 10 to 20 meters and varied from about +5 to –5 dB from 20 to 40 meters. The drop off measured for distances beyond 40 meters was considerable, about 10 dB from 40 to 75 meters.

Both Bent 5 piles were driven through a dewatered casing. The north pile had lower levels than the south pile. Pile driving was stopped during the initial portion of driving the south pile due to high sound levels. The casing was further dewatered so that the water level was well below the river water bottom. When pile driving resumed, sound pressures were lower. Since levels were lower at all sites including the 75-meter position, the decrease in sound levels cannot be solely attributable to the further dewatering of the casing. At the end of the pile driving event, sound levels were highest at 40 meters, while levels at 10 and 20 meters were similar. Sound pressures at 65 meters were more than 10 dB lower than 10 and 20 meter levels and 15 dB lower than the 40-meter levels.

This project included extensive analyses of the recorded signals from each measurements position for most of the pile driving events. Only a few examples are shown in Figures I.3-23 through I.3-25. The examples show how the signal at 20 meters from the Bent 5 south pile became further dampened as the pile was driven further into the ground. Note the relatively high frequency content of the signal during the initial part of the drive. It is thought that the saturated gravel riverbed below the river aids in the more efficient propagation of the signal during the initial portion of the pile driving. As the pile is driven further into the ground below the river, the signal is attenuated.

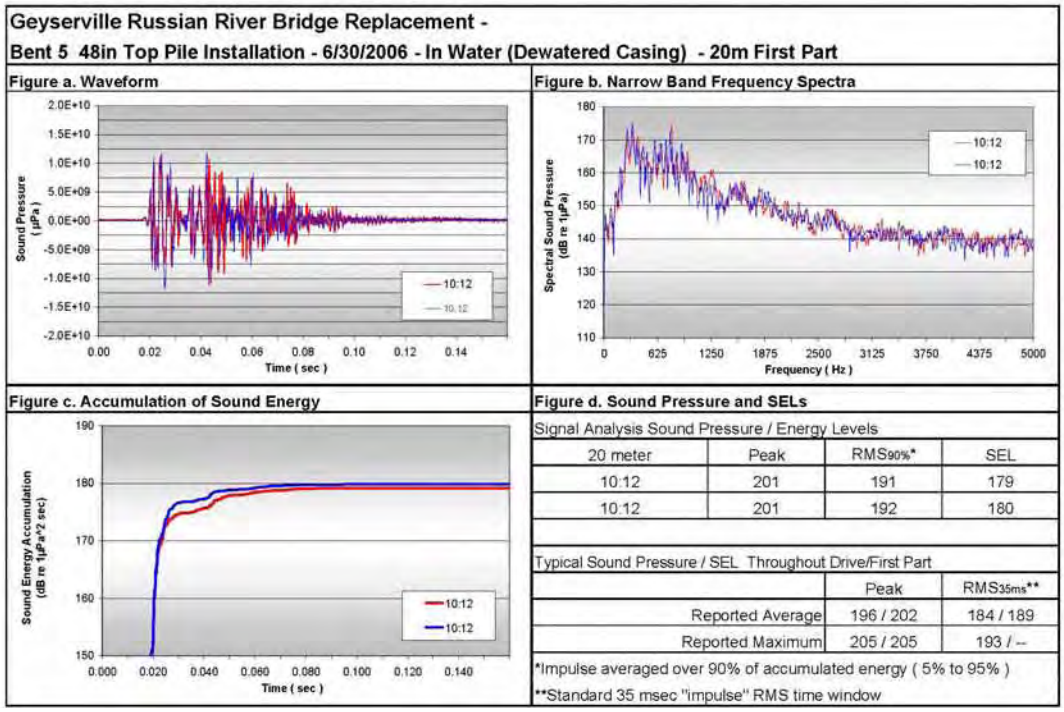

Figure I.3-23 Representative signal analysis for 48-in. piles driven 20 meters away through dewatered casing in 2 meters of water – beginning portion of drive at the Russian River

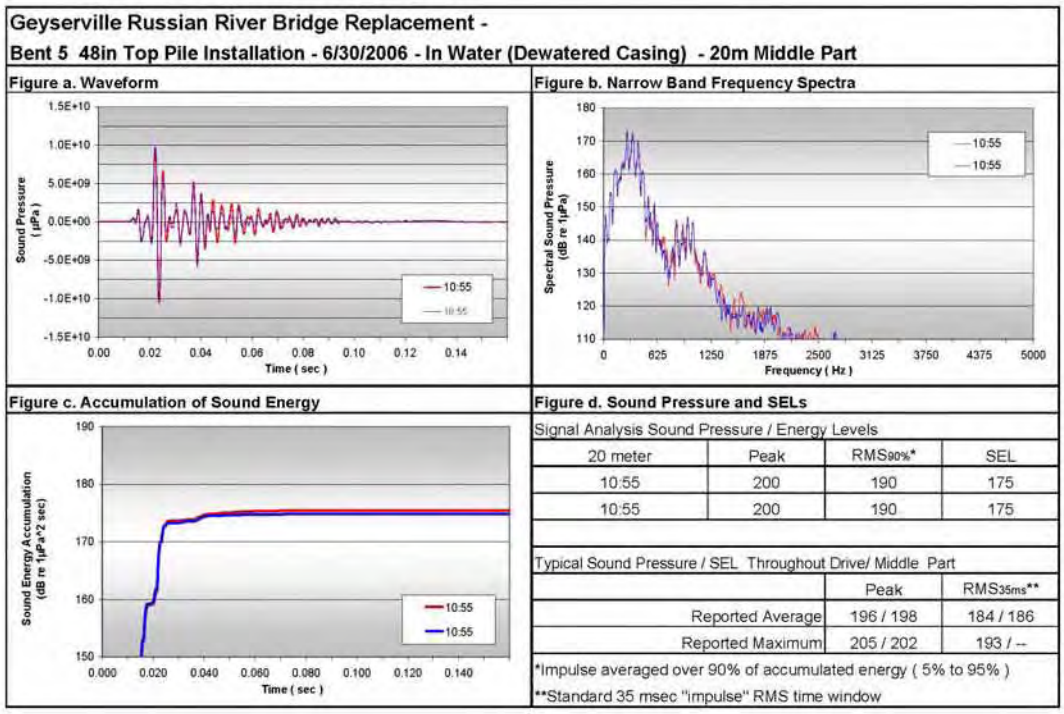

Figure I.3-24 Same as previous, except middle portion of 48-in pile drive at the Geyserville Bridge, Russian River

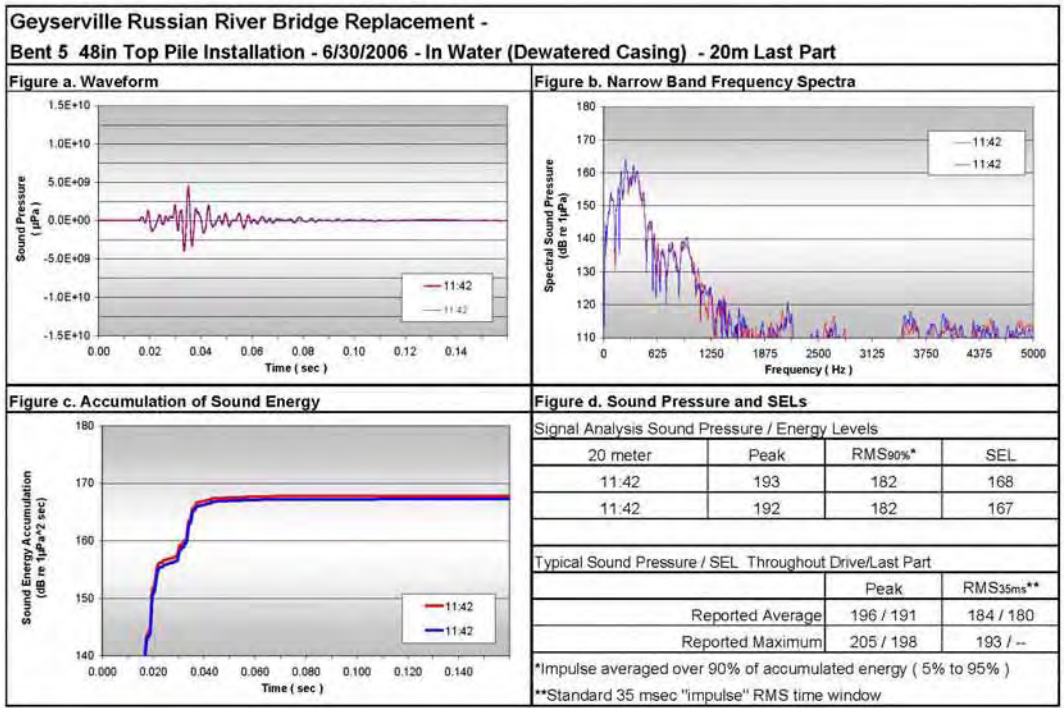

Figure I.3-25 Same as previous, except middle portion of 48-in pile drive at the Geyserville Bridge, Russian River

I.3.10 40-inch Piles, Bay Ship and Yacht Dock, Alameda, CA

Measurements were made for about twenty 1-meter (40-inch) steel shell piles driven at the Bay Ship & Yacht Co. dock in Alameda, California (San Francisco Bay)[11]. These piles were driven in June 2006. Bay Ship and Yacht Co. is in the estuarine waters of San Francisco Bay across from the Port of Oakland. These waters are routinely dredged to allow the passage of large ships. The pile were driven in 10- to 15-meter deep (about 40 feet) water using an air bubble curtain system. A Del Mag D-80 impact hammer was used to drive the piles. This hammer has a rated energy of about 300 kilo joules . Figures I.3-26a and I.3-26b shows the pile driving operation and air bubble curtain system used to attenuate underwater sound.

Figure I.3-106a Driving 40-inch piles with air bubble curtain in Alameda, CA

Figure I.3-26b Air bubble curtain used at Bay Ship and Yacht, Alameda, CA

Table I.3-17 summarizes the sound levels measured for the twenty different 40-inch piles. Two 30-inch piles were also driven. All piles were driven with the air bubble curtain system. The effectiveness of the system at reducing underwater sound was tested briefly on two piles (i.e., piles 5 and 14).

Table I.3-16 Summary of Sound Pressures Measured for the Driving of 40-inch Steel Piles, in Water at Bay Ship and Yacht Co. – Alameda, CA

Pile No.s and Date	Conditions*	Sound Pressure Levels in dB		
		Peak	RMS	SEL
Piles 1-4, 6/19/2006	Water – Impact Driver at 10 meters	201	186	175
	Typical Max. Levels	205	188	NA
Piles 5, 6/19/2006	Water – Impact Driver at 10 meters			
	Attenuated (air bubble curtain)	194	180	170
	Unattenuated	208	195	180
Piles 6, 6/20/2006	Water – Impact Driver at 10 meters	193	178	NA
	Typical Max. Levels	200	182	NA
Piles 7&8**, 6/20/2006	Water – Impact Driver at 10 meters	198	185	175
	Typical Max. Levels	202	187	NA
Piles 9-12, 6/21/2006	Water – Impact Driver at 10 meters	195	182	NA
	Typical Max. Levels	205	188	NA
Piles 13, 15,16, 6/22/2006	Water – Impact Driver at 10 meters	200	185	NA
	Typical Max. Levels	207	190	NA
Piles 14, 6/19/2006	Water – Impact Driver at 10 meters			
	Air bubble curtain lowered	198	187	170
	Air bubble curtain raised	208	195	180
Piles 17 + restrikes, 6/28/2006	Water – Impact Driver at 10 meters	199	184	NA
	Typical Max. Levels	204	189	NA
Piles 18-22, 6/29/2006	Water – Impact Driver at 10 meters	200	187	NA
	Typical Max. Levels	207	190	NA

* All piles were attenuated with the air bubble curtain system except for a brief test during Pile 5.
** 30-inch diameter piles.

The data presented are a combination of unattenuated, partially attenuated, and fully attenuated conditions. Complications with the air bubble curtain were caused by mechanical connections with the frame connected to the hammer. Pile driving usually began with the air bubble curtain system slightly raised above the bottom. The system would be slowly lowered as the pile was driven further into the ground. As a result, sound pressures were usually loudest at the beginning of the pile driving period. Figure I.3-27 shows a typical variation in peak and RMS levels over a driving period (i.e., pile 13).

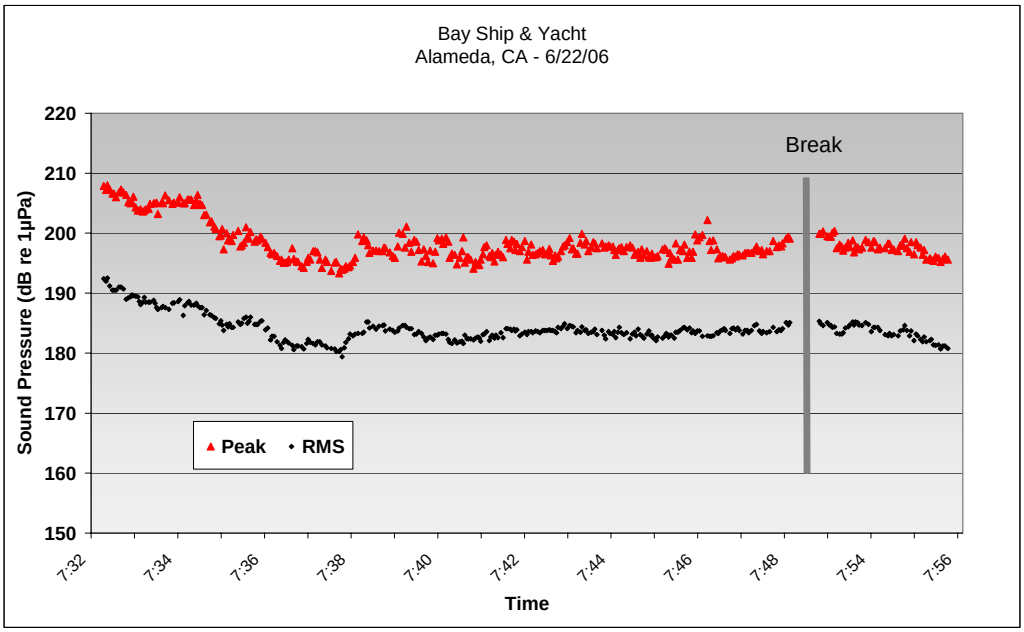

Figure I.3-117 Time history of pile driving event for pile #13 where levels are highest when air bubble curtain system is raised slightly above the bottom - Alameda, CA

When the air bubble curtain system was operating properly (or properly situated), peak sound pressures were about 195 to 200 dB and RMS sound pressure levels were about 180 to 185 dB. SEL levels were about 170 to 173 dB. Tests on the air bubble curtain system indicate that unattenuated peak pressures were up to 210 dB, RMS sound pressure levels about 195 dB and SEL levels around 180 dB. On and off tests of the air bubble curtain system indicated that about 10 to 15 dB of attenuation was provided.

Signal analyses were preformed on some of the pulses recorded. Figure I.3-28 shows signals analyzed during the air bubble curtain on/off tests for pile number 5. The signal analyses illustrate the benefits of the air bubble curtain system, which not only show the lower sound levels across much of the frequency spectra, but also a lower rate of accumulated sound energy.

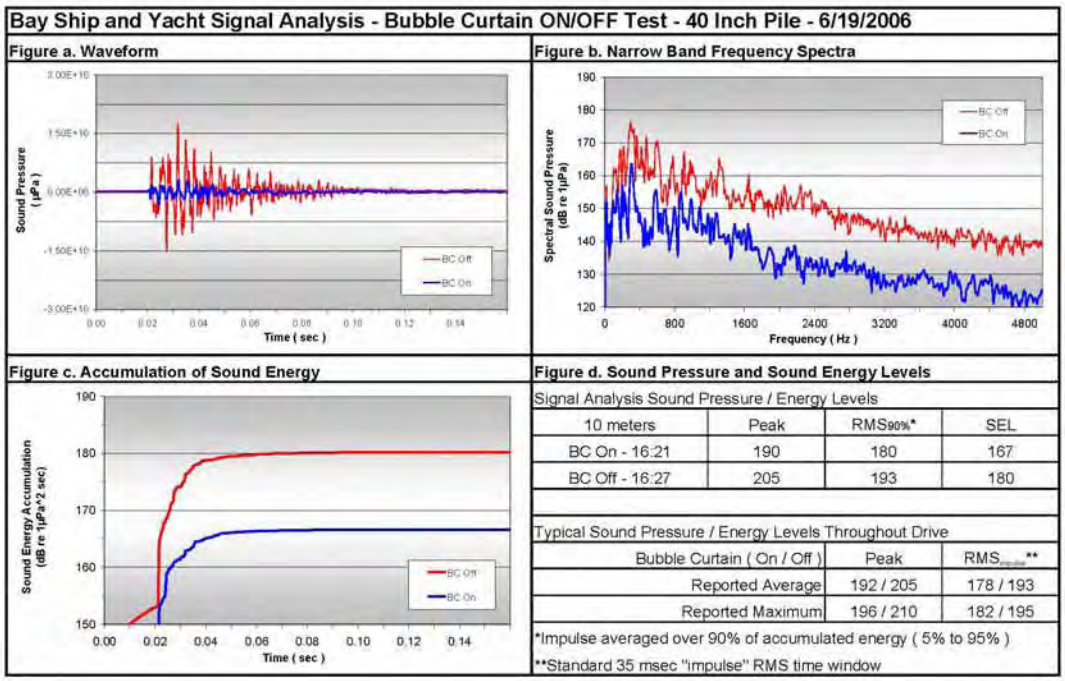

Figure I.3-28 Representative signal analysis for 40-in. piles during test of air bubble curtain system (on and off) at Bay Ship and Yacht – Alameda, CA

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11. Illingworth & Rodkin, Inc. 2006. *Letter to Bill Cooke (Manson Construction Co.) reporting results of underwater sound measurements – Impact Driving of 40 & 30-Inch Steel Piles*. August 14.

I.4 Steel H-Type Piles

This chapter describes results for projects that involved the installation of steel H-type piles. Typically, there is little information known about the hammer or driving energies used to install these piles. Most of these projects were small and some only involved the measurements when one or two piles were driven. One project used an air bubble curtain attenuation system, two projects involved piles driven on shore next to the water. Where available, measurement results for vibratory pile installation are included.

I.4.1 12-Inch Steel H-Type Piles – Noyo River Bridge Replacement, Fort Bragg

Temporary H piles were driven on shore adjacent to water and in water to support a temporary construction trestle. This trestle was constructed as part of the Noyo River Bridge Replacement project in Fort Bragg, CA[1]. The bridge lies along the Pacific Coast at the mouth of the river. Fishing fleets and recreational boats frequently use the narrow channel under the bridge. Water depths vary based on tides, but are usually 1-2 meters (3 to 6 feet) outside the channel and 3 to 5 meters (10 to 15 feet) within the navigational channel. Underwater sound monitoring was conducted for the sole purpose of identifying safety zones for marine mammals (seals) that inhabit the area. Figures I.4-1a and I.4-1b shows typical H-pile installation in water and on land during construction of the temporary trestle.

Figure I.4-1a Impact driving of on-shore H-pile piles

Figure I.4-1b Impact driving of in-water H-pile piles

Measurements were made across the main channel of the harbor at positions ranging from 23m to 85m from the piles driven in very shallow water or on land. The piles driven in the deepest water were battered (i.e., driven at an angle) and driven adjacent to the navigation channel. For this reason, close-in measurements were not possible due to boat traffic and safety concerns. Measurements for in-water pile driving near the navigation channel were made at positions of 70 and 90 meters from the piles. The piles were driven with a small diesel powered impact hammer. Sound measurement results are summarized in Table I.4-1.

Table I.4-1 Summary of Sound Pressures Measured for the Driving of Steel H-type Piles for the Noyo River Bridge – Fort Bragg, CA

Pile	Conditions and Position	Sound Pressure Measured		
		Peak	RMS	SEL
Land	Next to water – 23m	174	159	--
	Next to water – 37m	169	158	--
	Next to water – 94m	157	145	--
Water	Shallow water – 30m	179	165	--
	Shallow water – 56m	178	164	--
	Shallow water – 85m	165	149	--
Water	Deeper water (Channel) – 70m	168	156	--
	Deeper water (Channel) – 90m	170	158	--

Underwater levels varied with distance and direction. Sound levels were 0 to 10 dB higher for piles driven in the water, when compared to those driven on shore near the water. Analyses of the acoustical signals were not analyzed as part of this project, and therefore, SEL levels are not available. Pile driving durations varied from 4 to 7 minutes. These piles were driven with a diesel impact hammer that struck the piles about once every 1.5 seconds.

I.4.2 10-Inch H-Type Piles for Sea Wall Construction, San Rafael, California

Six 10-inch (0.3m) wide H piles were driven on two separate days in April 2003 at the Seagate Property project site in San Rafael[2,3]. The purpose of the project was to construct a new sea wall. The first H-pile was driven using an impact hammer. Since peak sound pressures exceeded 180 dB, a vibratory hammer was used to install the remainder of the piles. Piles were installed into mud next to the existing sea wall. The water depth was about 2 meters where the piles were installed during measurements. The hydrophone was positioned at about 1 meter depth. Measurements were made primarily at 10 meters from the pile with supplementary measurements at 20 meters.

Underwater sound measurements results are summarized in Table I.4-2. At 10 meters during impact hammering, the average peak sound pressure was 185 dB, but most strikes were about 190 dB and some were light taps at around 180 dB. The typical RMS levels were 175 dB. Underwater sound pressures at 20 meters were over 10 dB lower, indicating the signals at 10 meters were comprised of relatively high frequency sound (i.e., above 500 Hz). Analyses of the acoustic signals were not performed, so frequency spectra and SEL data were not available. The duration of driving for each pile was short, approximately 30 seconds. An underwater noise attenuation system was not employed on this project.

Table I.4-2 Summary of Sound Pressures Measured for the Driving of 10-inch H Piles – San Rafael, CA

Pile	Conditions	Sound Pressure Measured		
		Peak	RMS	SEL
1	Unattenuated – Impact Hammer at 10m	190	175	
	Unattenuated – Impact Hammer at 20m	170	160	
2 – 6	Unattenuated – Vibratory Hammer at 10m	161	147	--
	Unattenuated – Vibratory Hammer at 20m	152	137	--

I.4.3 15 Inch Steel H Piles - Breakwater Construction at Ballena Bay, Alameda

Several steel H-piles were driven in open water at the Ballena Isle Marina in Alameda, California[4]. A total of eight field trips were made from February through early April, 2005 to measure the underwater sound from these piles. Extensive measurements were conducted since peak sound pressures could not be maintained below 180 dB. The purpose of the project was to construct a sea wall to replace the existing sea wall. Pile installation was performed using a diesel powered impact hammer. Two types of piles were driven: ~15 inch thin walled H-piles that were battered and ~15 inch thick walled H-piles that were driven vertically. Water depth was about 2-3 meters. Measurements were made at 10 meters and 1 meter deep or above the bottom for water deeper than 2 meters. An attenuation system was used to reduce underwater sound pressure levels. The attenuation system consisted of a thick plastic tube with air bubbles between the tube and pile. The tube usually settled into the bottom mud, making a good seal that contained the bubbles. Pictures of the pile driving and attenuation system are shown in Figures I.4-2a and I.4-2b.

Figure I.4-2a Impact driving of battered H-pile with attenuation system with vertical thin-walled H piles in foreground

Figure I.4-2b Close-view of confined air bubble attenuation system next to vertical H pile.

Results of underwater sound measurements are summarized in Table I.4-3. Measurements varied. The effectiveness of the system to reduce sound pressure levels was tested for a brief time period by turning the air delivery off during the driving of a vertical pile. Supplemental measurements for short time periods were made at 20 and 40 meters to provide an indication of the sound attenuation with distance.

Table I.4-3 Summary of Sound Pressures Measured for the Driving of 15-inch Steel H Piles – Ballena Isle Marina

Pile	Conditions	Sound Pressure Levels		
		Peak	RMS	SEL
Battered Air BC OFF	Unattenuated Test – Impact Hammer at 10 meters	187	164	154
Battered Air BC ON	Attenuated Test – Impact Hammer at 10 meters	174	160	151
Battered – Typical	Attenuated – Impact Hammer at 10 meters	180	165	155
Vertical – Typical	Attenuated – Impact Hammer at 10 meters	194	177	170
Vertical – Spot	Attenuated – Impact Hammer at 20 meters	190	175	N/A
Vertical – Spot	Attenuated – Impact Hammer at 40 meters	180	166	N/A
Vertical – Spot	Attenuated – Impact Hammer at 40 meters	175	160	N/A

Battered Thin H Piles

At 10 meters, and with no attenuation system, average peak sound pressures were 187 dB with a maximum peak of 199 dB. Average RMS sound pressures were 164 dB, with a maximum of 182 dB. The typical SEL was 154 dB. The attenuation system was tested on the very first day for a short period of time. The system appeared to reduce peak sound pressures by over 10 dB; however, RMS or SEL levels were not affected much with the system (about 2 to 3 dB of attenuation). Twenty different battered thin H piles with the attenuation system working were measured. The levels reported in Table I.4-4 are the typical highest levels measured. However, average peak, RMS and SEL levels for each driving event varied by about 5 dB. It appears that the peak pressure was caused by high frequency sound emanating off of the pile that was effectively reduced by the attenuation system. However, much of the sound energy that comprises the RMS and SEL was lower frequency sound that was not really affected by the attenuation system. The duration of driving for each pile varied considerably, from 3 minutes to 20 minutes. The piles were driven with a diesel impact hammer that struck the

Vertical Thick-Walled H Piles

At 10 meters typical peak sound pressures were 195 dB for the thick walled vertical H piles. Maximum levels for each drive ranged from 198 to 202 dB. Typical RMS sound pressures were 180 dB, with maximum levels for each drive ranging from 180 to 183 dB. Typical SEL levels were 168 dB, with a maximum of 174 dB on the very first drive. The attenuation system was turned off temporarily during one drive, but sound levels remained consistent. Otherwise, no vertical piles were driven without the attenuation system in place. Lower hammer energy was used during two piles and found to reduce sound pressures by about 5 dB; however, little progress was made installing the pile. The duration of driving for each pile was about 10 minutes with the pile struck once every 1.4 to 1.5 seconds.

Signal Analysis

Sounds from pile driving were analyzed to measure the frequency content and SEL. The analyses of sounds from representative pile strikes are shown in Figure I.4-3 for a battered thin walled pile and Figure I.4-4 for a vertical thick walled pile. Note that H piles have higher frequency content than steel pipe or

steel shell piles. The thin walled piles had higher frequency content than the thick-walled piles, with substantial energy above 1,000 Hz. The attenuation system reduced much of the sound above 1,000 Hz for the thin walled piles, but did not have much affect for the thick walled piles. The piles were driven in shallow water (mostly 2-meter depth) that likely compromised the effectiveness of the attenuation system.

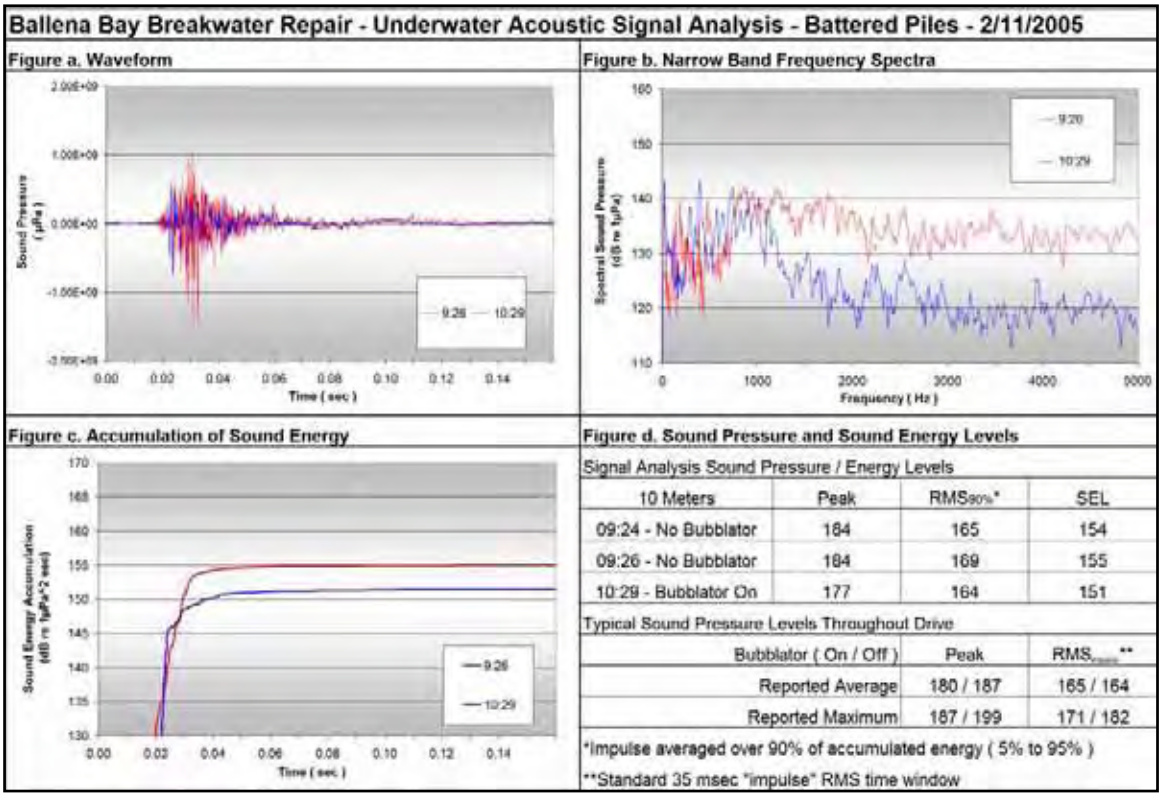

Figure I.4-3 Representative signal analysis for battered H Piles with and without the air bubble curtain attenuation system at Ballena Bay in Alameda, CA

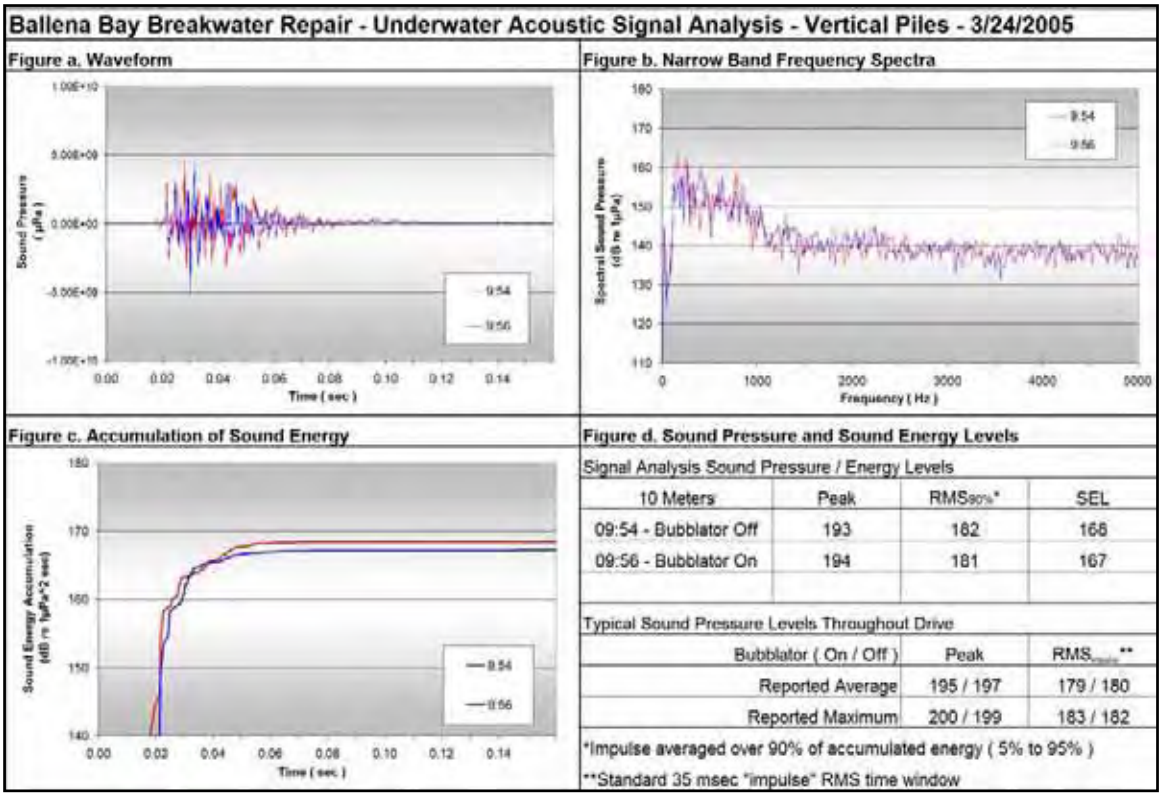

Figure I.4-4 Representative signal analysis for vertical H piles with and without the air bubble curtain attenuation system at Ballena Bay in Alameda, CA

I.4.4 Thick-Walled Steel H Piles- Interstate 80 Platte River Bridge Pile Driving

The driving of three permanent steel thick-walled "H" piles was measured in December 2005 as part of the Platte River Bridges construction project at Interstate 80 in Nebraska[5]. Piles were driven with a diesel-powered impact hammer in a dewatered cofferdam adjacent to a river channel. Water depth in the area was very shallow, ranging from less than 0.5 to 2 meters. The Platte River is wide, but shallow. The cofferdam next to the river was excavated to a depth of about 3 meters below the river bottom. In other words, piles were driven below the river. Figures I.4-5a and I.4-5b shows the pictures of the cofferdam and pile driving operation.

Figure I.4-5a H Pile driving at the Platte River in Nebraska.

Figure I.4-5b Dewatered cofferdam excavated below water level

Underwater sound measurements were made at 10 and 20 meters during the driving of the three different piles (see Table I.4-4). The average peak pressure at 10 meters was 172 dB and the highest was 180 dB. Average and maximum RMS levels were 160 and 168 dB respectively. The representative SEL was 147 dB. Higher sound pressures were measured further from the pile at about 20 to 25 meters, where the average peak sound pressures were 177 dB with a maximum of about 185 dB. Average and maximum RMS levels were 163 and 174 dB respectively. The representative SEL was 148 dB. Pile driving durations were 7 to 9 minutes and the hammer struck each pile about once every 1.4 seconds.

Table I.4-4 Summary of Sound Pressures Measured for the Driving of Steel H Piles – Platte River Bridge

Pile	Conditions	Sound Pressure Levels		
		Peak	RMS	SEL
1 – 3	Dewatered Cofferdam – Impact Hammer at 10 m	172	160	147
2 & 3	Dewatered Cofferdam – Impact Hammer at 25 m	177	164	148

The probable cause for measured levels to be higher at 25m from the pile than 10m is shielding from the excavated cofferdam. The 10-meter position was much closer to the excavated cofferdam than the 25-m position. The cofferdam was excavated to a level several meters below the river bottom. Therefore, direct transmission to the 10-meter position was somewhat shielded by that air space in the cofferdam.

Signal analyses of the representative pulses (see Figure I.4-6) indicated highly attenuated signals that contain primarily low frequency energy (i.e., below 1,200 Hz). This was expected since the piles were driven through a dewatered cofferdam with no direct contact with the water.

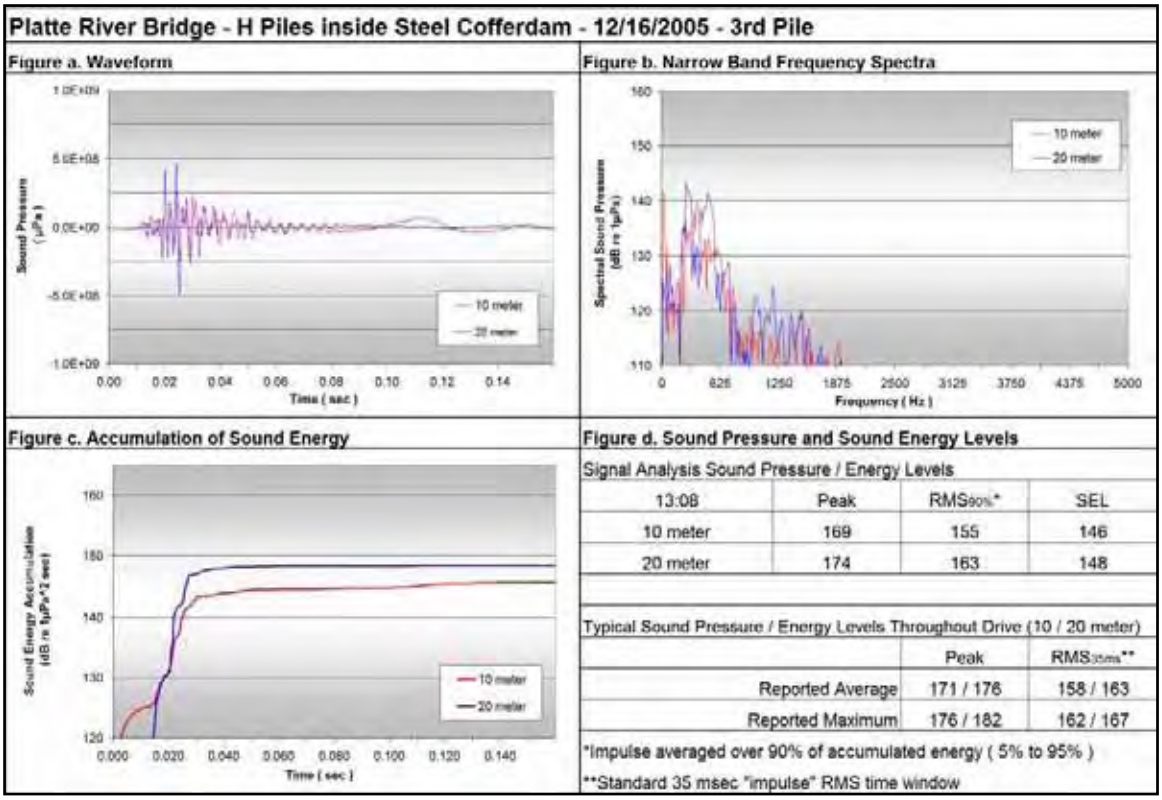

Figure I.4-6 Representative signal analysis for H piles driven in the Platte River, Nebraska

References

1. Illingworth & Rodkin, Inc. 2003. Underwater Sound Levels Associated with Pile Driving Activities Associated with Construction of the Noyo Bridge. Report to Caltrans dated March 18 and revised April 9, 2003.

2. Illingworth & Rodkin, Inc. 2003. *Letter to Justin Baxter (Jeff Luchetti Construction) reporting Underwater Sound Measurement Results for Seagate Property, San Rafael Canal Construction Pile Driving*. April 4, 2003.

3. Illingworth & Rodkin, Inc. 2003. *Letter to Justin Baxter (Jeff Luchetti Construction) reporting Underwater Sound Measurement Results for Seagate Property, San Rafael Canal Construction Pile Driving*. April 9, 2003.

4. Illingworth & Rodkin, Inc. 2005. *Letter to Bill Chase (Ballena Isle Marina) reporting Results of Underwater Sound Measurements for H-Type Piles at Ballena Isle Marina Breakwater Repair* May 13, 2005.
5. Illingworth & Rodkin, Inc. 2006. Results of Underwater Sound Measurements for the Driving of "H" Piles – Interstate 80 Platte River Bridges. Prepared for the Nebraska Department of Roads. March 24.

I.5 Concrete Piles

This chapter describes results for projects that involved the installation of concrete piles. All concrete pile installation is conducted using diesel impact hammers with wood cushion blocks that prevent damage to the pile caused by contact with the hammer. These cushions, which fit into the "helmet" of the pile driver assembly, substantially reduce the amount of energy delivered to the pile. Concrete piles have blunt tips and are usually about 0.3 to 0.6 meters (12-inch to 24-inch) in cross-sectional width. Most common, are the 0.6-meter (24-inch) octagonal piles used for wharf construction at port faculties. Some projects used pile jetting during a short portion of the drive, where high-pressure water is sprayed out the bottom of the pile to help penetrate dense sand layers. Sound pressures associated with concrete piles are much lower than comparable sized steel piles. Most of the projects described in this section involved measurements made 10 meters from the pile. Many projects used an air bubble curtain attenuation system, and one project involved pile driving at the shoreline that resulted in the highest measured sound levels.

I.5.1 16-Inch Square Concrete Piles, Concord Naval Weapons Station, California

Underwater sound levels associated with impact pile driving of concrete piles at the Concord Naval Weapons Station Pier 2 were measured in December 2002. This project involved the driving of 16-inch square, 25-meter or 80-foot long concrete piles. A Vulcan 016 (65 kilo joule or 48,000 ft.-lb.) steam-powered drop hammer was used to drive the first two piles (Piles 108 and 107). A Conmaco 200 (80 kilo joule or 60,000 ft.-lb.) steam drop hammer was used to drive the last three piles (Piles 103, 105, 106). The piles were driven vertically in approximately 7 meters (23 feet) of water immediately adjacent to the existing pier. The piles were driven to a depth of 10 meters (depth varied) below mud line. Underwater sound measurements for each pile were made at approximately 10 meters (33 feet) from the pile at a depth of 3 meters (10 feet) below the water line. The water depth was approximately 7 meters (24 feet). Only peak pressures and RMS sound pressure levels were measured. Analysis of the signals was performed to acquire narrow band sound frequency information (12 Hz bandwidth). Figure I.5-1a shows the pile driving operation while Figure I.5-1b shows the simple air bubble curtain used for the project.

Underwater sound measurement results are summarized in Table I.5-1. Measurements made during the driving of Piles 108, 107, and 103 yielded peak pressure levels of 176 to 186 dB and RMS sound pressure levels of 165 to 173 dB. The driving using the Vulcan 016 generated slightly lower sound levels, but the driving periods were longer.

Figure I.5-1a. Driving of 16-in square piles

Figure I.5-1b. Simple air bubble curtain system used to attenuate noise

Permit conditions for the project require the use of an air bubble curtain system since peak unattenuated sound pressures exceeded 170 dB. A simple air bubble curtain system was employed for the fourth and fifth piles (see Figure I.5-1b). This air bubble curtain system attenuated sound pressures by approximately 5 to 8 dB during the driving of Pile 105 at 10:00am when there was a slack tide so currents were light. There was considerable variability in sound pressures with each strike when the air bubble curtain system was operating. The reduction associated with the air bubble curtain was less for Pile 106, about 0 to 4 dB. Observations at the surface confirm that tidal current was affecting the bubble curtain so that bubbles were not completely enveloping the pile. This was probably the cause for the reduced attenuation on Pile 106.

Table I.5-1 Summary of Sound Pressures Measured for the Driving of Square Concrete Piles – Concord Naval Weapons Station

Pile	Condition/Hammer	Sound Pressure Levels Measured at 10 Meters		
		Peak	RMS	SEL
108	Unattenuated – Vulcan 016	182	167	--
107	Unattenuated – Vulcan 016	182	168	--
103	Unattenuated – Conmaco 200	184	172	--
105	Unconfined Air Bubble Curtain – Conmaco 200	178	168	--
105	Unattenuated Curtain OFF– Conmaco 200	184	173	--
106	Unconfined Air Bubble Curtain – Conmaco 200	182	170	--
106	Unattenuated Curtain OFF– Conmaco 200	182	170	--

Pressure over time analysis of the signals revealed complex characteristics of the pulses that were recorded (Figure I.5-2). The waveform indicated that the pulse lasted about 80 to 100 milliseconds. The initial portion of the waveform was represented by low frequency sound, followed by a higher frequency sound during the second half of the pulse duration. This was evident in the frequency spectra that showed low frequency sound at about 200 Hz and then increased sound amplitude between 1,000 and 3,000 Hz (Figure I.5-3). The air bubble curtain effectiveness, which was variable, attenuated the signal for frequencies mainly above 500 Hz.

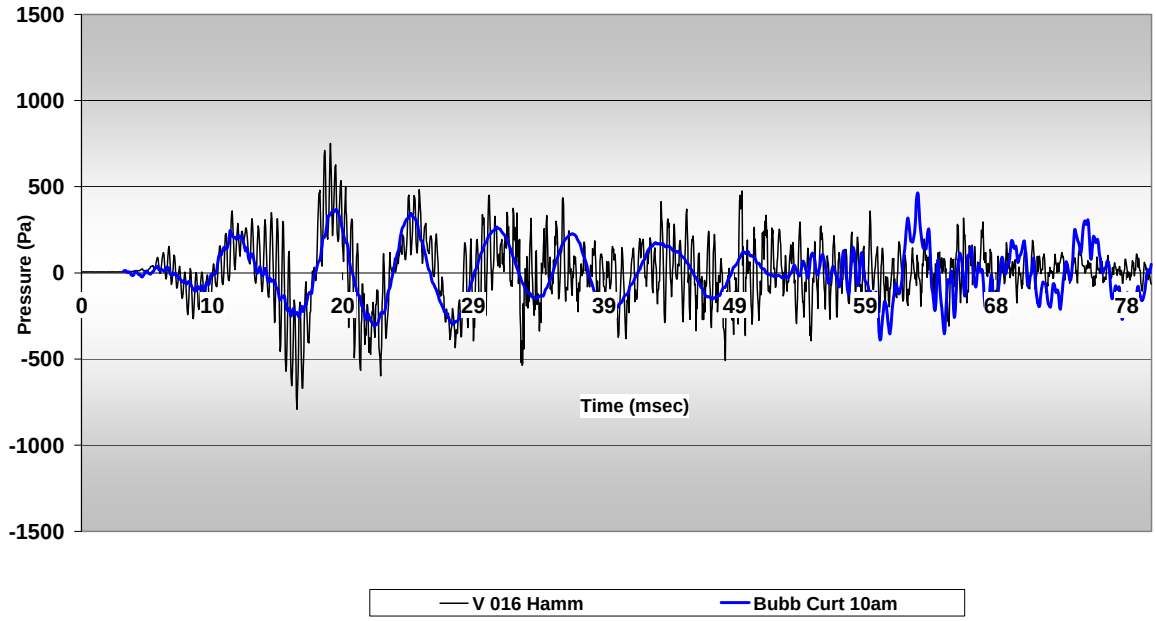

Figure I.5-2 Time history analysis of unattenuated and attenuated pile strikes over an 8-millisecond time period. Note initial low frequency sounds followed by lower amplitude, but higher frequency sounds. Air bubble curtain reduced the high frequency content of these pulses.

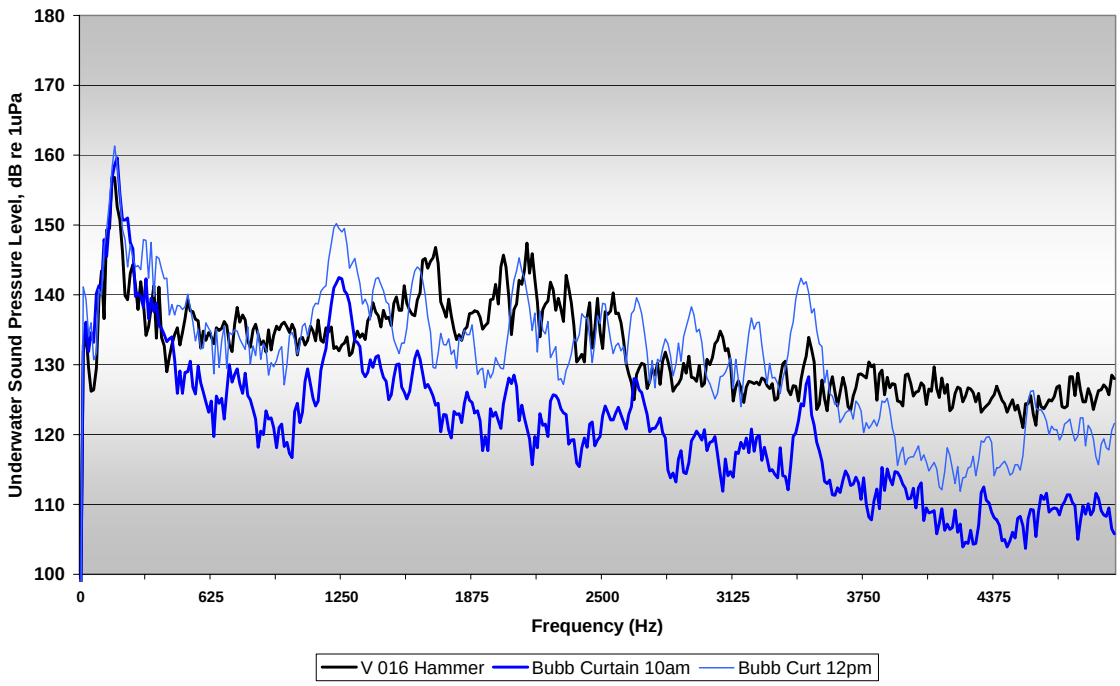

Figure I.5-3 Narrow band frequency spectra for pile driving with different hammers and bubble curtain conditions. Note the Bubble curtain at 10:00am was most effective when there was no effect from swift currents due to a slack tide condition.

I.5.2 24-Inch Octagonal Concrete Piles, Amports Pier 95, Benicia, California

Underwater sound levels were measured at Benicia, California on February 27, March12, and March 19, 2003. The project involved the driving of 24-inch octagonal 125-foot long concrete piles. The piles were driven vertically using a Del-Mag D66-22 diesel. The hammer set on maximum fuel setting the delivered a maximum impact energy of 220 kilo joules (165,000 ft.-lbs). During the March 12 sound tests, the hammer was set on a lower fuel setting and delivered impact energy of about 50% maximum energy. The piles are located in rows parallel to the shore designated A-H. The monitoring was completed for piles in rows B and C. The piles located in row C were generally in shallower water than in row B due to the slope of the bottom. Water depth at the piles was typically 3 to 7 meters and water depth at measurement locations ranged from 4 to 13 meters. Piles were driven to a depth of approximately 25 to 30 meters (90 feet), below mud line. Measurements were made at approximately 3 meters below the water line and at a distance of 10 meters from the pile. Additional measurements at 20 meters were made for selected piles. Tidal currents could be quite strong at times, exceeding 1 meter per second (2 knots). Most of the piles were driven using a confined air bubble curtain (CABC), or "bubbleator". The CABC consisted of a long plastic tube with air supplied to the bottom of the column with PVC pipe. Figure I.5-4a shows a typical pile driven while Figure I.5-4b shows the confined air bubble curtain system or "bubbleator" used for the project.

Figure I.5-4a. 24-in octagonal piles driven at Amports in Benicia, CA

Figure I.5-4b. "Bubbleator" used to attenuate underwater sound

Table I.5-2 summarizes the measurements made during the testing of the air bubble attenuation system for this project. Measurements were made at 10 meters for all piles, with supplemental measurements at 20 meters for some piles. Typical driving periods were 15 to 20 minutes, where the pile was struck about once every 1.4 seconds.

Table I.5-2 Summary of Sound Pressures Measured for the Driving of Octagonal Concrete Piles – Amports, Benicia

Date	Condition	Sound Pressure Levels in dB		
		Peak	RMS	SEL
Feb 27	Unattenuated – No CABC - 10 meters	183 typ. 192 max	170 typ. 172 max	--
Feb 28	Attenuated – Row C with short CABC On - 10 meters	165 typ. 175 max	152 typ. 162 max	--
Feb 28	Unattenuated – Same as above, but CABC Off	185	170	--
Mar 12	Attenuated – Row C with short CABC On - 10 meters	~185	~172	--
Mar 12	Attenuated – Row C with short CABC On - 20 meters	~179	~168	--
Mar 12	Unattenuated – Row C with short CABC On - 10 meters	~192	~176	--
Mar 12	Unattenuated – Row C with short CABC On - 20 meters	~186	~171	--
Mar 19	Attenuated – Row B with long CABC ON – 10 meters	172 typ. 181 max	157 typ. 167 max	--
Mar 19	Attenuated – Row B with long CABC ON - 20 meters	170 typ. 178 max	155 typ. 162 max	--
Mar 19	Attenuated – Row C with long CABC ON – 10 meters	162 typ. 167 max	145 typ. 150 max	--
Mar 19	Attenuated – Row C with long CABC ON - 20 meters	157 typ. 159 max	145 typ. 148 max	--

Unattenuated Pile Strikes

Concrete piles driven unattenuated were measured at two 10-meter locations on February 27 to establish unattenuated conditions. Levels were similar at each of the positions. Peak sound pressures were typically 180 to 183 dB. During a brief period of the drive (about 1 minute), peak pressures were 192 dB. RMS levels typically ranged from 168 to 170 dB, but rose to 172 dB during that short louder period of the drive. Additional unattenuated data were collected for short period of subsequent drives where the attenuation system was turned on and off for testing. Measurements were also made at 20 meters from the pile, which indicated about 5 dB lower levels than at 10 meters for both peak and RMS levels.

Attenuated Pile Strikes

Extensive testing of a confined air bubble curtain system was conducted on three different days. Measurements were made at 10 meters with supplemental measurements at 20 meters. The system was turned off near the end of some drives to test the effectiveness. Original designs were found to be adequate for the piles driven in shallower waters. In these cases, the attenuation system was found to reduce sound pressures by 15 to 20 dB. Piles driven in the deeper water were not attenuated adequately, because the attenuation system was too short. Improvements that included lengthening the system and providing resilient pile guides to the inside were found to be adequate in reducing noise for both the deeper and shallower piles. This study did find that the top of the attenuator had to be extended 1.5 meters (5 feet) above the water surface. The attenuator performance was substantially compromised when water could be drawn through the system. Lower hammer energies were tested, but not found to have much effect on the sound levels.

Sound pressures were attenuated by 20 to 30 dB when the system was operating as planned and the top of the attenuator was at least 1.5 meters above the water surface. Peak sound pressures were reduced below 170 dB at 10 and 20 meters, while RMS levels were reduced below 150 dB. The system was not as effective in deeper water, where water infiltration into the system could not be adequately controlled. Under these conditions, peak and RMS sound levels could only be reduced 10 to 15 dB. The drop off rate for attenuated pile strikes from 10 to 20 meters was about 2 to 5 dB for both peak and RMS sound pressures.

I.5.3 Concrete Piles - ~24-Inch Diameter Pier 40 Marina Construction, San Francisco, California

Eight square concrete piles, about 24 inches wide, were driven in July, 2004, at Pier 40 in San Francisco, California. The purpose of the project was to expand the existing marina. Piles where driven with a diesel impact hammer. The hammer setting was varied in order to meet regulatory criteria. Water jetting was also used to ease driving through dense sand layers and allow pile driving with lower hammer impact energies. Figure I.5-5 shows a driven square concrete pile.

Figure I.5-5. 24-in square piles at Pier 40, San Francisco, CA

Primary measurements were made at 10 meters from the pile, and some supplementary measurements were made at 20 meters for selected piles. Measurements are summarized in Table I.5-3. The water depth at the project site ranged from 2.5 to 4 meters, and hydrophone depth ranged from 1.5 to 3 meters accordingly. Drive durations varied from a few minutes to about 40 minutes. A difference in the substrate and hammer energy used was the cause for the variation in drive time. With the hammer set on a higher fuel setting, average and maximum sound levels at 10 meters were 185 and 190 dB peak and 172 and 177 dB RMS respectively. At 20 meters, sound pressure levels were about 3 to 5 dB lower. On the lowest fuel setting, average and maximum sound levels at 10 meters were 175 and 178 dB peak and 162 and 165 dB RMS respectively. At 20 meters, sound levels were about 10 dB lower. During the driving of the last pile, jetting was turned off to assess the effect on underwater noise. At 10 meters, with no jetting, average and maximum sound levels were 185 and 192 dB peak and 172 and 180 dB RMS respectively. Analysis of the signals was not conducted to obtain frequency spectra, waveforms and SELs.

These measurements found that peak sound pressures were generally about 185 dB with the hammer fuel setting at “High” and with no pile jetting. Highest peak sound pressures were almost 190 dB. Lowering the fuel setting and continuously using jetting resulted in lower sound pressures. Measurements made at 10 m from the pile in different directions were quite similar, indicating little variation in the radiation pattern near the pile. Sound pressures measured at 20m from the pile ranged from about 5 to over 10 dB lower than the 10m measurements. The least amount of attenuation occurred when the piles were driven at the highest fuel setting without any jetting.

Table I.5-3 Summary of Sound Pressures Measured for the Driving of Square Concrete Piles – Pier 40, San Francisco

Pile #,	Condition/Hammer	Sound Pressure Measured at 10 Meters		
		Peak	RMS	SEL
P-SS-30	Unattenuated – Hammer on High Fuel Setting	184	171	--
P-SS-26	Unattenuated – Hammer on High Fuel Setting	183	170	--
P-SS-28	Unattenuated – Hammer on High Fuel Setting	186	174	--
P-SS-29	Unattenuated – Measured 10m west	180	167	--
“ “	Unattenuated – Measured 10m east	180	167	--
P-SS-31	Unattenuated – Hammer on unknown Fuel Setting	183	170	--
P-NS-25	Unattenuated – Hammer on unknown Fuel Setting	183	169	--
P-NS-24	Unattenuated – Hammer on Lowest Fuel Setting with jetting	172	158	--
P-NS-25	Unattenuated – Hammer on Lowest Fuel Setting with jetting	175	162	--
“ “	Unattenuated – Hammer on Lowest Fuel Setting No jetting	186	173	--

I.5.4 24-inch Octagonal Concrete Piles - Berth 22, Port of Oakland

Several 24-inch octagonal concrete piles were driven at the Port of Oakland in August of 2004 and December of 2004[1]. The purpose of the project was to reconstruct Berth 22 at the Port of Oakland. Piles were driven with a Del Mag D-62-22, that has a maximum energy per blow of about 224 Kilojoules. Indicator piles were driven unattenuated during August 2004 when a fish in cage study was performed[2]. Figure I.5-6 shows pile driving of indicator piles at Berth 22. An attenuation system was used for production pile driving. Initially, this system was turned off many times to assess the acoustical performance. Measurements were mostly made at 10 meters from the pile and 3 meters deep. More distant measurements were made for selected piles. Water depth varied from 0 to 15 meters, based on the pile location. Piles were driven in five rows, where the first row was onshore and the outer row was in about 15m of water. Row A was in the deepest water, and Row E was at the shore. Typical duration of driving time per pile was about 15 to 30 minutes.

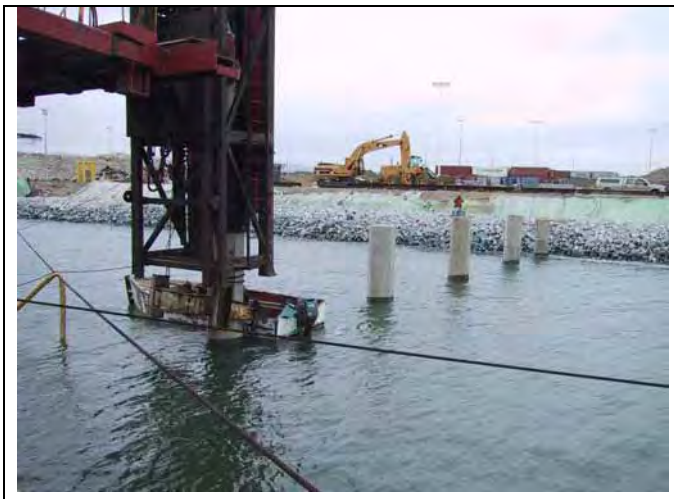

Figure I.5-6. Driving of 24-in octagonal indicator piles at Port of Oakland Berth 22. Pile being driven is in row A, while Row E is at the shoreline.

The August 2004 measurements were made during installation of indicator piles. The measurements were made as part of a fish in cage study. Results of that study are reported separately[2]. Illingworth & Rodkin, Inc. reported sound pressure measurements from that study along with other Berth 22 measurements.

An air bubble curtain system was used to reduce sound pressures. This system seemed to be the most effective in the deep water and not very effective in shallow water. In fact, a pile driven on shore next to the water resulted in the highest sound pressure levels. This was obviously an effect of the substrates that the pile was driven through.

Unattenuated Pile Driving

In Row A, the average sound levels at 10 meters were 187 dB peak, 176 dB RMS and 166 dB SEL. Peak sound levels reached 189 to 191 dB for a short period of the driving events. In Row B, sound levels were generally slightly lower than Row A levels. In Row C the average and maximum sound levels were even lower than Row A or B levels. In Row D, which was closest, the average and maximum sound levels were 191 and 193 dB peak and 179 and 181 dB RMS. In Row E the average and maximum sound levels were 190 and 196 dB peak and 178 and 186 dB RMS.

Attenuated Pile Driving

In Row A at 10 meters the average and maximum sound levels were 181 and 186 dB peak and 168 and 173 dB RMS. In Row B the average and maximum sound levels were 179 and 184 dB peak and 168 and 173 dB RMS. In Row C the average and maximum sound levels were 181 and 185 dB peak and 169 and 171 dB RMS. In Row D the average and maximum sound levels were 189 and 195 dB peak and 177 and 182 dB RMS. Row E piles were driven on land a few feet from the water's edge, thus no attenuation system was used and no attenuated data for these piles exists.

Table I.5-4 Summary of Sound Pressures Measured for the Driving of Octagonal Concrete Piles – Berth 22, Port of Oakland

Pile #	Condition/Hammer	Sound Pressure Measured at 10 Meters		
		Peak	RMS	SEL
Row A	Unattenuated	187	176	166
Row A	Attenuated	181	168	160
Row B	Unattenuated	185	174	162
Row B	Attenuated	179	168	158
Row C	Unattenuated	183	171	162
Row C	Attenuated	181	169	158
Row D	Unattenuated	191	179	167
Row D	Attenuated	189	177	168
Row E	On land adjacent to water (i.e., Attenuated)	190	178	172

Figure I.5-7 shows the signal analysis for two unattenuated pile strikes measured at 10 meters from the pile. These were typical of signals measured at 10 meters, although some higher frequency sounds occasionally resulted in higher peak sound pressures.

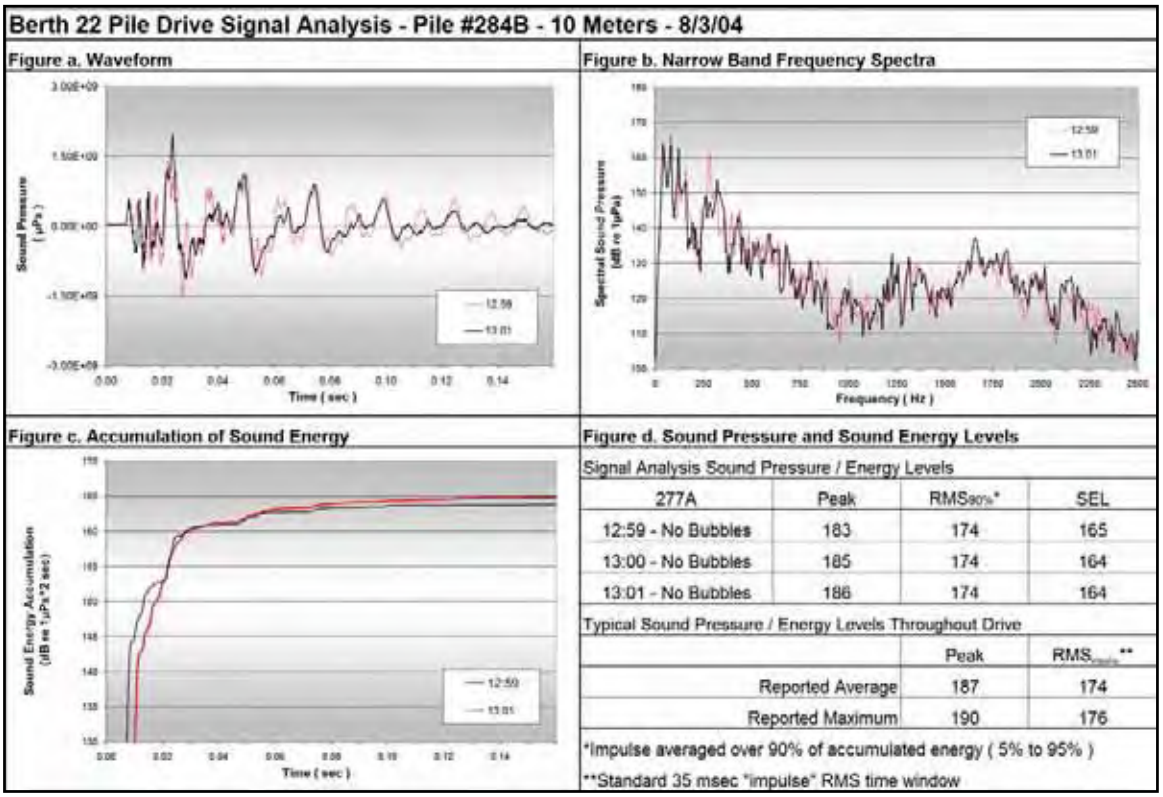

Figure I.5-7 Representative signal analysis for two pulses associated with a 24-inch concrete pile. Piles driven without attenuation system at Berth 22, Port of Oakland, CA during fish exposure study.

Pile driving at Row E resulted in the highest sound levels measured for concrete pile driving. Interestingly, these piles were driven at the shoreline, mostly on land. However, there was an engineered steep bank along the shore. In addition, these piles were driven through dense sandy layers without the use of jetting. A land-based pile driver was used to drive these shorter piles. Although these levels were higher, the driving times were about 10 minutes, as opposed to 30 to almost 40 minutes for the in-water piles. Sounds from this activity were measured at varying distances during the driving of four piles. At 10 meters, peak pressures ranged from about 185 to 195 dB, while RMS levels ranged from 175 to 185 dB. SEL levels were about 165 to 174 dB. Sound levels dropped off at about 5 dB from 10 to 20 meters. At 50 meters, levels were about 180 dB peak and 170 dB RMS. The signal analysis presented in Figure I.5-8 shows the relatively low frequency sound associated with this pulse. One pulse represents the lower amplitude sounds at the beginning of the drive and the other represents the loudest measured pulses near the end of the driving. Much of the substantial sound content was within the frequency range of 20 to 250 Hz.

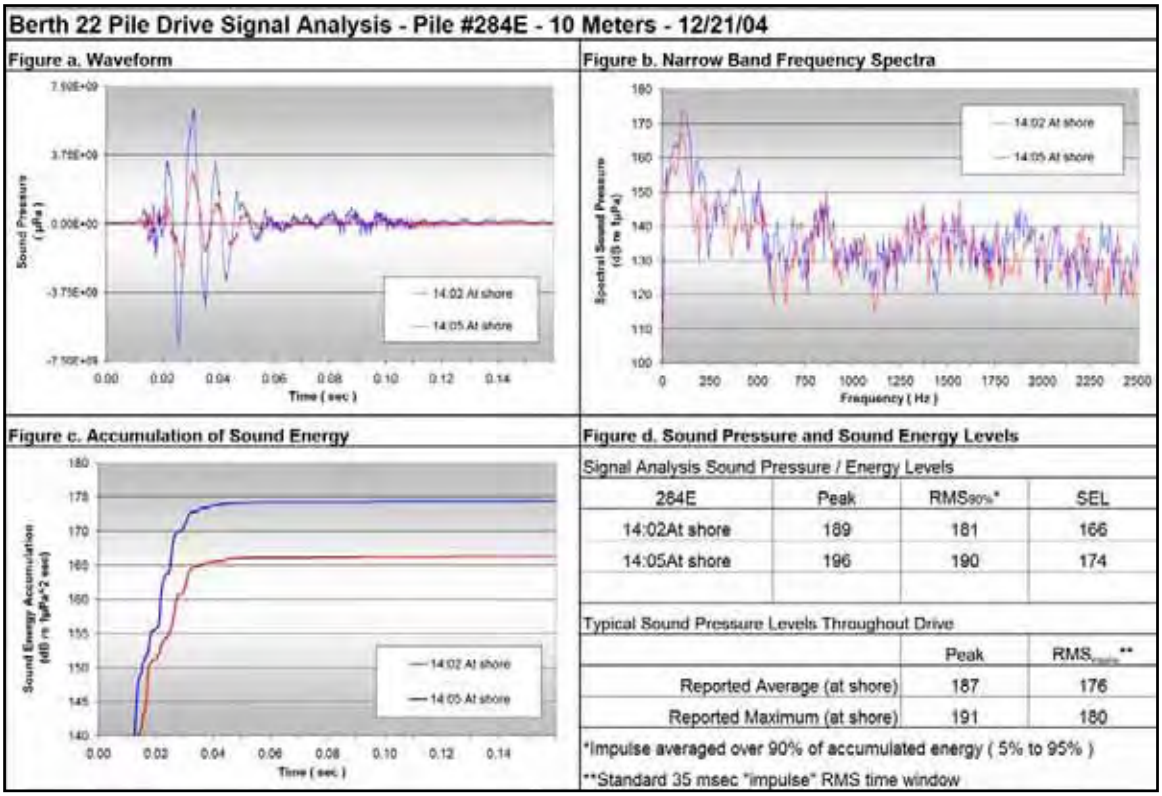

Figure I.5-8 Representative signal analysis for two pulses associated with a 24-inch concrete pile driven at the shoreline at Berth 22, Port of Oakland, CA.

I.5.6 24 inch octagonal Concrete Piles - Berth 22, Port of Oakland, Underwater Noise Monitoring during Fish Cage Study

As discussed previously, a fish cage study was conducted during the unattenuated driving of concrete indicator piles at Berth 22 at the Port of Oakland. Hydrophones were placed inside and outside of each fish cage. In addition, measurements were made at 100 meters from the pile in two different directions. Figure I.5-9 shows the deployment of a fish cage at 10 meters from the pile during pile driving of a Row A pile. The photograph was taken near the 100-meter hydrophone position. Piles for this study were driven at Row A (13 meters deep) and Row B (10 meters deep). Hydrophones and fish cages were placed at a depth of 8 meters. Fish were not exposed for the entire driving period, since exposure periods were held constant for each driving event tested.

Figure I.5-9 Pile driving during fish exposure study at the Berth 22, Port of Oakland. Picture taken 100 meters west of pile driving activity, while fish were being exposed at 10 meters from the pile.

Results of the measured sound levels are presented in Table I.5-5. These are the average levels measured during the loudest part of each pile-driving event. Usually pile driving began with lower levels and increased during the first minute of the driving event. Maximum peak sound pressures were about 190 dB, while maximum RMS levels were 178 dB and SEL levels were 168 dB.

Table I.5-5 Summary of Sound Pressures Measured for the Driving of Octagonal Concrete Piles – Berth 22, Port of Oakland

Pile #	Condition/Hammer	Sound Pressure Measured at 10 Meters		
		Peak	RMS	SEL
277B	Unattenuated Fish Cage – 10 meters	188	176	--
277B	Unattenuated – 100 meters SW	170	158	--
277B	Unattenuated – 100 meters NW	175	162	--
277A	Unattenuated Fish Cage – 10 meters	187	174	165
277A	Unattenuated – 100 meters SW	167	156	146
284B	Unattenuated Fish Cage – 10 meters	186	175	164
284B	Unattenuated – 100 meters SW	174	163	152
284A	Unattenuated Fish Cage – 10 meters	188	176	166
284A	Unattenuated – 100 meters SW	174	162	152

I.5.7 24 inch octagonal Concrete Piles - Berth 32, Port of Oakland, Underwater Noise Monitoring

Five 24-inch octagonal concrete piles were driven at Berth 32 at the Port of Oakland in one day in September 2004. The purpose of the project was to strengthen the existing berth. A Del Mag D-62 diesel impact hammer was used to drive the octagonal reinforced concrete piles (see Figure I.5-10). The hammer energy was approximately 224 kilo joules of energy on each blow. Attenuation systems were not used during these measurements.

Figure I.5-10. Driving of 24-in octagonal piles at Port of Oakland Berth 32.

The piles were driven in water that was over 10 meters deep, and were measured at a distance of 10 meters, at 3 meters deep. The sound pressure data summarized in Table I.5-6 indicates fairly repeatable sound pressure levels for the five different piles measured. For typical pile strikes, peak sound pressures were 185 dB with a range of 181 to 189 dB. RMS sound pressure levels were about 173 dB with a range of about 170 to 180 dB. Analyses of pile strike pulses indicate SELs of about 161 to 163 dB. The typical range in sound pressures over the course of a pile-driving event was 3 to 5 dB. The results of these measurements were consistent with data collected for other unattenuated 24-inch concrete piles.

Table I.5-6 Summary of Sound Pressures Measured for the Driving of Octagonal Concrete Piles – Berth 32, Port of Oakland

Pile #	Condition/Hammer	Sound Pressure Measured at 10 Meters		
		Peak	RMS	SEL
1	Diesel Hammer – unattenuated	185	173	162
2	Diesel Hammer – unattenuated	185	173	163
3	Diesel Hammer – unattenuated	184	174	161
4	Diesel Hammer – unattenuated	185	173	163
5	Diesel Hammer – unattenuated	185	173	161

Signal analyses for two pile strikes during the third pile are shown in Figure I.5-11. These sounds are typically characterized by low frequency sound content of about 20 to 500 Hz.

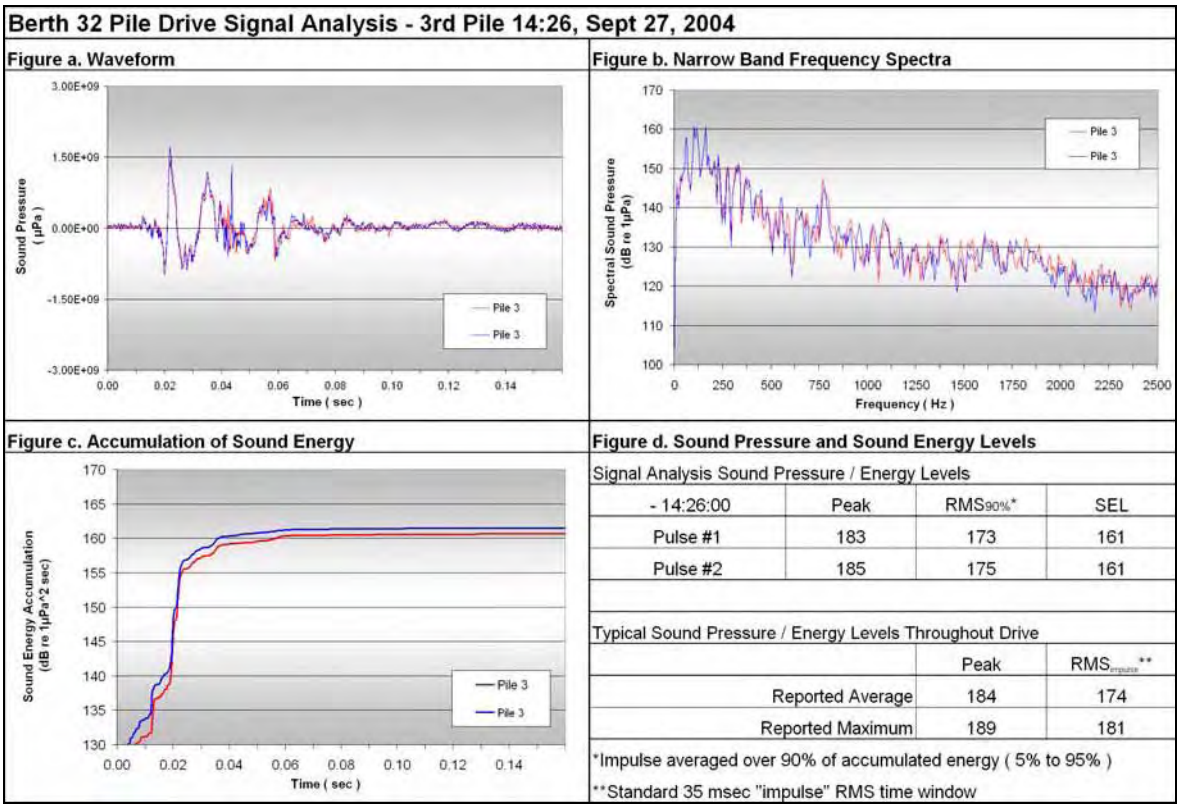

Figure I.5-11 Representative signal analysis for two pulses associated with a 24-inch concrete pile. Piles driven without attenuation system at Berth 32, Port of Oakland, CA

I.5.8 24 inch Octagonal Concrete Piles - Berth 32 Port of Oakland

Additional underwater sound measurements for five octagonal reinforced concrete piles were conducted at Pier 32 at the Port of Oakland in April 2005. The Del Mag D-62 diesel impact hammer was also used to drive these five piles. Measurements were made at 10 meters from the pile and at a depth of 3 meters from the water surface. An air bubble curtain system was deployed for the driving events, but was turned off for brief periods to assess its performance in reducing underwater sound pressures. Pile driving activities with the air bubble curtain system operating are shown in Figure I.5-12.

Figure I.5-12. Driving of 24-in octagonal piles at Port of Oakland Berth 32 with an air bubble curtain system to attenuated sounds.

Results from the driving of five piles are summarized in Table I.5-7. Testing of the air bubble curtain systems occurred during driving of the first and fourth piles. In general, the peak sound pressure levels with the sound attenuation system in operation ranged from 177 to 180 dB. The associated RMS sound pressure levels ranged from 166 to 170 dB and the SEL levels ranged from 154 to 160 dB. Unattenuated levels varied with peak pressures of about 185 to 187 dB, RMS levels of 163 to 172 dB and SEL levels of 158 to 165 dB. These unattenuated levels were consistent with previous measurements made at Berth 32 and other similar projects. It appears from these measurements that the air bubble curtain system reduced peak pressures by 5 to 10 dB and RMS levels by about 5 dB. SEL levels were reduced by 1 to 5 dB. The performance of the system appeared to vary somewhat, where consistent levels occurred for Piles 1, 2, 3 and 4, but much lower levels for the fifth pile. Analysis of the data indicate that the variation may have been attributable to the air bubble curtain performance.

Table I.5-7 Summary of Sound Pressures Measured for the Driving of Octagonal Concrete Piles – Berth 32, Oakland

Pile #	Condition/Hammer	Sound Pressure Measured at 10 Meters		
		Peak	RMS	SEL
1	Attenuated / Diesel Hammer	178	168	157
1	Unattenuated / Diesel Hammer	187	172	158
2	Attenuated / Diesel Hammer	180	167	157
3	Attenuated / Diesel Hammer	180	167	158
4	Attenuated / Diesel Hammer	180	167	158
4	Unattenuated / Diesel Hammer	185	176	165
5	Attenuated / Diesel Hammer	173	163	153

Signals analyzed for a bubble curtain test are shown in Figure I.5-13. Review of the narrow band frequency spectra indicates that bubble curtain performance varied. The attenuated pulse shown for 11:22 (prior to the air bubble curtain being turned off) indicates substantial attenuation at most frequencies. The greatest reduction was at frequencies above 250 Hz, where up to 20 dB of attenuation occurred. The attenuated pulse at 11:47 showed much less attenuation; however, there was about 10 dB of attenuation at the low frequencies that contain much of the sound content. This analysis indicates that a problem may have occurred with the air bubble curtain system after the system was turned off. Usually air bubble curtains are effective at reducing the higher frequency sounds.

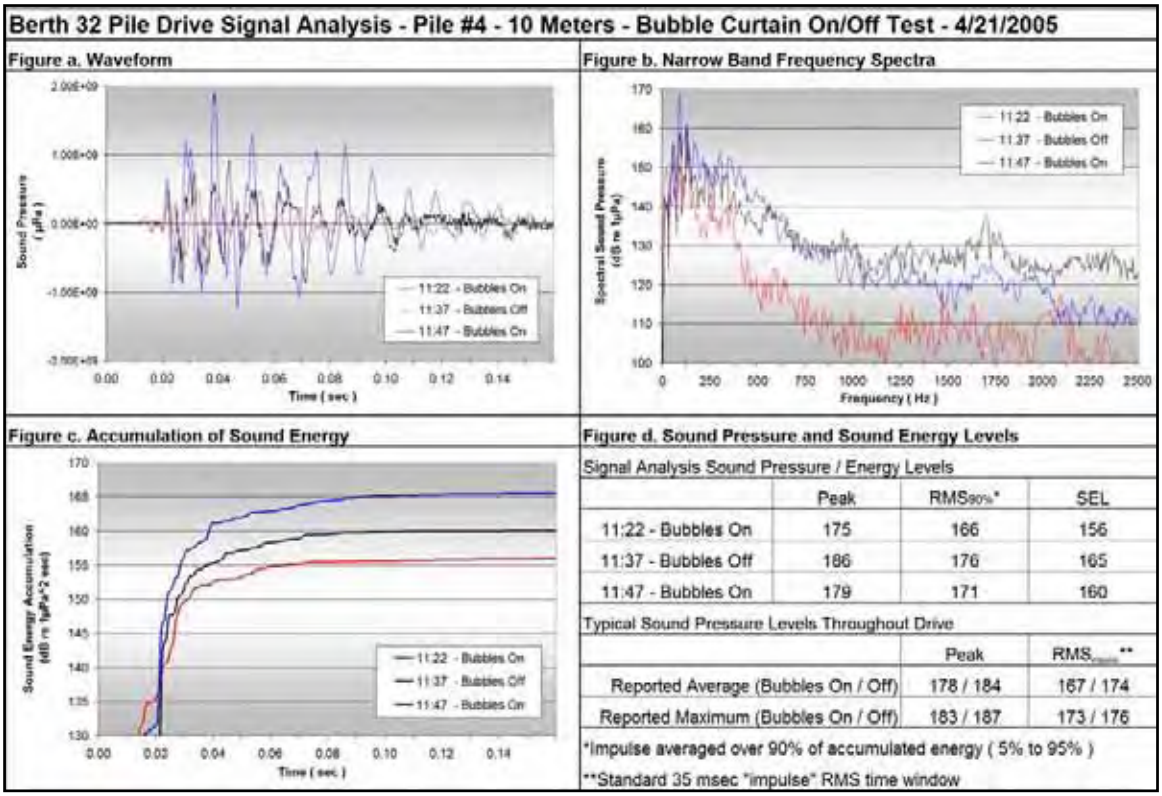

Figure I.5-13 Representative signal analysis for three different pulses associated with a 24-inch concrete pile. Air bubble curtain system was evaluated through on and off settings. Piles driven at Berth 32, Port of Oakland, CA

References

1. Illingworth & Rodkin, Inc. 2003. Structural Repairs to Pier 2 Naval Weapons Station, Concord, California - Report of Underwater Sound Level Measurements Resulting from Pile Driving. Report to Miller Thompson Constructors dated January 17, 2003.
2. Illingworth & Rodkin, Inc. 2003. Reconstruction of Pier 95 (Amports), Port of Benicia – Report of Underwater Sound Level Measurements Resulting from Pile Driving. Report to Manson Construction Company dated April 17, 2003.
3. Illingworth & Rodkin, Inc. 2004. Letter to Steve Hutchinson at Dutra Construction – Subject: *Underwater Sound Measurement Results – Pier 40 Construction Pile Driving (Concrete Piles)*, dated July 13, 2004.
4. Illingworth & Rodkin, Inc. 2004. Port of Oakland Berth 22 Underwater Sound Measurement Data for Pile Driving Activity, August 2-4, 2004. Report to Manson Construction Co. dated August 18, 2004.
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7. Illingworth & Rodkin, Inc. 2004. Letter to Todd Bruce at Dutra Construction – Subject: *Port of Oakland Berth 32 Concrete Pile Installation – Results of Underwater Sound Measurements*, dated October 25, 2004.
8. Illingworth & Rodkin, Inc. 2005. Port of Oakland Berth 32 Underwater Sound Measurement Data for the Driving of Octagonal Concrete Piles, April 18 & 21, 2005. Report to Manson Construction Company dated June 10, 2005.

I.6 Steel Sheet Piles

Sheet piles are usually interlocking steel "AZ" type piles that are about 2 feet or 0.6 meters wide and range in length. They are commonly used to construct walls and cofferdams in marine environments. These piles are usually installed using a vibratory driver/extractor. At the Port Of Oakland, long steel sheet piles were installed in relatively deep water using an impact hammer with a steel extension or follower. This chapter describes results for the few projects that involved the installation of steel sheet piles. Typically, there is little information known about the hammer or driving energies used to install these piles. These projects did not involve the use of attenuation systems.

I.6.1 Vibratory and Impact Driving of AZ25 Steel Sheet Piles – Berth 23, Port of Oakland

Underwater sound pressure levels were measured during the impact driving of steel sheet piles as part of the Berth 23 construction project at the Port of Oakland[1]. The steel sheet piles were first installed with a King Kong APE 400B vibratory driver/extractor hammer to a level below the waterline. The approximately 15-meter long sheet piles were then driven to their tip elevation with an ICE 60S diesel impact hammer. The tip elevation for the piles was underwater near the mud line, where water depth was about 12 to 14 meters. The impact hammer was fitted with a steel extension to allow the driving of the sheet piles below water (see Figure I.6-1). An underwater camera system was used to align the steel extension of the impact hammer to the sheet piles underwater. Measurements focused on the sounds produced from impact driving of these piles; however, some measurements of vibratory installation were made.

Figure I.6-1 Driving of steel sheet pile underwater using hammer follower

Table I.6-1 summarizes results of underwater the sound measurements made for the driving of 5 piles. These are the average sound pressures measured during the driving event. Levels varied about 5 dB throughout the course of a driving event. These sheet piles were installed in 12 to 15 minutes, with pile strikes about once every 1.4 seconds or 43 to 44 strikes per minute. Measurements were made at distances ranging from 5m to 40m, but primarily at 10m. No underwater sound attenuation systems were used. Ambient levels were measured at 125 dB RMS, well below the levels imparted by the pile driving.

The first sheet pile driven was measured from a boat that was maneuvered to stay about 10m from the pile, but distances varied slightly. Measurements for the second pile were made at several distances as the boat was maneuvered during breaks in the driving. Prior to the completion of driving the 2nd pile, the installation of a sheet pile using a vibratory hammer was measured. These data were reported separately for 10 meters[2], but peak pressures were about 175 to 177 dB at 10m and 166 dB at 20m. Measurements for the 3rd, 4th and 5th piles were made with the boat tied to the dockside so a distance of 10m from the pile could be maintained. In addition to the 10-meter position, a 20-meter position was added for driving of the 4th and 5th piles. These positions were along the sheet pile wall, not normal to the face of the pile as was done for the 1st and 2nd pile driving events. A fairly steady peak pressure of 202-205 dB was measured at the 10-meter position. RMS levels were generally 186 to 188 dB and the SEL was about 175 dB. The 4th pile, driven from 14:20

to 14:33, was measured simultaneously from the dockside at positions of 10 meters and 20 meters. Levels were only about 2 dB lower at 20 meters. The 20-meter position had more variability in levels, where peak pressures varied from 194 dB in the early part of the drive to near 210 dB near the end of the drive. The 10-meter peak pressures varied from about 200 dB to 210 dB. In terms of peak pressure, the 5th driving event had the highest levels but RMS and SEL levels were not much higher than other driving events. Ambient levels were measured at 125 dB RMS (impulse).

Table 1.6-1 Summary of Sound Pressures Measured for the Driving of Steel Sheet Piles for Berth 23, Port of Oakland, CA

Pile	Conditions and Position	Average Sound Pressure Measured in dB		
		Peak	RMS	SEL
1st Pile	10 meters normal to the sheet face	205	189	178
2nd Pile	5 meters normal to the sheet face	209	194	--
	10 meters normal to the sheet face	204	189	178
	20 meters normal to the sheet face	200	185	--
	40 meters normal to the sheet face	188	173	--
Vibratory Installation	10 meters normal to the sheet face	177	163	162
	20 meters normal to the sheet face	166	--	--
3rd Pile	10 meters parallel to the sheet face	203	187	175
4th Pile	10 meters parallel to the sheet face	203	188	178
	20 meters parallel to the sheet face*	205	186	175
5th Pile	10 meters parallel to the sheet face	205	189	179
	20 meters parallel to the sheet face*	202	189	178

*Measurements only made for loudest part of drive

The distance related attenuation of sound varied whether facing the sheet piles or parallel to the sheet wall. When normal, sound pressures dropped off at a rate of about 5 dB per doubling of distance from 5 meters to 20 meters. The rate from 20 meters to 40 meters was over 10 dB. Measurements were only made at 10 meters and 20 meters parallel to the wall. The drop off rate was much less, about 2 dB. Sound was radiated through the adjoining panels, which reduced the drop off rate in these directions parallel to the wall.

Signal analysis of representative pulses indicated considerable high frequency content, when compared to other impact pile driving pulses. The example shown in Figure I.6-2 is for pulses measured at 10 meters and 20 meters during the installation of the 4th sheet pile. The RMS impulse level (measured with the SLM) was similar or slightly lower than the calculated RMS (over 90% of the energy). The SEL was about 25 to 27 dB lower than the peak pressure and 13 dB lower than the RMS level (90%). The majority of sound energy in the pulse was contained within the first 30 to 40 milliseconds (ms), but the pulse lasted over 100 ms. Unlike most impact pile driving, these sounds were relatively broadband, with much of the sound content in the frequency range of 25 to 4,000Hz.

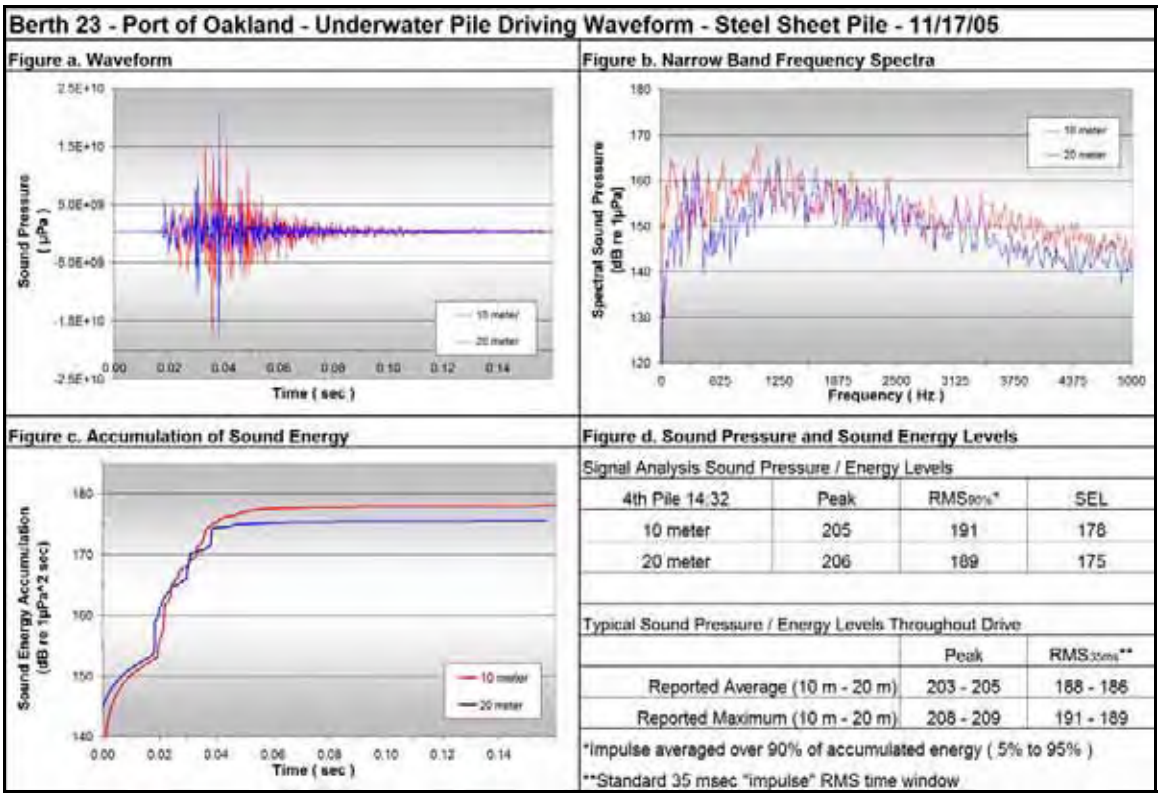

Figure I.6-2 Representative signal analysis for sheet piles driven with impact hammer. Pulses received at 10 and 20 meters parallel to sheet wall. Berth 23, Port of Oakland.

Signals for vibratory installation of a single sheet pile installation were conducted for sounds received at 10 meters (see Figure I.6-3). The vibratory installation involved just the stabbing of the sheet pile. Vibratory installation results in fairly continuous sounds, therefore, they are described slightly differently. An impulse RMS is not applicable, because these sounds are not impulsive. Because the sounds are continuous, the averaging period used to calculate the RMS is not that critical. The difference between a very short period of 0.035 seconds and 1 second was found to result in about 1 dB difference. The SEL is usually associated with an event, such as a pile strike. For vibratory installation, the event is either defined as the entire duration of the sound or a fixed time. Using the duration of the event would not provided data that could be compared to other pile driving events. Therefore, we present the SEL as measured over one continuous second of vibratory pile installation.

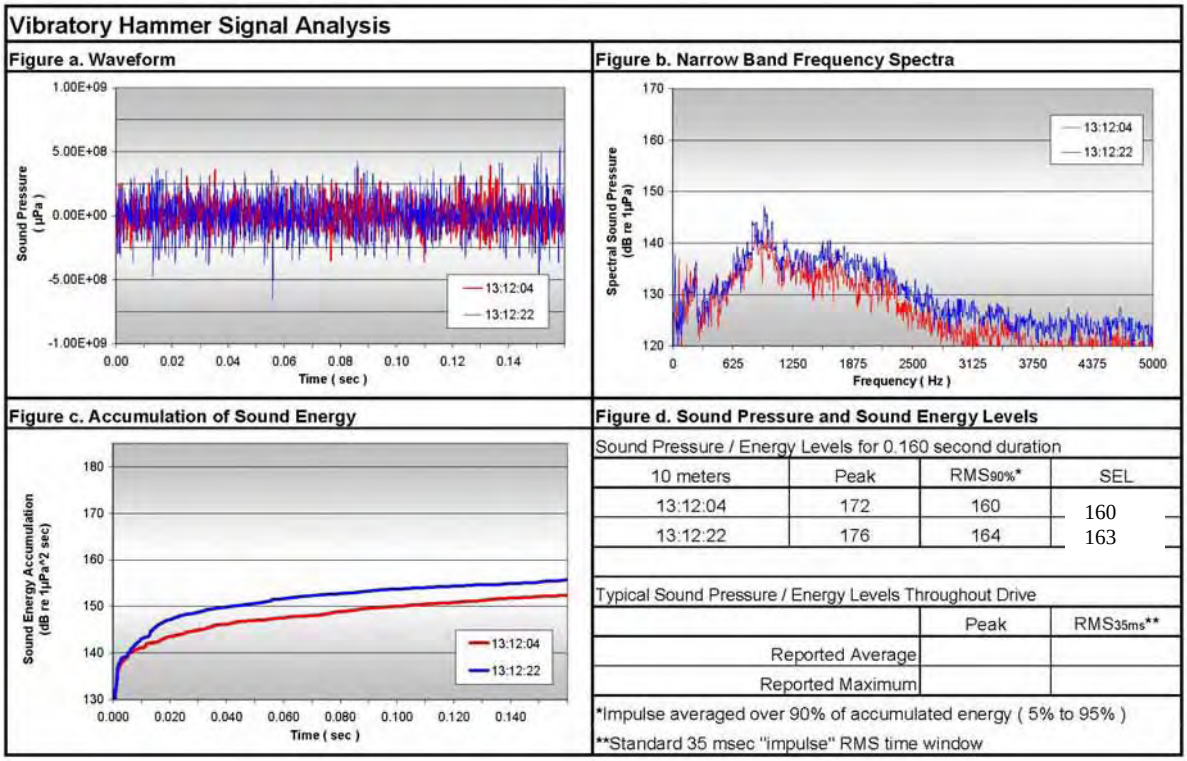

Figure I.6-3 Representative signal analysis for sheet piles installed with vibratory driver/extractor. Pulses at 10 meters normal to sheet wall face. Berth 23, Port of Oakland.

The signal analysis shows the fairly continuous broadband sound. Much of the sound content is contained over the frequency range of 400 to 2,500 Hz. The hammer frequency is 23 Hz; therefore, distinct very low frequency tones are associated with the rapid pile strikes. SEL accumulates throughout this continuous sound event.

I.6.2 Vibratory Installation of AZ25 Steel Sheet Piles – Berth 30, Port of Oakland

Underwater sound levels associated with the installation of steel sheet piles were measured in March 2006 at Berth 30 at the Port of Oakland[3]. This operation was similar to that described above for Berth 23, except a method involving a vibratory driver/extractor to avoid high amplitude sounds was tested. The model APE 400B King Kong hydraulic vibratory hammer was used to drive the steel sheet piles. The hammer was fitted with a steel extension (follower) to allow the driving of the piles below water line. Pile lengths were about 15 meters and water depth was about 12 meters.

Measured sound pressure data for the installation of 5 piles is presented in Table I.6-2. These piles had been stabbed and driven to the point where a follower had to be used. Two measurement systems were used at 10 meters that had different positions and depths. Both systems measured an ambient sound pressure level of 132 dB (RMS) when the nearby workboat motor was running. Levels between the two sensor varied by 0 to 7 dB over the course of the five driving events. The deeper sensor (5-meter depth) measured higher sound levels. The required sensor depth was 3 meters.

Table I.6-2 Summary of Sound Pressures Measured for the Vibratory Driving of Steel Sheet Piles for Berth 30, Port of Oakland, CA

Pile	Conditions and Position	Average Sound Pressure Measured at 10 meters in dB		
		Peak	RMS	SEL
1st Pile	10 meters from face, 3-meter depth	175 185 max	--*	160 165 max
2nd Pile	10 meters from face, 3-meter depth	171	--*	159
	10 meters from face, 5-meter depth	172	--*	160
3rd Pile	10 meters from face, 3-meter depth	166	--*	154
	10 meters from face, 5-meter depth	172	--*	160
4th Pile	10 meters from face, 3-meter depth	167	--*	155
	10 meters from face, 5-meter depth	174	--*	162
5th Pile	10 meters from face, 3-meter depth	169	--*	157
	10 meters from face, 5-meter depth	174	--*	161

*Sound pressure levels were not reported, but would be similar to the SEL for 1 second.

The sound pressure levels for the first driving event varied considerably. Initially, sound pressures were high and then dropped about 10 dB half way through the driving event and continued to decrease further until installation of the pile was complete. Levels near the completion of the driving event were about 20 dB lower than the initial maximum levels. Level associated with the 2nd, 3rd, 4th, and 5th driving events were fairly consistent. Peak pressures were generally in the range of 170 to 180 dB for the deeper hydrophone. Except for the first driving event, peak pressures at the 3-meter depth (NOAA required position) were 165 to 175 dB. One second SELs were typically 12 dB lower than peak pressures, typically ranging from 155 to 162 dB, depending on the pile and sensor position. Pile installation ranged from 5 minutes to 18 minutes. The first 4 piles took 5 to 10 minutes to install, while the 5th pile took 18 minutes.

A representative signal analysis for these pile-driving events is presented in Figure I.6-4. Unlike the signals reported for Berth 23, these showed more tonal characteristics. These characteristics were slightly different for each pile driven. The difference is likely related to the excitement of the interlocked sea wall.

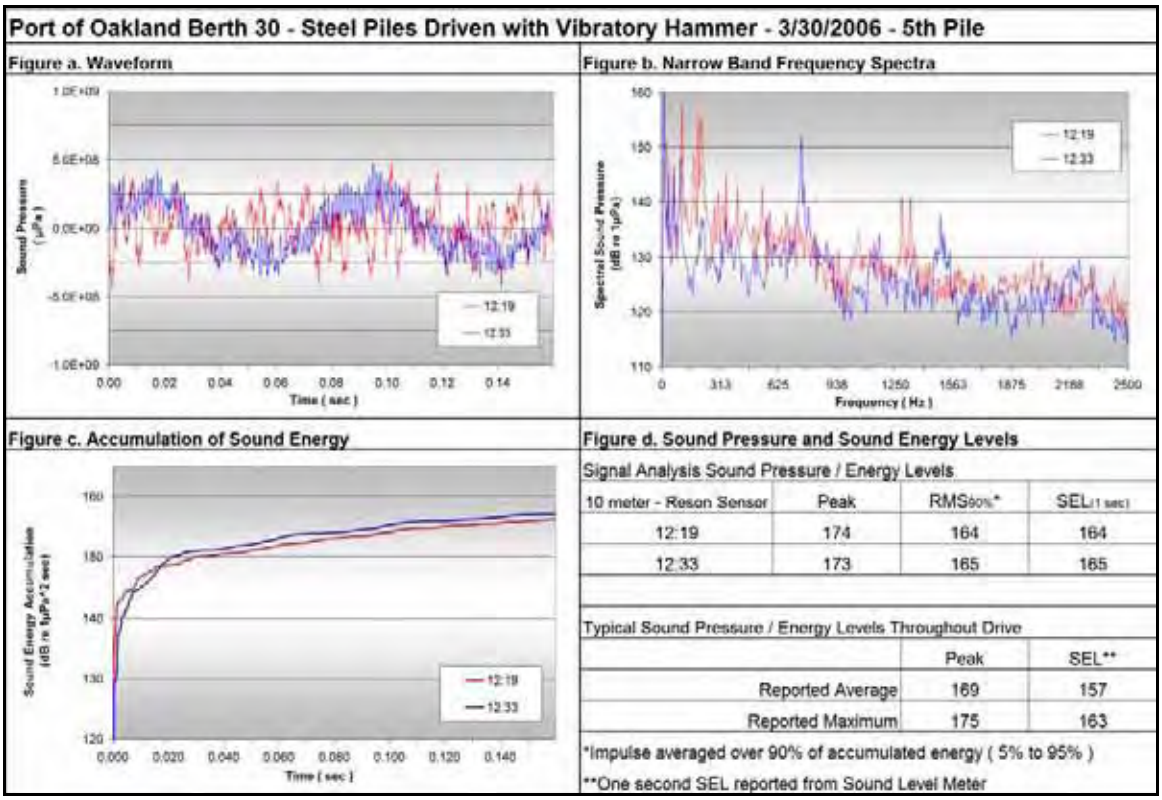

Figure I.6-4 Representative signal analysis for sheet piles installed with vibratory driver/extractor. Pulses at 10 meters normal to sheet wall face. Note low frequency signal (blue) measured late in driving event. Berth 30, Port of Oakland.

Additional data to be considered for future updates:

-Berth 35 vibratory installation of underwater sea wall (similar to Berth 30). These data are consistent with those measured at Berth 30.

-Ten Mile River cofferdam construction on land and in water (shallow water environment)

References

1. Illingworth & Rodkin, Inc. 2006. Port of Oakland Berth 23 – Underwater Sound Measurement Data for the Driving of Steel Sheet Piles and Square Concrete Piles – November 17 & December 3, 2005. Report to Vortex Marine Construction, dated January 12, 2006.

2. Illingworth & Rodkin, Inc. 2006. *Letter to Thanh Vuong (Port of Oakland) analyzing vibratory and impacts driving sounds of sheet pile sounds measured at Berth 23, Port of Oakland*. February 28, 2006.

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I.7 Timber Piles

Timber piles are uncommon in California. There has been only one opportunity to measure the installation of these piles. This occurred during marina construction in Alameda, California. Measurements are described in this section.

I.7.1 Impact Driving of Timber piles for Marina Construction – Alameda, California

Underwater sound pressure levels were measured for driving of four wood piles using a 3,000-pound drop hammer[1]. The piles were driven to secure pleasure craft slips at the Ballena Bay Marina in Alameda, California (see Figure I.7-1). Primary measurements were made at 10 meters from the pile. Supplementary measurements were made at 20 meters for the first, third and fourth piles. Measurements for 10-meters in two separate directions were made for the second pile. The water depth was about 2 to 4 meters, so the hydrophones were positioned at 1 to 3 meter depths. A 3,000-pound drop hammer was used to insert the wood dock piles. Drop heights for most pile strikes were recorded. A cushion block was used between the hammer and the pile. This cushion consisted of two 3/8-inch thick layers of rubber matting, a composite plastic block and about 7 inches of wood. The blocks were replaced when peak sound pressures exceeded 180 dB. Variations of the block composition were tested on the first two piles. It appeared that the composite plastic with wood resulted in lower underwater sound pressures.

Figure I.7-1 Driving of timber piles at Ballena Bay Marina using a 3,000-pound Drop Hammer

Table I.7-1 summarizes results of underwater the sound measurements made for the driving of 4 piles. There was quite a range in sound levels as drop heights ranged from 7 to 15 feet and cushion blocks were periodically changed to reduce sound levels. The range of sound levels were reported, since these typically varied by 10 dB or more.

At 10 meters, peak sound pressures were generally in the range of 170 to 180 dB and RMS sound pressure levels ranged from 160 to 168 dB. There were some short periods where sound pressures exceeded 180 dB peak and 170 dB RMS at 10 meters. The highest measured levels were 191 dB peak and 176 dB RMS. Sound pressures were typically 10 dB lower at 20 meters from the pile. Measurements made at 10 meters in two different directions were quite similar. The piles took about 30 minutes to drive, but pile strikes were infrequent since a drop hammer was used. Strikes typically occurred about once or twice per minute.

Signal analysis of a representative pulses indicates considerable low frequency content, when compared to other impact pile driving pulses. The example shown in

Table I.7-1 Typical Range of Sound Pressures Measured for the Driving of Timber Piles at Ballena Bay Marina in Alameda, CA

Pile	Position	Sound Pressure Measured in dB		
		Peak	RMS	SEL
1st Pile	10 meters	172 – 180 max. 188	163-168 max. 176	--
	20 meters	165 – 171 max. 181	155-158 max. 170	--
2nd Pile	10 meters	172 – 178 max. 182	163-170 max. 172	--
3rd Pile	10 meters	170 – 182 max. 191	158-172 max. 175	--
	20 meters	165 – 178 max. 181	154-165 max. 167	--
4th Pile	10 meters	170 – 177 max. 179	160-166 max. 167	--
	20 meters	165 – 171 max. 173	155-160 max. 162	--

Figure I.7-2 is for a pulse measured at 10 meters during the installation of the 4th pile. The sounds are comprised of low frequency content and appear to include very low frequency ground borne sound reflection that continuous beyond the 0.17 second window of analysis. Most of the sound content is below 400 Hz. The SEL continues to accumulate through the analysis window as the ground borne sound adds acoustic energy.

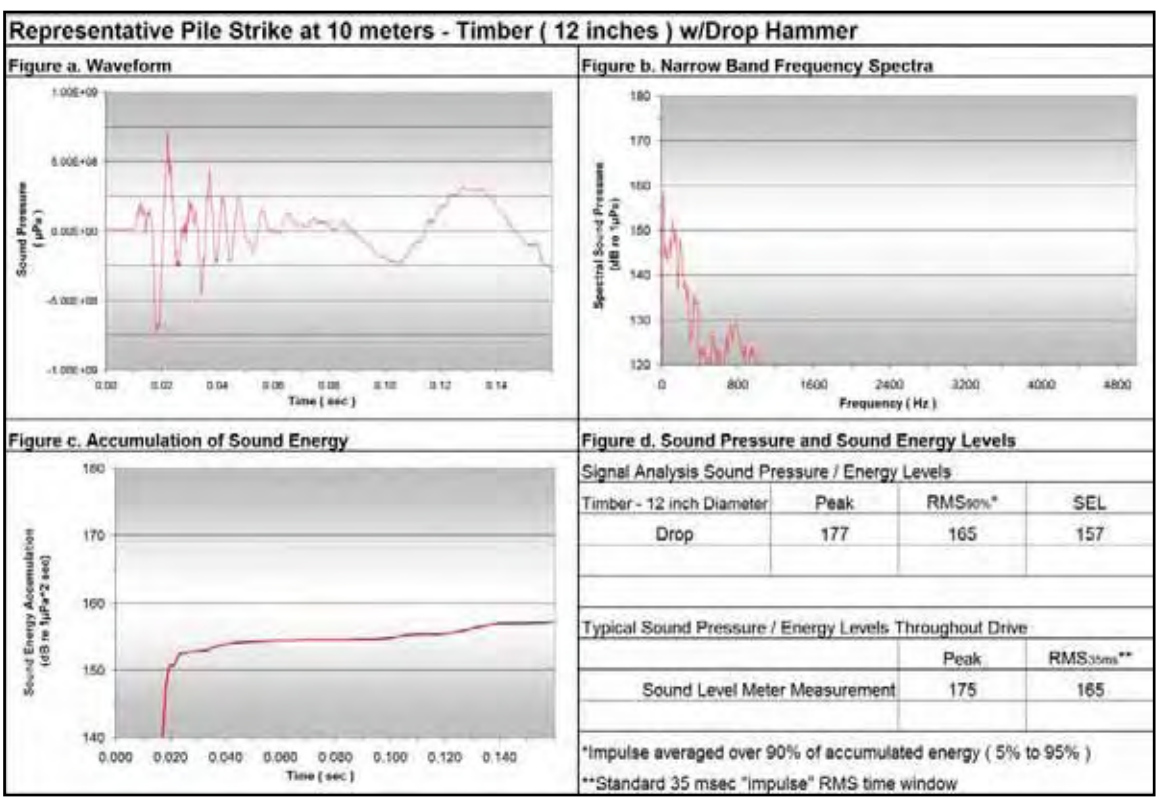


Figure I.7-2 Representative signal analysis for timber pile driven with a drop hammer. Pulse received at 10 meters from the pile. Ballena Bay Marina in Alameda, CA

References

1. Illingworth & Rodkin, Inc. 2004. *Letter to Jon Marty (Western Dock Enterprises) transmitting Underwater Sound Measurement Results for Ballena Bay Dock Construction Pile Driving (Wood Piles)*. March 25, 2004

I.8 New Benicia-Martinez Bridge Project

Construction of the Benicia-Martinez Bridge involved the driving of large diameter open ended steel shell piles, which were approximately 2.4-meters in diameter. A large hydraulic hammer was used to drive the piles at hammer energies up to 570 kilojoules (kJ). This project included extensive measurements of underwater sounds conducted during the driving of these large piles.

I.8.1 Project Description

Construction of the new northbound Benicia-Martinez Bridge began in 2002 (Figure I.8-1). The new bridge crosses the Carquinez Strait between the City of Benicia in Solano County and the City of Martinez in Contra Costa County. The 2.7 kilometer (1.7-mile) long bridge will carry northbound vehicles along Interstate 680. The existing bridge currently carries both southbound and northbound traffic and will carry southbound traffic only in the future. An existing railroad bridge will remain between the two spans. Pile driving began in 2002 and was completed in July 2003. The piles were then anchored to the bedrock. The piles are 2.4 meters (m) or 8-feet in diameter.

Sound measurements were conducted during the driving of 2.4-meter diameter piles at different pier groups. Each pier group consisted of about 8 piles set in a driving template. A large hydraulic hammer was used to drive the piles. During the driving, hammer energies were typically in the range of 500 to 570 kJ (370,000 to 420,000 foot pounds). Some of the pier locations were in open water at least 400 meters from shore. Water depth was estimated to be between 12 and 15 meters in the main channel.

Figure I.8-1 Construction of the New Benicia-Martinez Bridge

I.8.2 Measurement Results

Detailed underwater sound measurements were conducted during the driving of the large steel shell piles. The measurements were conducted from April through July 2002 for unattenuated conditions. Attenuation systems were tested in late July/August 2002 and January 2003. The effectiveness of the selected attenuation system was monitored in 2003. Underwater sound measurements were conducted by two firms; Illingworth & Rodkin, Inc. (I&R) and Greeneridge Sciences Inc. (GS). Although GS was a subconsultant to I&R, the measurements and analyses were made independently to ensure quality control. Measurements were first made to characterize underwater sound pressures associated with driving the piles without the inclusion of control features to reduce the sound pressure levels. Measurements were then conducted to evaluate the attenuation provided by a large steel pile casing (3.7-m diameter) under different conditions (i.e., with water, bubbled, dewatered).

Unattenuated Measurements

Construction began on the bridge without any underwater noise restrictions on pile driving. When observed impacts occurred (i.e., injured fish), unattenuated pile driving was restricted to slack tide periods while noise attenuation devices were considered. Except for during short periods used to test attenuation devices, unattenuated pile driving ceased after July 2002. Measurement data summarized at specific distances are shown in Table I.8--1.

In Water (Piers 8, 9, and 13)

Measurements were made by I&R for the unattenuated open water conditions on 4 separate days. I&R measured underwater peak sound pressure levels ranging from 227 dB (re 1 µPa) at 4 meters from the outside of the pile to 178 dB at approximately 1,100 meters. The bulk of I&R's measurements were made at mid-level depths (i.e., 5 to 7m) from distances of 15 m to 300 m, where sound levels ranged from about 215 dB to 197 dB. Some measurements were made at depths near the surface and bottom. I&R found a 4 to 6 dB variation in sound levels over depth, with near surface levels (at 1 meter depth) being the lowest. Table I.8-2 shows the variation in sound pressures measured at 4 m, 50 m, and 310 m for different depths.

Table I.8-1 Summary of Unattenuated Sound Pressures Measured for the Benicia-Martinez Bridge

Approximate Distance[1]	Sound Pressure		
	Peak	RMS	SEL
5 m	227	215	201
10 m	220	205	194
20 m	214	203	190
50 m	210	196	184
100 m	204	192	180
500 m	188	174	164
1,000 m	180	165	155

[1] Measured from the pile at about mid depth (10-15-m deep water)

Table I.8-2 Measured Sound Levels for Various Depths - Benicia-Martinez Bridge

Depth	Sound Pressure		
	Peak	RMS	SEL
4 m from pile (12 m deep)			
2 m	220	207	--
4 m	223	210	--
10 m	224	210	--
50 m from Pile (12 m deep)			
2 m	209	194	181
4 m	209	196	183
6 m	210	196	184
10 m	209	196	184
11 m	208	196	184
310 m from Pile (9 m deep)			
2 m	197	184	--
7 m	199	186	--

GS conducted unattenuated measurements on two separate days. Measurements were made near the surface at 1 and 2 m, mid depth at 5 m, and near the bottom at 10 m. Near the surface, peak sound pressure levels ranged from 226 dB at 14 m to 163 dB at 1,614 m. Mid-depth levels ranged from 220 dB at 14 m to 189 dB at 317 m. At the 10-m depth, peak sound pressure levels ranged from 222 dB at 14 m to 173 dB at 1,614 m. With the exception of the near field measurements (at 14 m), the mid to lower depth measurements were almost always 4 to 10 dB higher than the shallow measurements. Levels measured at the 1-m depth varied considerably more than the levels measured at other depths.

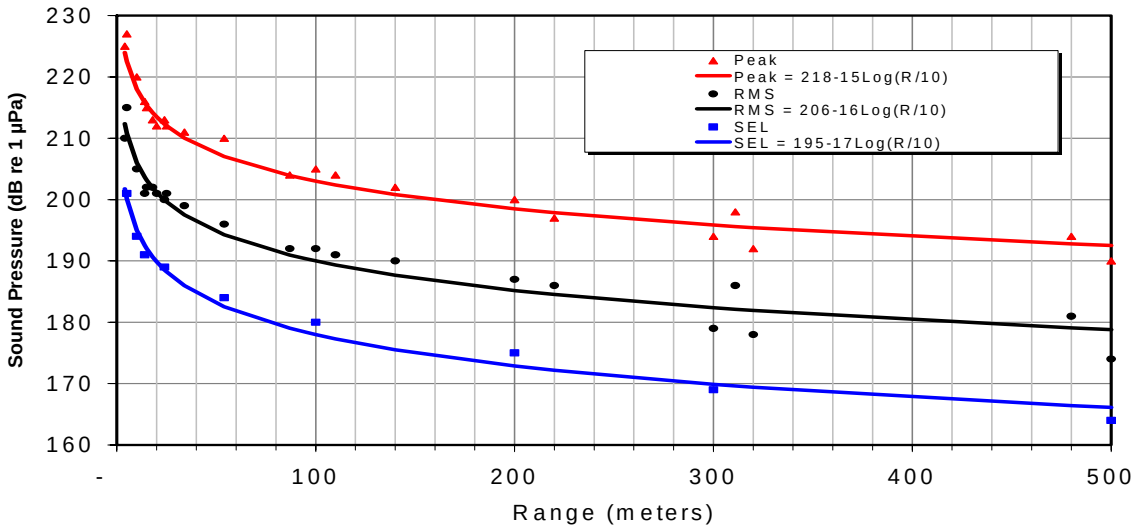
Measurements made by I&R and GS were compared and found to closely agree. Measurement results typically did not vary by more than 2 dB. Data collected by both I&R and GS were combined to derive the relationship between the distance from the pile being driven and the peak underwater sound pressure level. Equations that predict the received peak sound pressure level were developed for mid- or 5-meter depth.

$$RL_{peak} = 218 - 15 \log (R/10)$$
$$RL_{RMS} = 206 - 16 \log (R/10)$$
$$RL_{SEL} = 195 - 17 \log (R/10)$$

Where RL is the received level in dB re 1 µPa and R is the distance from the pile in meters for values of R between 10 and 500 meters.

Figure I.8-2 illustrates the relationship between measured sound levels and distance from the pile in open water. Sound levels dropped off at a faster rate in shallow water as was found when measuring under very shallow conditions at Pier 6.

Figure I.8-2 Relationship Between Measured Sound Level and Distance from Pile – Unattenuated, Open Water



Cofferdam (Pier 6)

Limited underwater sound measurements were made at Pier 6, which was in a cofferdam with water (Figure I.8-3). The water depth inside and around the cofferdam was quite shallow, about 1.5 to 2 meters deep. Measurements were conducted both inside and outside the cofferdam to a distance of about 50 m. Analyses of the signals were not conducted and, therefore, SEL data are not available. The data summarized in Table I.8-3 indicate that sound pressures were much lower than those measured under open water unattenuated conditions. This appeared to be mostly due to the very shallow water conditions and not to the attenuation provided by the cofferdam. The measurement data indicate that the cofferdam may have reduced sound pressures by 10 dB; however, there was substantial variation in sound pressures both inside and outside of the cofferdam. Therefore, it is difficult to identify the amount of sound reduction provided by the cofferdam with water inside under shallow water conditions.

Figure I.8-3 Cofferdam with Water used for the Benicia-Martinez Bridge

Table I.8-3 Measured Sound Levels for Cofferdam with Water - Benicia-Martinez Bridge

Approximate Distance	Sound Pressure		
	Peak	RMS	SEL
Inside Cofferdam			
5 m	215	203	--
10 m	208	199	--
19 m	203	194	--
Outside Cofferdam			
12 m	193	206	--
22 m	198	184	--
36 m	190	170	--
54 m NW	179	162	--
54 m NW	185	167	--

Isolation Casing

Underwater sound levels for piles driven with a steel pipe sleeve or casing were measured to evaluate the reduction in underwater sound levels from unattenuated conditions. The casing, which was 3.8-meters in diameter, was tested under three conditions; (1) with water in the casing, (2) with a bubble ring placed at the bottom of the casing in operation, and (3) with the casing dewatered[1]. Figure I.8-4 shows the air bubble curtain condition. Measurements were conducted by both I&R and GS at relatively close-in distances. Results of these tests are summarized in Table I.8-4. Analyses of the pulse signals for the different test conditions are illustrated in Figure I.8-5. A summary of the results is described in the following sections.

Table I.8-4 Measured Sound Levels for Isolation Casing Tests - Benicia-Martinez Bridge

Approximate Distance	Sound Pressure		
	Peak	RMS	SEL
Bare Pile			
14 m	216	201	191
24 m	213	201	189
54 m	210	196	184
100-106m	204	191	180
Casing with Air Bubbles			
14 m	192	176	--
24 m	189	173	
54 m	187	174	163
100-106m	--	--	--
Casing Dewatered			
14 m	--	--	--
24 m	191	175	--
54 m	185	173	162
100-106m	181	172	160

Figure I.8-4 Isolation Casing/Air Bubble Curtain System tested for the Benicia-Martinez Bridge

Isolation Casing with Water

Underwater sound measurements indicated that the casing with water provided very little noise reduction. At 24 m from the pile, GS measured a 0 dB difference in the peak sound pressure levels. At 14m, GS measured increased sound levels; however, this unusual variability may be due to near field effects. At

[1] Reyff, J., P. Donavan, C. R. Greene Jr. Underwater Sound Levels Associated with Construction of the Benicia-Martinez Bridge. *Produced by Illingworth & Rodkin, Inc. and Greeneridge Sciences under contract to the California Department of Transportation, Task Order No. 18, Contract No. 43A0063.* August 2002.

54 m, I&R measured 2 dB reduction in peak levels. Close examination of the acoustical data obtained for this test at 54 meters did not indicate any substantial changes in the acoustical pressure waveform. The frequency analysis indicated a small reduction in sound levels above about 1600 Hz.

Isolation Casing with Bubbles

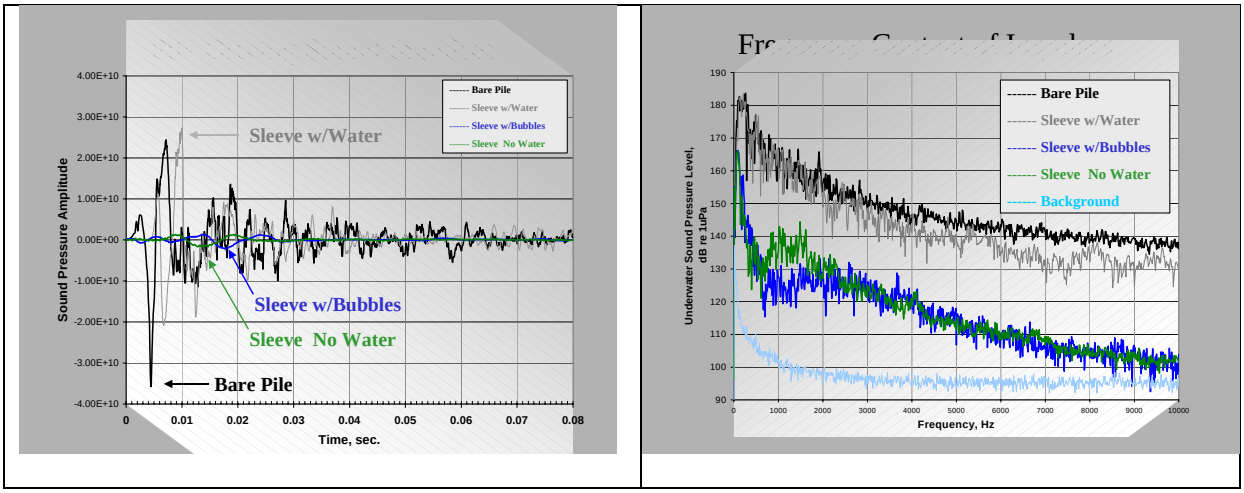
Results for the casing with bubbles showed a dramatic reduction in underwater sound levels. GS measured reductions in peak sound pressure levels of 30 to 34 dB at 14 m and 23 to 31 dB at 24 m. I&R measured a reduction of 23 dB peak and 21 dB SEL at 54 m (measured at mid-depth only). A close examination of the acoustical pressure waveforms recorded at 54 m showed a fast rise time in pressure that occurred within the first 5 ms. A rapid fluctuation in underpressure to overpressure occurred within about 2 ms. The decay time of the pulse was relatively slow, lasting about 50 to 100 ms. Much of the energy associated with the pulse occurred within the first 50 ms. The narrow-band frequency analyses showed that the greatest acoustical energy was in the 50 to 350 Hz range and that most of the energy was contained over the range of 25 to 1600 Hz. Based on these data, the bubbled casing condition was most effective at close-in distances.

Isolation Casing without Water

At the request of NOAA Fisheries, testing was also conducted with the water removed from the isolation casing. Results for the dewatered casing were similar to the casing with bubbles results. I&R measured a reduction in peak sound pressure levels of 25 dB at 54 meters, 2 dB lower than the measured bubble condition, and GS measured a reduction of 22 dB peak at 24 meters, levels 2 dB higher than the bubble condition.

Bubble Curtain System, Bubble Tree

After the IC/ABC measurements, the construction contractor designed an unconfined bubble curtain system to be used for the remainder of the bridge construction. Because of the pile template, a fully circular bubble curtain could not be used. A bubble tree design was developed to accommodate the pile template. This system included four bubble trees positioned on each quadrant of the pile. Each tree consisted of partial circular rings stacked vertically at multiple levels, with up to 9 stages (Figure I.8-5). Each stage or ring was either open or closed. The system was designed to completely surround the pile with bubbles continuously. Four 1,500 cubic foot per minute (cfm) oil free air compressors were used to supply air to the bubble tree system.



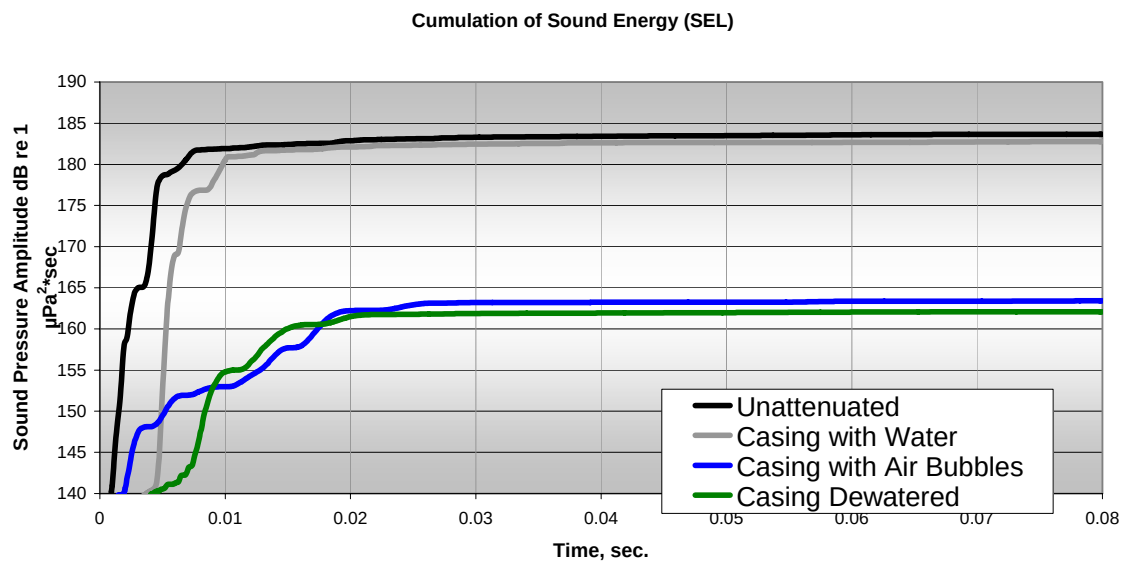


Figure I.8-5 Signal Analyses of Underwater Sound Pulses at 54 m – Isolation Casing Tests

Prior to the development of the bubble tree system, there had been concerns that unconfined air bubble curtain systems would be compromised by currents, which would sweep the bubbles away from the pile. It was therefore assumed that a confined bubble curtain system, such as the Isolation Casing/Air Bubble Curtain, would be advantageous. Although successful in dramatically reducing sound pressures, the confined bubble curtain system with the casing was too costly to implement because the existing pile template would have had to be redesigned and fabricated. This would have caused substantial financial constraints on the project due to the extra work required and the resulting delays. To compensate for currents, multiple stages were included in the bubble tree system and considerable more air was provided to the system. Each "tree" was designed to provide sufficient bubble coverage to one quadrant around the pile; therefore, four bubble trees would provide adequate coverage without having to modify the pile template.

Testing Results (Pier 13)

Plans were developed to measure at 3 different fixed positions that were approximately 100 meters from the pile (actual distances varied from 95 m to 150 m due to tidal currents and final placement of buoys by the contractor). Each position was oriented in a different direction so that the directionality of the system could be tested under different current conditions. Measurements were conducted at two depths: approximately 2 meters below the water surface and between 5 and 10 meters below the water surface. A fourth measurement position was added at approximately 50 meters from the pile. Measurements were made during the driving of two piles. One pile was driven during an ebb tidal current and the other was driven during a flood tidal current. The testing sequence of the air bubble curtain system included an "ON" condition, an "OFF" condition and an "ON" condition that lasted at least 10 minutes. Detailed measurement results were reported to Caltrans[2].

Figure I.8-6 Air Bubble Curtain Tree System used at the Benicia-Martinez Bridge

Findings indicate that this system was just as effective as the isolation air bubble curtain system. Peak sound pressures were reduced by 19 to 33 dB, sound pressure levels (in terms of RMS) were reduced by 17 to 29 dB, and the SEL was reduced by 20 to 25 dB. At most measurement positions, peak sound pressures were reduced by over 22 dB and sound pressure levels were reduced by over 25 dB. A summary of measured sound pressures for both the isolation casing air bubble system and the air bubble tree are compared with unattenuated conditions in Table I.8-5. Results are graphically compared with unattenuated conditions in Figure I.8-7. The signal analyses of the pulse recorded at 95 m west of the pile during the test illustrate the attenuation provided by the system (Figure I.8-8).

Table I.8-5 Measured Sound Levels for Air Bubble Tree Tests - Pier 13

Position	Sound Levels in dB re 1 µPa		
	Unattenuated Pile	Isolation Casing/ABC	Air Bubble Tree
~50m	Peak = 210 RMS = 196 SEL = 184	Peak = 187 RMS = 174 SEL = 163	Peak = 182* RMS = 168* SEL = 159*

[2] Reyff, J. *Underwater Sound Levels Associated with Construction of the Benicia-Martinez Bridge - Results of Measurements Made at Pier 13 with the UABC Operating.* Produced by Illingworth & Rodkin, Inc. for Caltrans under Contract 43A0063, Task Order No. 18. April 2003.

~100m	Peak = 204 RMS = 191 S E L = 1 8 0	Peak = 181 RMS = 172 S E L = 1 6 2	Peak = 185* RMS =170* SEL = 160*

* Average of Pile 1 and Pile 4 measurements for mid depths.

Figure I.8-7 Results of Pier 13 Measurements Compared to Unattenuated Sound Levels

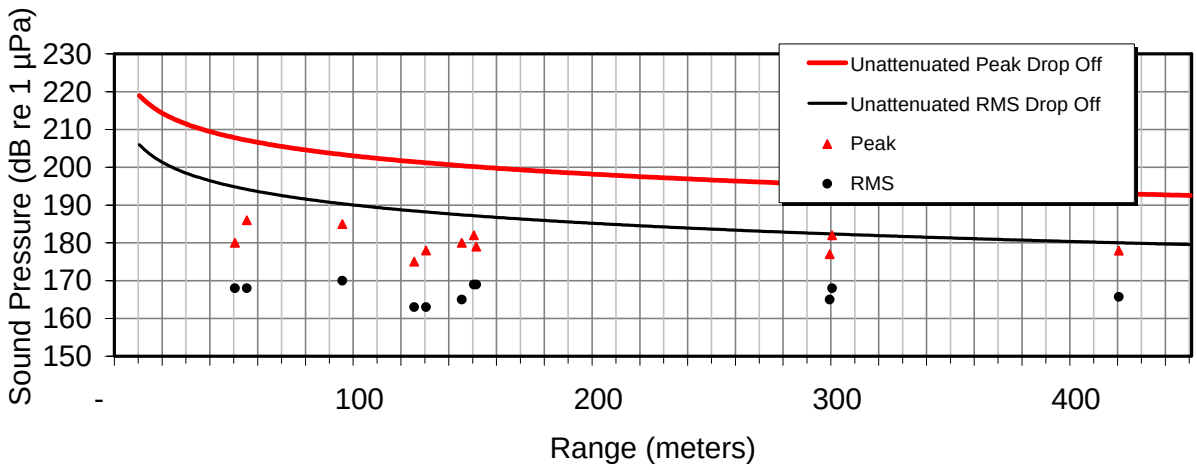
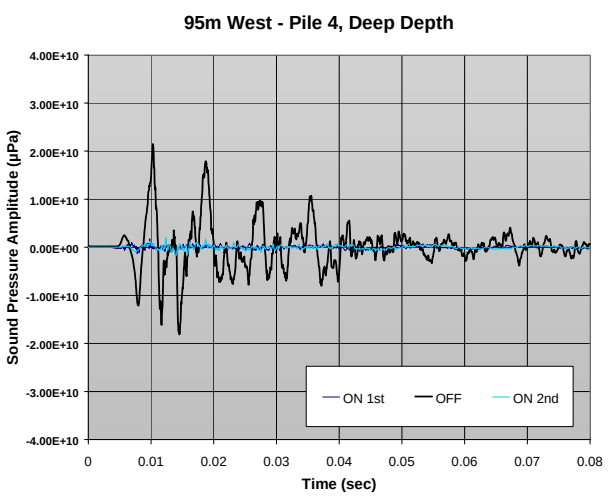
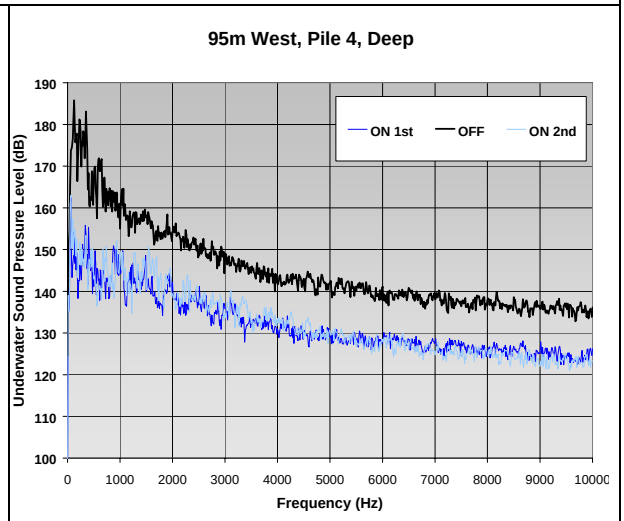
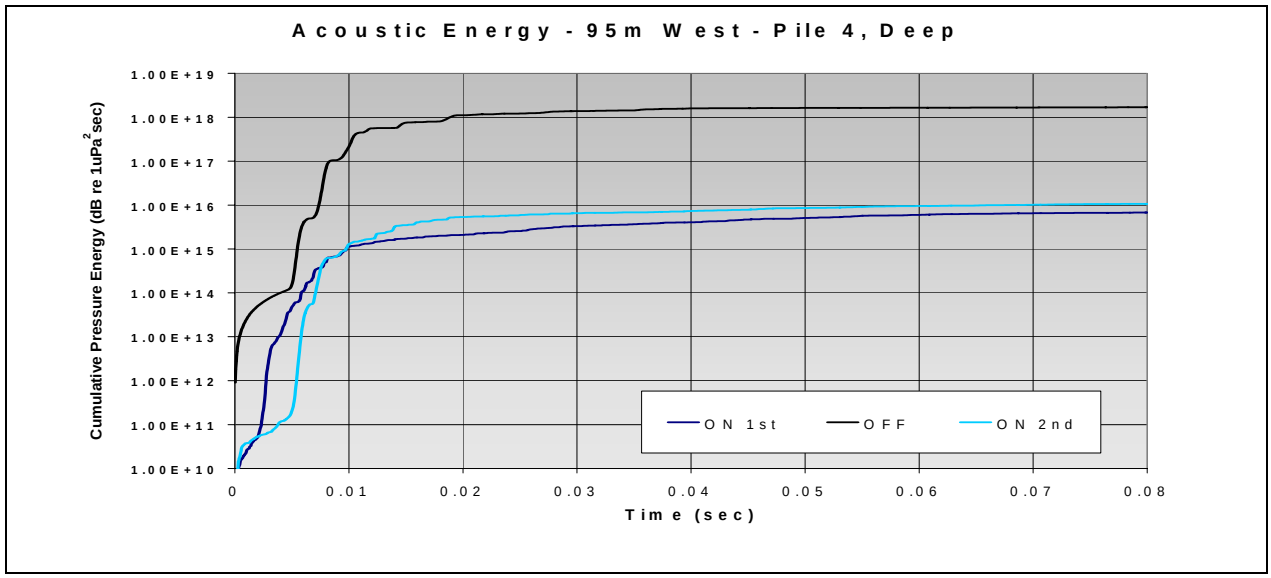


Figure I.8-8 Signal Analyses of Underwater Sound Pulses at 95 m West – Air Bubble Tree







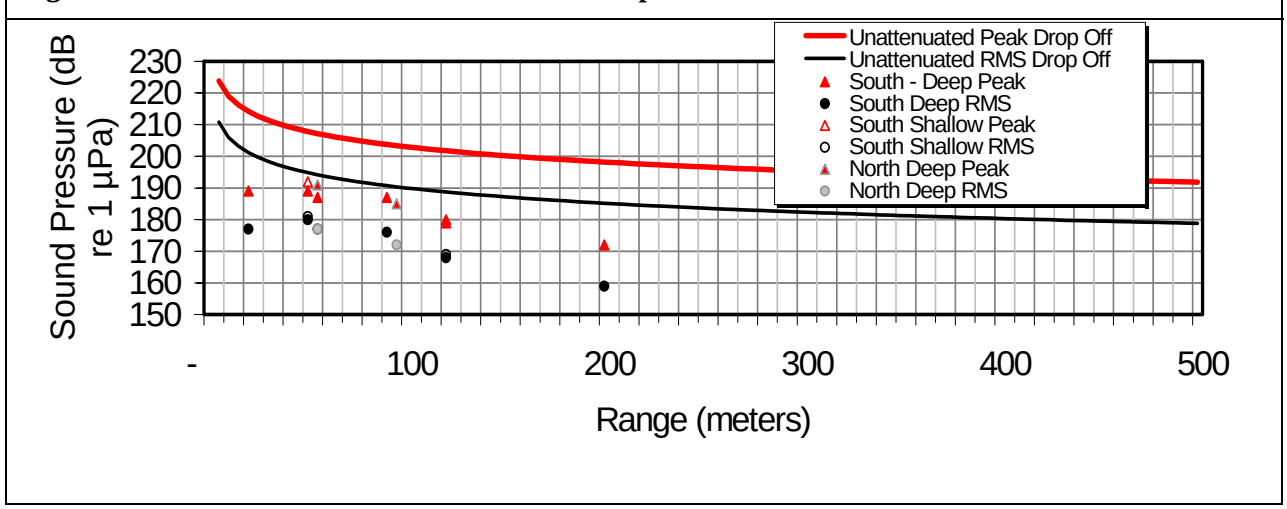
Compliance Monitoring Results

Measurements were made to document underwater sound levels and air bubble curtain performance during production pile driving. Measurements were made at Piers 7, 11, 12, and 15. Only Peak and RMS sound pressure levels were reported under the compliance monitoring tasks.

Pier 7

During this measurement day, two piles were driven. The first pile had been previously driven to refusal. Center-relief drilling had been conducted and driving of the pile was completed in a 20-minute period. The second pile was driven from a stabbed position to a point of refusal. Results, in terms of Peak and RMS sound pressures are shown graphically and compared with unattenuated levels measured for other piers (Figure I.8-9). Results indicate about 10 to 20 dB of attenuation from the air bubble curtain system.

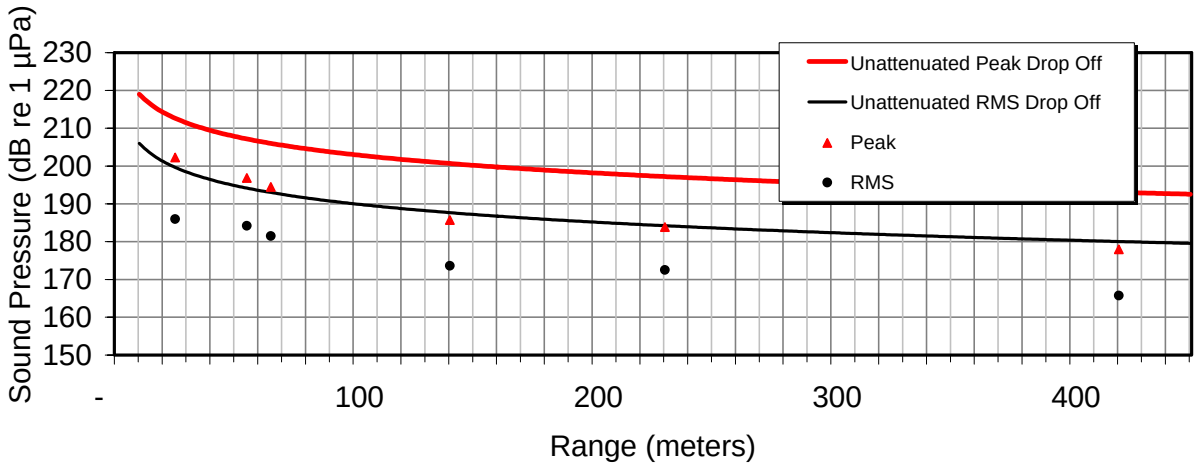
Figure I.8-9 Results of Pier 7 Measurements Compared to Unattenuated Sound Levels



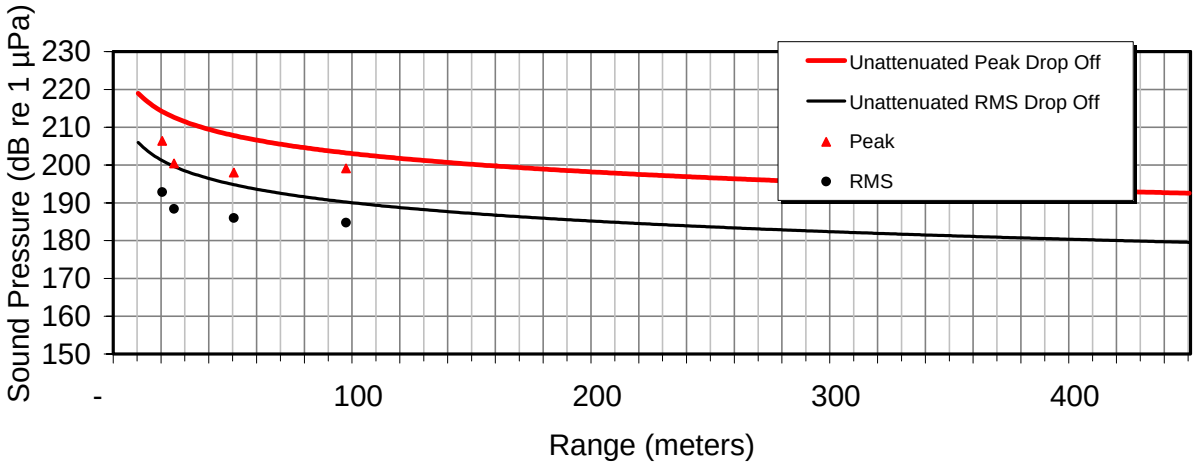
Pier 12

Measurements were conducted for Pier 12 on two separate days (April 25 and May 8, 2005). Center relief pile driving was conducted, where drilling is conducted inside the pile and then the pile is driven to refusal. This method prevents damage to the hammer and pile. The results, in terms of Peak and RMS sound pressures, are plotted against unattenuated conditions (Figure I.8-10) as discussed previously for Pier 7. Both tests show only about 5 to 15 dB of attenuation, indicating that there may have been operational problems with the air bubble curtain system or substantial flanking of sound through the ground surfaces below the water.

Figure I.8-10 Results of Pier 12 Measurements Compared to Unattenuated Sound Levels



Center Relief Pile Driving, Pile 2 – April 25, 2003

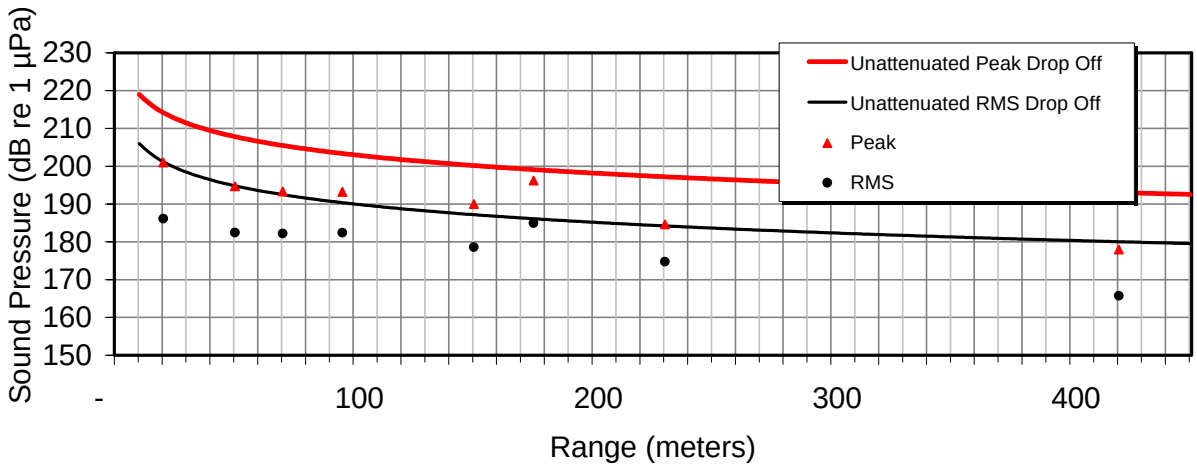


Center Relief Pile Driving, Pile 7 – May 8, 2003

Pier 11

Measurements were conducted for the entire driving period of Pile 7 at Pier 11 on May 21, 2003. The air bubble curtain system provided about 10 to 14 dB attenuation. However, a measurement on the west side was only 4 dB lower than the predicted unattenuated condition, indicating that there may be a "sound leak" in the UABC system on the west side. Results are plotted graphically in Figure I.8-11).

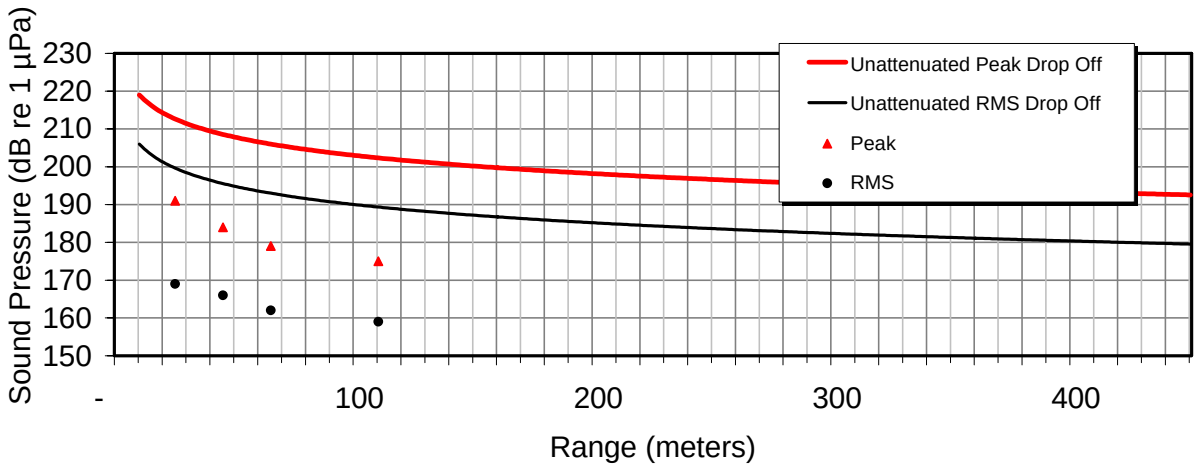
Figure I.8-11 Results of Pier 11 Measurements Compared to Unattenuated Sound Levels



Pier 15

Measurements were made during the driving of Pile 7 at Pier 15 (pile at south side of Pier) on the morning of July 2, 2003, under a strong ebb current. Pier 15 is in relatively shallow water (about 4 to 6m deep) near the north shore. Results, plotted graphically in Figure I.8-12), were similar to those obtained for Pier 13. The air bubble curtain system provided about 20 dB to 30 dB of attenuation.

Figure I.8-12 Results of Pier 15 Measurements Compared to Unattenuated Sound Levels



References:

1. Reyff, J., P. Donavan, C. R. Greene Jr. Underwater Sound Levels Associated with Construction of the Benicia-Martinez Bridge. *Produced by Illingworth & Rodkin, Inc. and Greeneridge Sciences under contract to the California Department of Transportation, Task Order No. 18, Contract No. 43A0063.* August 2002.

I.9 San Francisco-Oakland Bay Bridge East Span Replacement Project

I.9.1 Project Purpose/Description

The East Span Seismic Safety Project (East Span Project) replaces the existing East Span of the San Francisco-Oakland Bay Bridge (SFOBB) with a new bridge that features a pre-cast segmental "skyway" and a single tower self anchored suspension structure in central San Francisco Bay (see Figure I.9-1).

Figure I.9-1 Artist rendering of the new San Francisco-Oakland Bay Bridge East Span

The project has four primary components (see Figure I.9-2).

- Geofill at the Oakland Touchdown
- Oakland Approach Structures
- Skyway structures
- Single tower self anchored suspension structure/YBI transition

To facilitate an efficient and cost-effective building program, the Main Span component was separated into several construction contracts. In addition, a separate contract will be used to remove the existing bridge when construction is complete. Work on the Self anchored suspension and YBI transitional components of the project are currently under construction.

The project setting is in the central San Francisco Bay between San Francisco and Oakland, east of YBI. The study area consists of the construction zone along the north side of the existing East Span. See (Figure I.9-2) for the project location and study area. The project area is bounded by YBI on the west, Oakland Inner Harbor to the south and the Oakland Touchdown to the east. To the north, San Francisco Bay stretches out for nearly 14 kilometers (9 miles) before it is bounded by the Richmond-San Rafael Bridge.

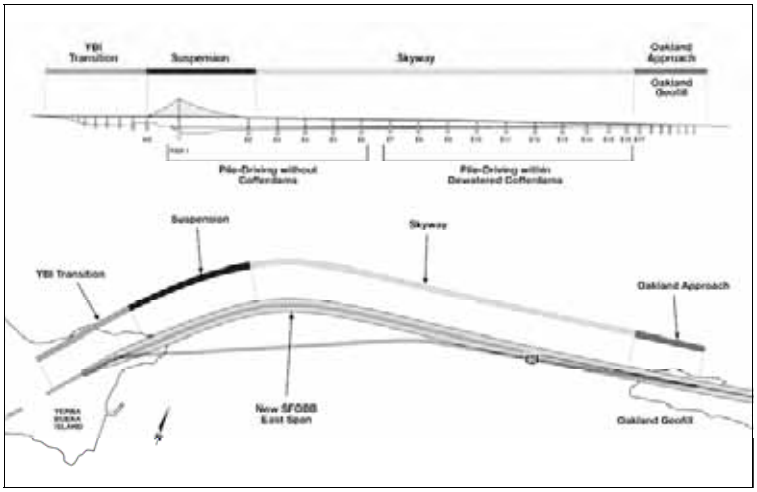


Figure I.9-2 Project Components - San Francisco-Oakland Bay Bridge East Span

The SFOBB project included driving of large piles (2.7m or 8-foot diameter), which were over 100 m (330 feet) long. Piers that would support the new bridge include at least 6 of these piles, with four piles installed at an angle (battered). In addition, blasting was conducted at YBI for construction of piers on land near the water.

I.9.2 Hydroacoustic Measurement Plans

Hydroacoustic measurements were made during the driving of test piles (referred to as the Pile Installation Demonstration Project [PIDP]) and during the driving of production piles during project construction. At preparation of this document, all piles for the Skyway portion of the bridge had been driven. Hydroacoustic measurements were also made during blasting activities at Pier W1 at YBI. The blasting was conducted on land, but near the water.

Plans were developed for underwater sound measurements for production pile driving. Hydroacoustic measurements were conducted during the PIDP and PIDP Restrike[1, 2]. The production part of the project included two studies that required hydroacoustic monitoring: (1) the Fisheries and Hydroacoustic Monitoring Program and (2) the Marine Mammal Monitoring Program.

- The Fisheries and Hydroacoustic Monitoring Program required underwater sound measurements to characterize the sound field during pile driving. Plans were developed prior to measurements and documented in the Fisheries and Hydroacoustic Monitoring Program Plan[3]. Specific underwater sound measurement positions were specified in the plan. In addition, the plans for conducting the fish cage study were described, which included underwater sound measurements to document the sound exposure received by fish from pile driving.

- Protection of marine mammals, primarily pinnipeds or seals, was conducted through implementation of the Marine Mammal Monitoring Program Plan[4]. The program elements included monitoring of pinnipeds in the area and establishment of a marine mammal safety zone (MMSZ) through hydroacoustic measurements. Monitoring plans documented the methodology and frequency of hydroacoustic monitoring activities to comply with the Incidental Harassment Authorization issued by National Marine Fisheries in 2003[5].

In addition to the programs noted above, additional hydroacoustic monitoring activities were carried out on this project to further document hydroacoustic conditions around pile driving (especially pile driving in dewatered cofferdams), document hydroacoustic effects of the air bubble curtain system, and monitor conditions during blasting at YBI near the water.

I.9.3 Hydroacoustic Measurements

I.9.3.1 2000 Pile Installation Demonstration Project

The 2000 PIDP involved the installation of three piles into the floor of San Francisco Bay. The objective of the PIDP was to test and evaluate technical, engineering and environmental factors associated with driving large hollow steel piles approximately 100 meters long (Caltrans 2001). The PIDP involved utilization of two sizes of hammers, three different pile alignment configurations, and two different types of hydroacoustic attenuation systems. The piles were 108 m (356 ft) long and had an inside diameter of 2.4 meters (8 feet), and an outside diameter of 2.57 m (8.5 ft). Pile 1 was a vertical pile, where no hydroacoustic attenuation devices were used. Pile 2 was a battered pile (driven at an angle) that was angled to the east and included a single ring air bubble curtain. Pile 3 was inserted at a different location and was also battered, but angled to the west. A proprietary fabric under water barrier attenuation system (Gunderboom) was used for Pile 3. As with the SFOBB East Span Seismic Safety project, two different sizes of Menck hydraulic hammers were used. The MHU500T or smaller hammer had a maximum capacity of about 550 kilojoules (368,750 foot pounds) and the MHU1700T (Figures I.9-3a and I-9.3b), had a maximum capacity of about 1,780 kilojoules (1,253,750 foot pounds).

Figure I.9-3a Small Hydraulic Hammer (MHU500T) used for much of the pile-driving

Figure I.9-3b Large Hydraulic Hammer (MHU1700T) Hammer used for last ¼ of pile-driving where resistance was greatest

Results of acoustical measurements made during the PIDP were reported to the California Department of Transportation[1]. The underwater sound measurements for the 2000 PIDP were not comprehensive, but important data came from measurements at hydrophone depths of 1 and 6 m, without a sound attenuation system in place. Results are reported in Table I.9-1. Measurements were made at different distances and different depths. Attenuation systems were used for PIDP piles 2 and 3.

Table I.9-1 Summary of Sound Pressures Measured for the 2000 PIDP, San Francisco-Oakland Bay Bridge – East Span

Pile	Hammer/Distance/Condition/ depth	Sound Pressure Levels in dB		
		Peak	RMS	SEL
PIDP 1 Section 1D (top)	Menck1700T Hammer (900 kilojoules)			
	100 meters Unattenuated – 1-m depth	197	185	~172
	100 meters Unattenuated – 3-m depth	205	192	~178
	100 meters Unattenuated – 6-m depth	207	196	~183
	360 meters Unattenuated – 1-m depth	181	167	~157
	360 meters Unattenuated – 3-m depth	188	175	~164
	360 meters Unattenuated – 6-m depth	191	179	~168
PIDP 2 Section 2D (top)	Menck500T Hammer (550 kilojoules)			
	200 meters Unattenuated – 1-m depth	197	184	~172
	200 meters Unattenuated – 3-m depth	201	189	~178
	200 meters Unattenuated – 6-meter depth	197	186	~174
PIDP 2 Section 2D	Menck1700T Hammer (1,000 kilojoules)			
	200 meters Partially Attenuated – 1-m depth	199	187	~175
	200 meters Partially Attenuated – 3-m depth	201	190	~177

[1] Illingworth & Rodkin, Inc. 2001. Final data report: Noise and vibration measurements associated with the Pile Installation Demonstration Project for the San Francisco-Oakland Bay Bridge East Span. August 2001.

(top)	200 meters Partially Attenuated – 6-m depth	199	188	~176
PIDP 3 Section 3D (top)	Menck1700T Hammer (1,500 kilojoules)			
	100 meters East Unattenuated (Gunderboom OFF)– 1-m depth	193	179	~167
	100 meters East Unattenuated (Gunderboom ON)– 1-m depth	189	175	--
	100 meters West Unattenuated (Gunderboom ON)– 1-m depth	188	175	~163
	100 meters West Unattenuated (Gunderboom OFF)– 1-m depth	197	184	~173
	500 meters West Unattenuated (Gunderboom ON)– 1-m depth	170	160	~148

The unattenuated measurements for PIDP Pile 1 indicated a source level of 209 dB peak, 198 dB RMS, and 185 dB SEL at 100 meters. These levels were based on measurements for the 6-meter depth. Lower noise levels were found for depths near the surface. Measurements were made at 200 meters for PIDP Pile 2 when a simple air bubble curtain system was used (see Figure I.9-4a). These measurements were made with both the smaller MHU500T and larger MHU1700T hammers. Use of the larger hammer resulted in underwater sound levels that were 1 to 2 dB higher. The air bubble curtain system did not appear to provide measurable attenuation. There was no air bubble curtain ON/OFF test, so the effectiveness of the system could not be directly measured. Comparison of measurements between Pile 1 and Pile 2 indicated about 0 to 2 dB attenuation from the system. Tidal currents and insufficient air supply likely compromised the effectiveness. A Gunderboom System was used for PIDP Pile 3 (see Figure I.9-4b). This system, which is able to confine bubbles close to the pile, was found to reduce sound pressures by about 5 to 10 dB. It should be noted that PIDP Pile 3 was driven in shallower waters and had unattenuated levels that were about 10 dB lower than those measured for PIDP Pile 1.

Figure I.9-4a. Simple air bubble ring used during the driving of PIDP Pile 2

Figure I.9-4b. Proprietary fabric air bubble curtain (Gunderboom) used during PIDP Pile 3

Levels were always lowest near the surface (1-meter depth). A spreading loss formula was derived, which corrected for hammer size and measured excess attenuation and yielded approximately 30 dB loss per tenfold increase in distance.

I.9.3.2 PIDP Restrike

The PIDP Pile Restrike Project was conducted in 2003 for geotechnical evaluation of pile stability and to demonstrate the effectiveness of a bubble curtain system that was designed to provide protection to fisheries resources in San Francisco Bay. For the Restrike Project, the Menck1700T hydraulic hammer, MHU1700T, with a capacity of 1,780 kilojoules or kJ was used at or near full capacity. The geotechnical evaluation was intended to demonstrate the limits of pile "takeup" over time to verify that the pile elements of the foundation would be strong enough to support the construction loadings that are anticipated while the footing is still relatively young. The criteria used to determine stability was 670 strikes with less than 250 millimeters (approximately 1 ft) movement. A secondary objective was to evaluate a bubble curtain system that was improved over the single-ring system used during the 2000 PIDP. This two-ring bubble curtain discharged considerably more air than the 2000 PIDP bubble curtain system and was fitted much more tightly around the pile than either the single-ring bubble curtain or the fabric barrier system.

Figure I.9-5a Air bubble curtain system with compressors in background

Figure I.9-5b Air bubble curtain system in operation during the PIDP Re-strike

Measurements results for each of the three piles struck are presented in Table I.9-2 for both attenuated and unattenuated conditions. The reduction in sound pressures provided by the bubble curtain system ranged considerably. The direct reduction in sound pressures, which was evaluated by comparing bubble curtain ON and OFF measurements, for Piles 1 and 2 was 6 to 17 dB for peak pressures and 3 to 10 dB for RMS sound pressure levels. Piles 1 and 2 were located next to each other in fairly deep water (about 12 meters depth). Reductions at Pile 3, which was in shallower water, were over 20 dB for both peak pressures and RMS sound pressure levels on the north side. However, the reductions on the south side for Pile 3 were much less. Close to Pile 3 on the south side, the reductions were on the order of 5 to 7 dB. Further away at about 450m south, the reductions were only about 2 dB. Uneven bottom topography around Pile 3, which could have compromised the bubble curtain performance near the bay bottom, was suspected to have resulted in the lower reductions to the south. However, subsequent production pile measurements indicate that groundborne sound generation from vibration produced by the pile driving was likely the cause. It is important to note that overall sound pressures associated with Pile 3 were lower than those with Piles 1 and 2. Measurements of peak pressures made at about 100m were consistent with the measurements made during the PIDP in 2000. Those measurements were the basis for predictions of the maximum peak pressures during SFOBB east span construction. With the exception of the 450m south position, predicted peak pressures used in the Biological Opinion were lower than those measured. At 450m south, measured peak pressures were 5 to 8 dB higher than predicted. This was the result of the groundborne sound generation in that direction that was not known at the time of the predictions. Conversely, unattenuated peak pressures at 450m to 500m north were 0 to 6 dB lower than predicted.

Table I.9-2 Summary of Sound Pressures Measured for the 2003 PIDP Restrike using the MHU1700T Hammer at Full Energy, San Francisco-Oakland Bay Bridge – East Span

Pile	Distance/Direction/Condition	Sound Pressure Levels in dB		
		Peak	RMS	SEL
PIDP 1	100 meters South Attenuated	196	185	--
	100 meters South Unattenuated	206	192	--
	460 meters South Attenuated	189	178	--
	460 meters South Unattenuated	198	185	--
	100 meters South Attenuated	201	189	--
	100 meters South Unattenuated	207	194	--
	460 meters South Attenuated	175	162	--
	460 meters South Unattenuated	182	171	--
PIDP 2	100 meters South Attenuated	197	185	--
	100 meters South Unattenuated	208	195	--
	460 meters South Attenuated	191	180	--
	460 meters South Unattenuated	--	--	--
	100 meters South Attenuated	196	184	--
	100 meters South Unattenuated	205	193	--
	460 meters South Attenuated	180	171	--
	460 meters South Unattenuated	190	177	--
PIDP 3	100 meters South Attenuated	193	182	--
	100 meters South Unattenuated	199	186	--
	460 meters South Attenuated	184	173	--
	460 meters South Unattenuated	187	175	--
	100 meters South Attenuated	179	169	--
	100 meters South Unattenuated	198	184	--
	460 meters South Attenuated	<180	<170	--
	460 meters South Unattenuated	184	172	--

Signal analyses presented in Figure I.9-6 show the acoustical pulses for measurements made at 100 meters south of the piles. Each pulse lasted about 80 milliseconds or longer and most of the disturbance occurred during the first 25 to 35 milliseconds. In all cases, the reduction in acoustical energy is evident. The bubble curtain system was effective at reducing sound pressure levels above 1000 Hz in all cases and above 300 Hz in some cases. The reductions were over 20 dB above 2000 Hz. The reduction in higher frequencies is evident by the smoother increase and decrease in pressure over time. These signals also illustrate the site differences for both bubble curtain ON and OFF conditions between the location of Pile 1 and 2 and the location of Pile 3. At Pile 3, sound pressures were much lower even without the bubble curtain ON. The measured reduction between ON and OFF conditions was less at Pile 3, but the resulting attenuated levels were lower than any of the levels measured at Piles 1 or 2. Shallower conditions and different substrates probably contributed to the overall reduced levels.

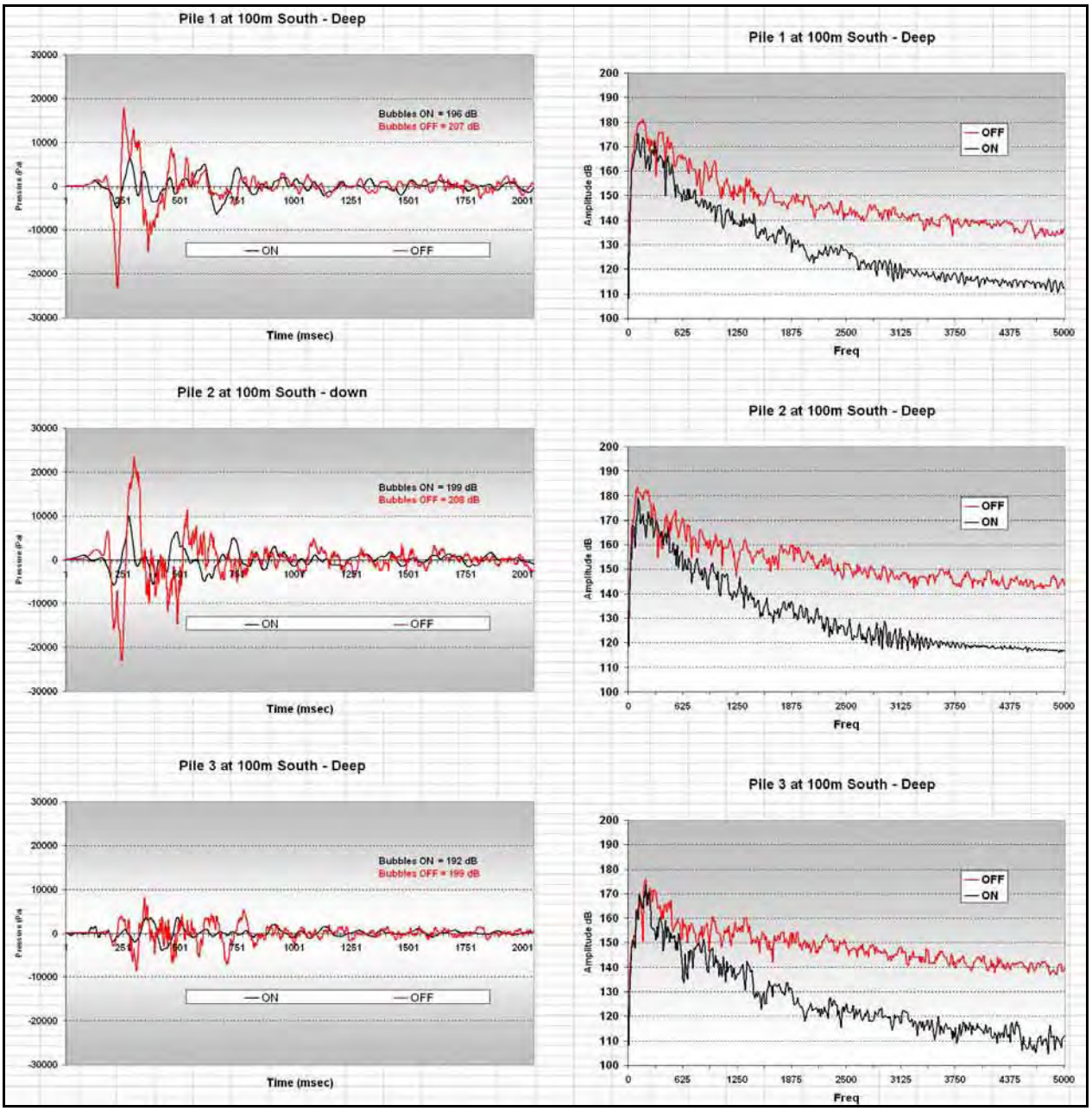


Figure I.9-6 Representative signal analyses for PIDP Restrike measurements made at 100 meters from three different piles with and without air bubble curtain attenuation. San Francisco-Oakland Bay Bridge – East Span

I.9.4 Production Pile Driving

As of this writing, the San Francisco-Oakland Bay Bridge East Span Replacement construction is still ongoing. However, much of the pile driving has been completed. Some pile driving is still planned for the self-anchored suspension tower. Much of the pile driving was conducted for the Skyway portion of the bridge, which involved 28 piers that consisted of 6 large diameter piles about 100 to 110 meters long. Twenty of the piers were constructed in the shallower waters, where dewatered cofferdams were used. In these cases, piles did not have direct contact with the water. Eight of the piers were constructed in water, where an air bubble curtain system was used to attenuate under water sounds to protect fish and marine

mammals. Extensive noise measurements were conducted for this project as part of the *Fisheries Hydroacoustic Monitoring Program*, the *Marine Mammal Monitoring Program*, and supplemental measurements to test the air bubble curtain system effectiveness. This was the most intensive underwater sound-monitoring program implemented for a construction project that involved marine pile driving. In all, several hundred underwater sound measurements were made on 19 separate days for production pile driving. This is in addition to the measurements made for the 2000 PIDP, the 2003 PIDP Restrike, Pier T1 CIDH casings, and Pier E2 foundation pile driving measurements. Acoustic measurement results obtained from this project are contained in several project biological compliance reports that are available over the internet at www.biomitigation.org (select biological mitigation reports, then the subject: Hydroacoustics)[6,7,8,9,10,11]. Because the measurement results are extensive for this project, they are summarized in this chapter. The reader is referred to the project *Hydroacoustic Monitoring Report* for a full description of the data collected for this project[9].

I.9.3.3 Production – Dewatered Cofferdam

Twenty of the bridge piers were constructed in dewatered cofferdams. The dewatered cofferdam provided the greatest reduction in peak SPLs created by impact pile-driving into the water column. This is due to the air within the dewatered cofferdam mostly decoupling the pressure wave from the surrounding water column, resulting in substantially lower underwater sound pressures transmitted outside of the cofferdam. However, flanking of sound through the ground substrate was detected in the region that was generally south of the piles. Sound pressures in this region reached about 200 dB peak (190 to 192 dB RMS) at about 100 to 150 meters (328 to 492 feet) from the pile. The sound pressures were lower nearer to the pile. Sound pressures in other directions were typically 180 dB peak (170 dB RMS) or less at all monitoring locations.

Figure I.9-7 SFOBB Pile Driving in dewatered cofferdam at Pier E7E (deepest cofferdam) using Menck 1700MHU

Each cofferdam included six 100-meter long, 2.4-meter diameter, piles that were driven into the bottom of the San Francisco Bay using 550 kiloJoule and 1,780 kiloJoule hydraulic hammers (see Figure I.9-7). Pier E16E included the first piles driven in a dewatered cofferdam in shallow water, with depths of mostly about 3 to 4 meters. The Menck MHU500T, providing about 550 kiloJoules of energy was used to drive the top half of this pile. About 200 feet of pile had been driven into the ground before these measurements were made. Sound pressures measured between 25 and 65 meters from the pile were mostly less than 180 dB peak, 170 dB RMS, and 160 dB SEL. Surprisingly, a position that was 95 meters west had much higher sound levels. At this position, sound pressures reached 196 dB peak, 184 dB RMS and 172 dB SEL. This was an isolated area around the pile, where sound levels were lower at all other positions. More extensive monitoring was conducted at Pier E15W near Pier E16E to investigate these higher sound levels. Again, a small area of substantially higher sound levels was found, while all other areas around the pile had much lower levels. In general, measurements made from 35 meters to 300 meters from the pile had sound pressure levels under 190 dB peak and 180 dB RMS. One isolated area at 70 to 80 meters southwest of the pile had levels 202 dB peak and 189 dB RMS near the end of the drive, when almost 100 meters of pile was driven into the ground. Measurements under similar conditions for Pier E12W found higher sound levels in fairly isolated areas. The area of elevated sound pressures was larger in area and had higher levels. While most levels around

the pile were 20 dB lower, the area about 100 to 150 meters from the piles in the west through south positions had sound pressures up to 205 dB peak and 194 dB RMS. These levels were measured during the final driving stages (deepest driving) when the MHU1700T hammer was used that is rated at 1,750 kilojoules. Measurements were made at Pier E11W when the bottom pile sections (i.e., first 50 meters of pile) were driven using the MHU500T hammer. In this case, most sound pressure levels were below 185 dB peak and 175 dB RMS, with the exception of the south through southeast directions. In these directions, sound pressures were elevated to about 190-195 dB peak, 180-183 dB RMS, 170-173 dB SEL. The highest levels occurred between 90 and 120 meters from the pile during the last 5 minutes of pile driving. Levels were lower both closer and further from the pile. Water depth was about 5 meters. This was the first 50-meter section of pile that was driven. Measurements were not made for the top portion when the MHU1700T hammer was used.

More extensive measurements were made for other piers with dewatered cofferdams, but in deeper water when only the top pile sections were driven with the MHU1700T hammer. Pier E10E included a full acoustic characterization during the driving of top pile sections. Measurements were made when both the MHU500T and MHU1700T hammers were used. Drop off rates were plotted for these driving conditions (see Figures I.9-8a and I.9-8b). For the most part, sound pressures were below 190 dB peak and 180 dB RMS in all directions except the louder isolated cases that typically occurred in the southerly direction. The loudest levels were found at 100 meters from these long piles. In the louder directions, highest sound levels were found at 100 meters from the pile, where sound pressures were 190 to 205 dB peak and 180 to 190 dB RMS. SEL levels analyzed for individual strikes showed roughly a –10-dB relationship to RMS levels.

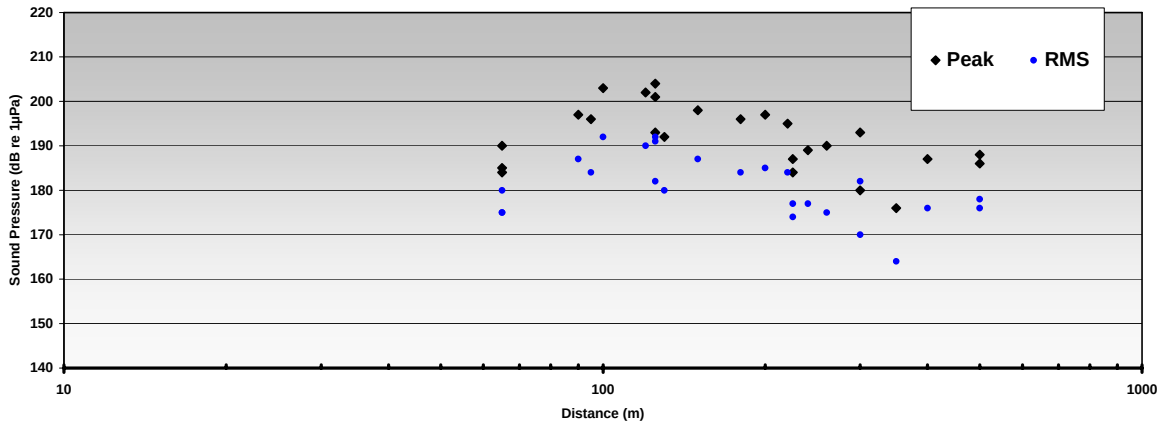


Figure I.9-8a Drop off in sound pressure levels with dewatered cofferdam in southerly (louder) direction

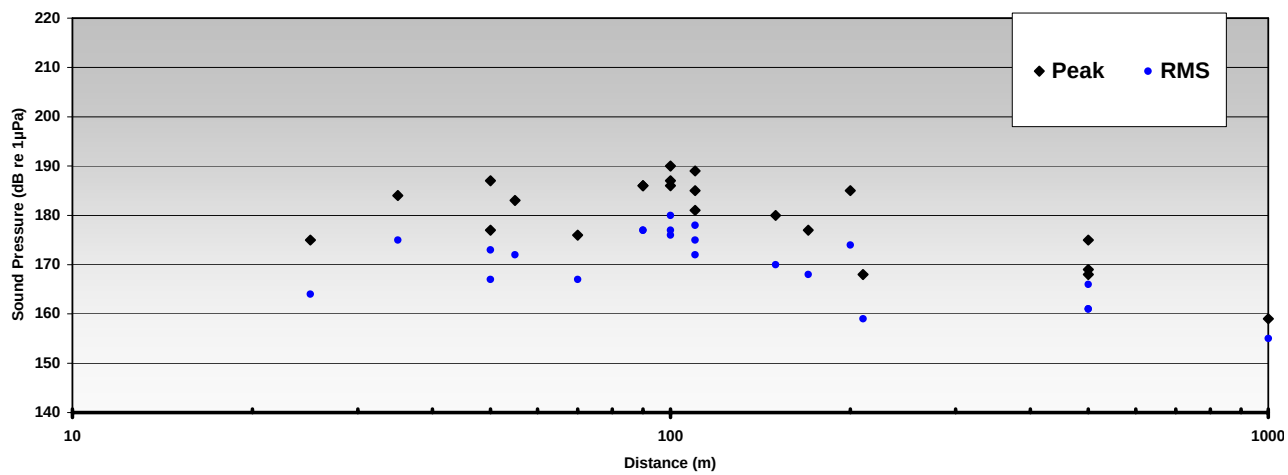


Figure I.9-8b Drop off in sound pressure levels with dewatered cofferdam in other (quieter) directions

These measurements at Pier E10E found that sound pressures were attenuated by 20 to 30 dB or more in all but the southerly directions, when compared to unattenuated open water conditions. Relatively and unexpectedly high levels were measured to the south beyond 100 meters from the pile (primarily south-southeast). These levels were only attenuated by about 5 to 10 dB. In fact, peak pressures as high as 204 dB were measured at 120m south-southeast for Pier E10E. Sound pressures were about 5 to 10 dB lower in the southwest direction, indicating some focusing of these relatively high sound pressures. Some additional measurements made during the driving of a pile at Pier E9E confirmed these findings. These measurements also found levels as high as 170 dB peak just off the east side of Yerba Buena Island (about 2,000 m [6,560 feet] west)[2] while measurements at 100m (328 feet) west were 187 dB peak. More limited measurements were made at Pier E7E, which is the most westerly pier where a dewatered cofferdam was used. Interestingly, Pier E7E is located near Pile 3 of the PIDP. Measurements indicated that the reduced levels were present in the northerly direction as well as the southerly direction. However, higher levels were seen to the southeast. The highest level measured in that direction was about 195 dB peak at 220m (720 feet). At 100m (328 feet) south, pressures were about 5 to 10 dB lower than with the air bubble curtain on at Pile 3 during the PIDP. At 500m (1,640 feet) south, peak pressures were about 3 to 5 dB lower than the PIDP Re-strike Pile 3 air bubble curtain "on" conditions. At 200m (656 feet) north, the cofferdam levels were about 2 dB lower than the air bubble curtain "on" conditions with PIDP Re-strike Pile 3.

Signal Analysis for Dewatered Cofferdam Measurements

Signal analyses of representative pulses generated from pile driving in dewatered cofferdams were examined from data at Piers E16E and E10E. Pile driving in dewatered cofferdams eliminates the direct coupling of the steel pile and the water. Ground-borne propagation of the pulse is believed to have resulted in localized areas of low-frequency sound in the water generally south of the piers. At Pier E16E, signal analyses (see Figure I.9-9 and Figure I.9-10 and note that pressure scales are different) are presented for one depth at two distances, 95 meters (312 feet) and 50 meters (164 feet). Note that water depth around Pier E16E was relatively shallow, about 1.5 to 3meters (5 to 10 feet). These data provide illustrations for signals associated with the unusual findings at this pier where localized sound pressures were higher at further distances than closer distances. Of particular interest in these charts is the relatively slow accumulation of sound energy where the signal was heavily attenuated at the 50-meter

[2] This level was measured in water near Yerba Buena Island during hydroacoustic measurements conducted to measure blasting on the island as part of the W2 pier construction project.

position. It can also be seen that sound energy is concentrated in the low frequency region below 400 Hz. Low frequency sound will not propagate in very shallow water. The pile extends down to 100 meters (328 feet) below the mud line when driving is complete. The pulse also propagates through the ground and radiates into the water at the mud line. The source of this sound is ground-borne vibration caused by the pile interacting below the mud line. Signals for pulses measured during pile driving at other dewatered cofferdams showed similar characteristics. Some of the measurements made close to the cofferdam, included some high frequency sounds, but these were of low amplitude. The highest amplitude sounds measured for the dewatered cofferdam condition for this project (about 120 meters southeast of Pier E10E) had low frequency characteristics similar to that measured 95 meters west of Pier E16E.

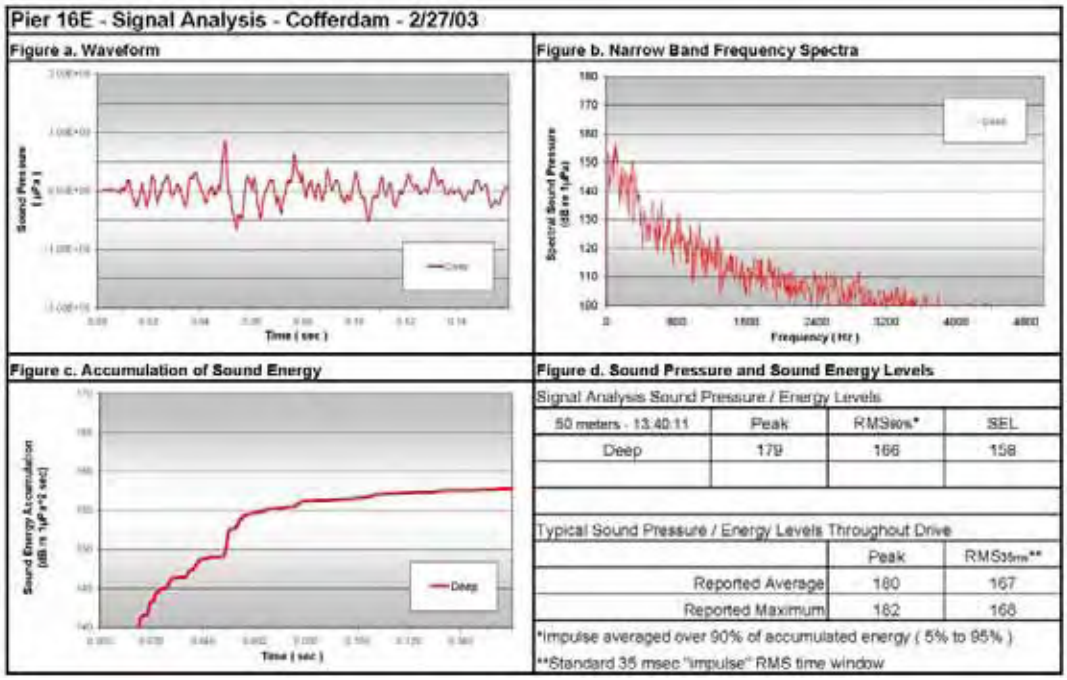


Figure I.9-9. Pulse from pile driven in dewatered cofferdam at Pier E16E (very shallow water) measured 50 meters from Pile. San Francisco-Oakland Bay Bridge East Span Replacement Project

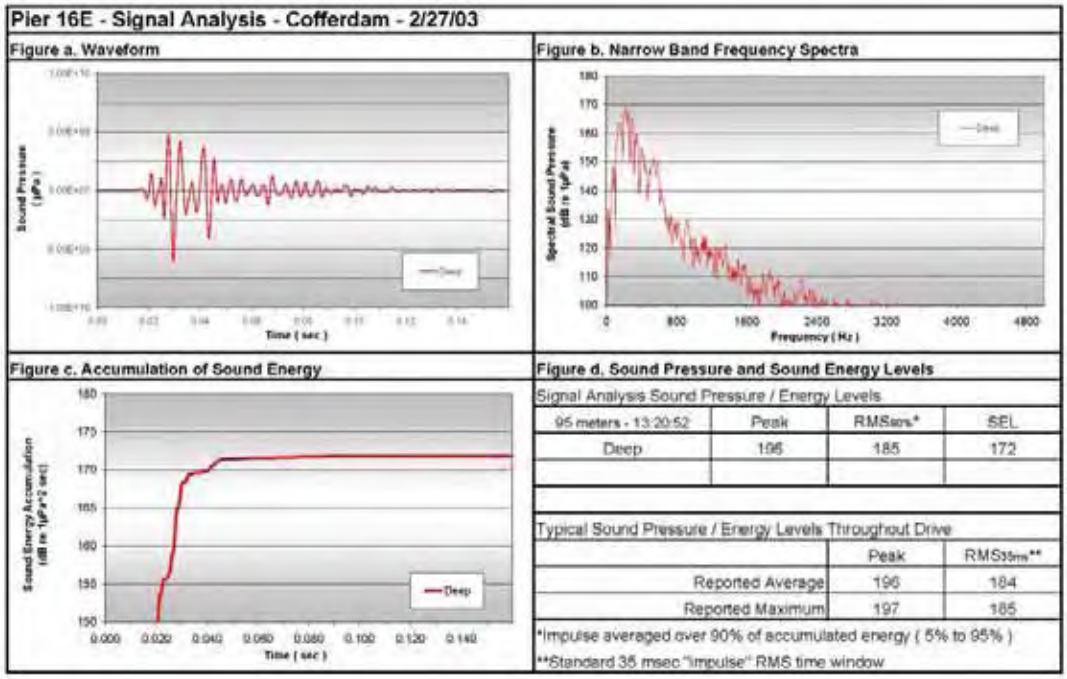


Figure I.9-10. Pulse from pile driven in dewatered cofferdam at Pier E16E (very shallow water) measured 95 meters from Pile. San Francisco-Oakland Bay Bridge East Span Replacement Project

Time History of Sound Pressures – Dewatered Cofferdam

Sound pressures from individual pile-driving pulses vary throughout the driving of a particular pile, the variability and the amplitude of the measured signals at a particular location, and the duration of pile driving. An example of these variations are shown in Figure I.9-11 for peak pressures measured almost continuously during a day of Pile driving at Pier E10E when hydroacoustic characterization was performed. Continuous measurements of the top sections of a group piles at Pier E10E were measured at three distances (about the 50m [164 feet] north 100m [328 feet] north and 120m [394 feet] southeast positions). These data are interesting, because they illustrate the levels associated with the two different hammers and how they varied over time. Measurements at 50m (164 feet) and 100m (328 feet) varied, where levels were not always lower at 100 meters (328 feet) as one would expect. They also show that levels did vary by 5 dB or more over the particular driving periods, where all sites tended to show the same trend in levels, but there were exceptions. While levels showed similar trends for piles 4 and 5, all three positions had different trends for pile 6 when the large hammer was used. In general, levels measured with the MHU1700T hammer were slightly higher than levels measured with the MHU500T hammer. These data demonstrate that there is no simple relationship between received sound pressure level, position and hammer energy, especially when the source of the sound is ground-borne.

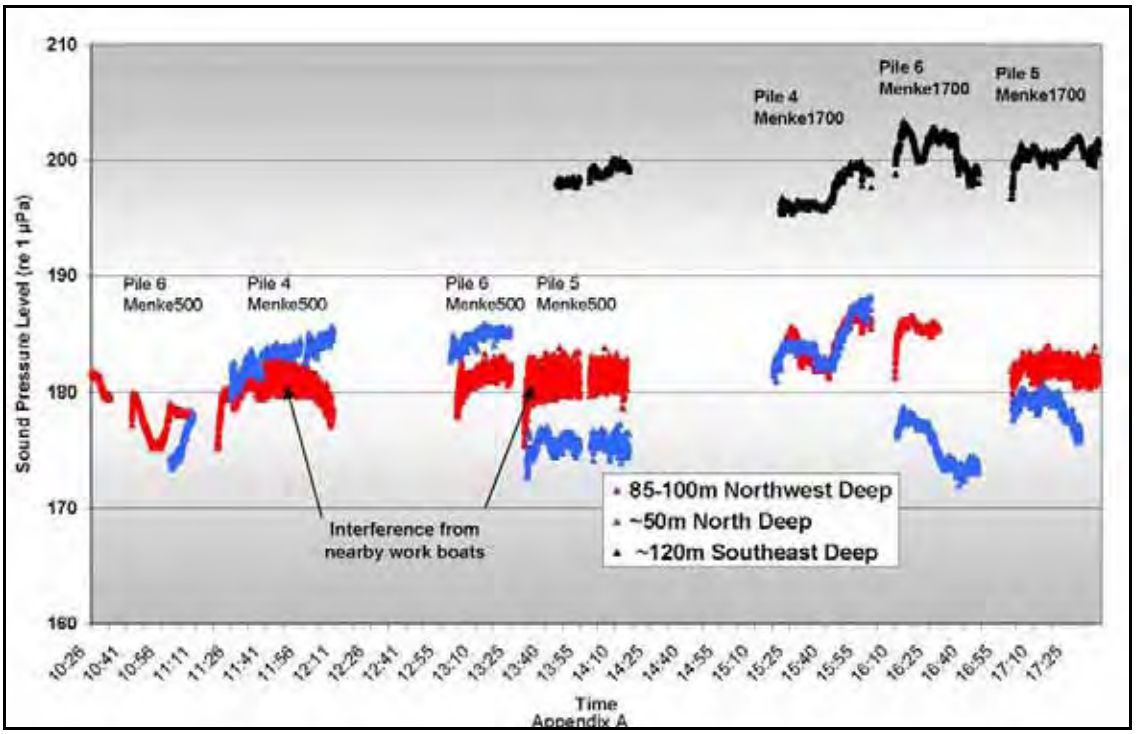


Figure I.9-11. Peak pressures measured at three different positions during the course of pile driving in one day at Pier E10E (dewatered cofferdam). San Francisco-Oakland Bay Bridge East Span Replacement Project

I.9.3.4 Production – In-Water Piers

The air bubble curtain system was used to attenuate underwater noise levels for the 8 piers that were located in deeper water (Piers E6E and E6W through E3E and E3W). Water depths ranged from about 10 to 12 meters at Pier E6E and E6W to almost 15 meters at Piers E3E and E3W. Sound pressures were reduced by the air bubble curtain, as evidenced by comparing sound pressures generated during production pile driving with those measured during the PIDP and PIDP Re-strike. The air bubble curtain system was tested by measuring sound pressures at certain distances with the system on and off. Air bubble curtain performance is discussed later.

Resulting sound pressures typically ranged from about 190 to 205 dB peak and 180-193 dB RMS at 50 m to 190 to 200 dB peak and 180 to 185 dB RMS at 100 m. At positions close to the pile (i.e., 100 to 200 meters), sound pressures were always highest on the upstream side of the air bubble curtain system where bubbles tended to be washed away by the tidal currents. At 500m there was a wide range in sound pressure levels of 170 dB to 190 dB peak and 160 to 178 dB RMS. Sound pressures measured at 500 m (1,640 feet) or further away were likely comprised of mostly ground borne sounds, and therefore, were mostly unaffected by the air bubble curtain. Measurements were made very close to the piles at Pier E5E and Pier E3E. Sound levels at measurement positions downstream and normal to the current indicate substantial attenuation with highest levels next to the bubble curtain of 200 to 205 dB Peak and 185 to 195 dB RMS. When a current was present, sound pressures were much higher at the upstream side. For instance, a peak sound pressure of 215 dB and RMS of 199 dB was measured next to the bubble curtain on the upstream side, while positions normal or downstream of the current were 10 to 15 dB lower. Measurements were made out to 4,400 meters in both north and south directions. Sounds from pile driving could be measured at a position 2,000 meters north of the pile where peak pressures were 169 dB and RMS levels were 162 dB. At 4,400 meters north, pile driving was barely audible, but reliable measurements above background of 130 dB RMS could not be made. Sounds at 2,000 and 4,400 meters

to the south were not audible above background noise levels of 130 to 140 dB. Waters 2,000 to 4,400 meters south were shallower. Separate measurements made for a different pier indicated peak pressures of 170 dB peak and 162 dB RMS at 2,200 meters north.

The maximum levels measured were 220 dB peak, 201 dB RMS and 190 dB SEL at a distance of 5 to 7 meters from the pile (the average was about 5 dB lower). This was an unattended measurement made inside the pile-driving template at the closest position that could be measured with the air bubble curtain system operating. The lowest levels measured were undetectable, below about 130 dB RMS, at 2,000 meters south and 4,400 meters north.

Figure I.9-12 shows the plot of measured peak and RMS sound pressures over distance. Sound pressures were estimated to drop off at a rate of 18 to 19 dB per 10-fold increase in distance from the pile. The drop off rate was highly variable due to air bubble curtain performance for near source measurements and variable groundborne sound radiation for distant positions. About 10 dB of variation was recorded for all measurement distances. Obviously, a single measurement point cannot be used to describe sound radiated from this pile driving activity.

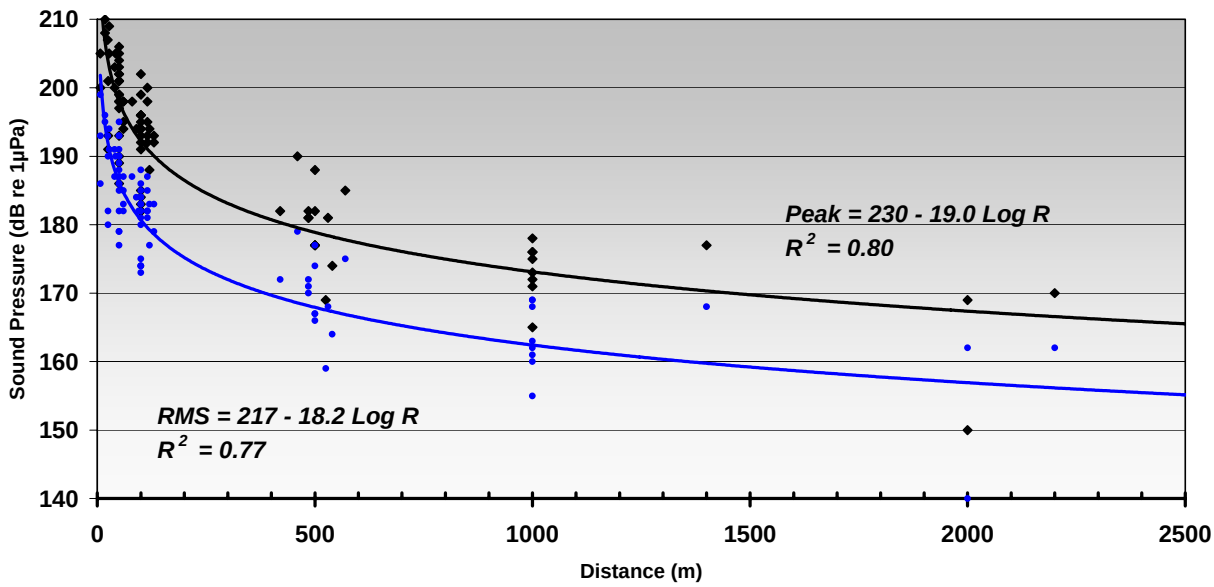


Figure I.9-12. Drop off in sound pressure levels with the air bubble curtain system during in-water pile driving. San Francisco-Oakland Bay Bridge East Span Replacement Project

Since currents usually ran north-south, measurements to the east or west were generally unaffected by their effect on the air bubble curtain system. Measurements were generally louder to the west, where waters were deeper, than to the east. At 100 meters, the variation could be about 5 dB. At 500 meters, the variation increased upwards to 20 dB.

Most measurements were made at two depths: two meters below the water surface and two meters above the water bottom. Measurements at the deeper sensor were usually slightly higher, especially for RMS sound pressure levels. Higher peak pressures were infrequently measured at the shallower sensor, while the corresponding RMS levels was similar or slightly lower than the RMS level measured at the deeper sensor. A test of sound levels for different depths at Pier E4E indicated that sound pressure levels were fairly uniform from near the bottom up until almost one meter below the surface. For depths 1 meter or less, sound pressures were substantially lower and difficult to measure.

Signal Analysis for In-Water Pile Driving

Signal analysis was conducted for representative pulses at the Piers where measurements were conducted for in-water pile driving (Piers E6E, E5E, E3E, E4E, E3W, and E4W). An air bubble curtain system was used to reduce sound pressures, except for brief periods of testing at Piers E6E, E3E, and E4W. In all, hundreds of signals were analyzed and presented in project reports[8,9,10,11]. Figures I.9-13 through I.9-17 show the pulses from pile driving for distances of 55 meters, 110 meters, 570 meters, 1,400 meters and 2,200 meters generally to the north of the pile driving. These illustrate the attenuation of these pulses as one moves further from the pile. These examples were chosen for the direction that had the lowest rate of attenuation, which appears to be caused by the pulse transmitted through the ground.

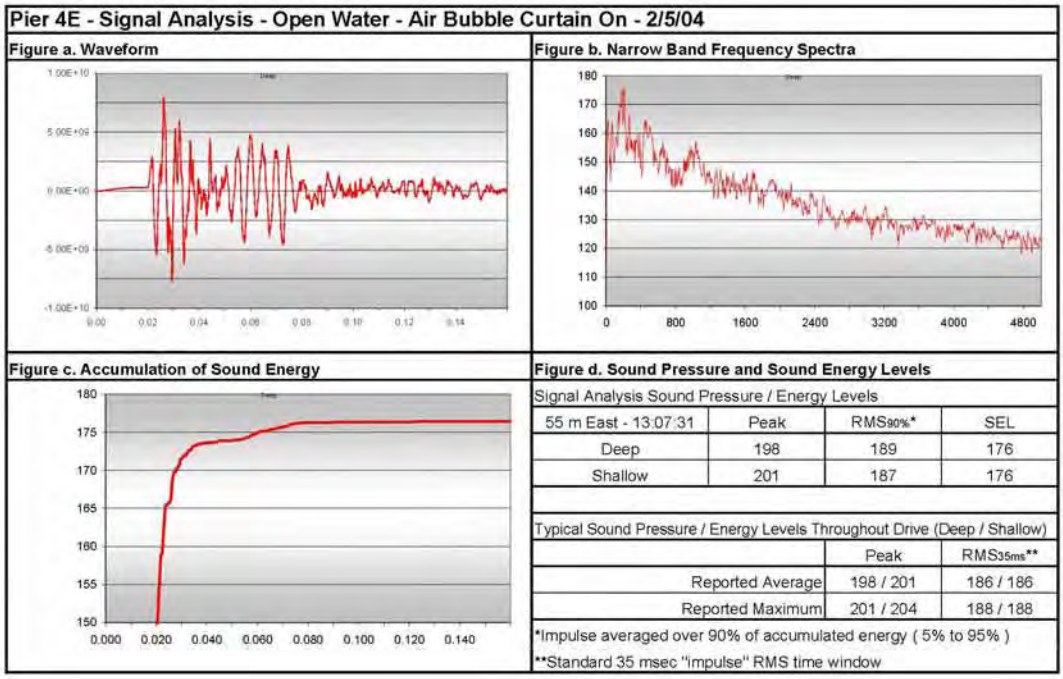


Figure I.9-13. Pulse from pile driven in in water with air bubble curtain at Pier E4E measured 55 meters from Pile. San Francisco-Oakland Bay Bridge East Span Replacement Project

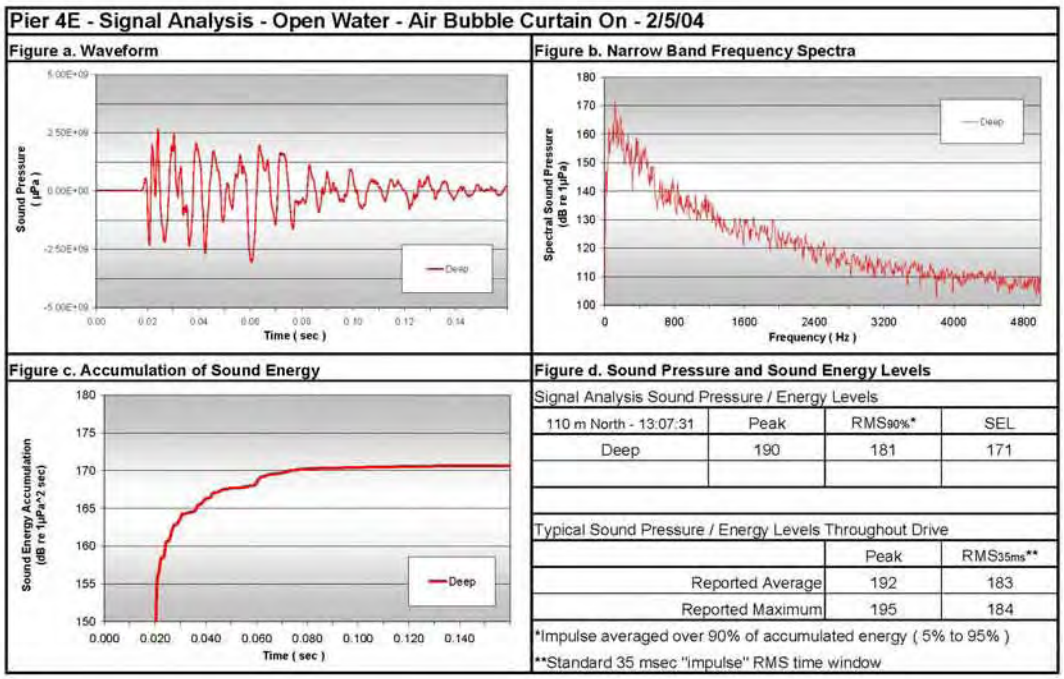


Figure I.9-14. Same as Figure I.9-11, except 110 meters from pile. San Francisco-Oakland Bay Bridge East Span Replacement Project

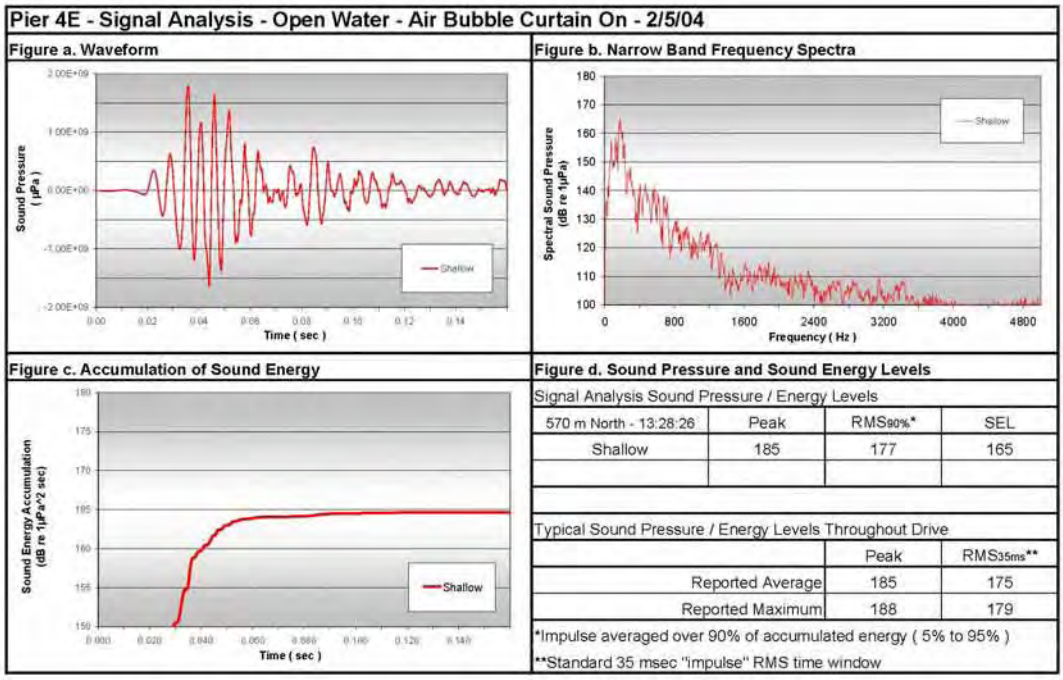


Figure I.9-15. Same as Figure I.9-11, except 570 meters from pile. San Francisco-Oakland Bay Bridge East Span Replacement Project

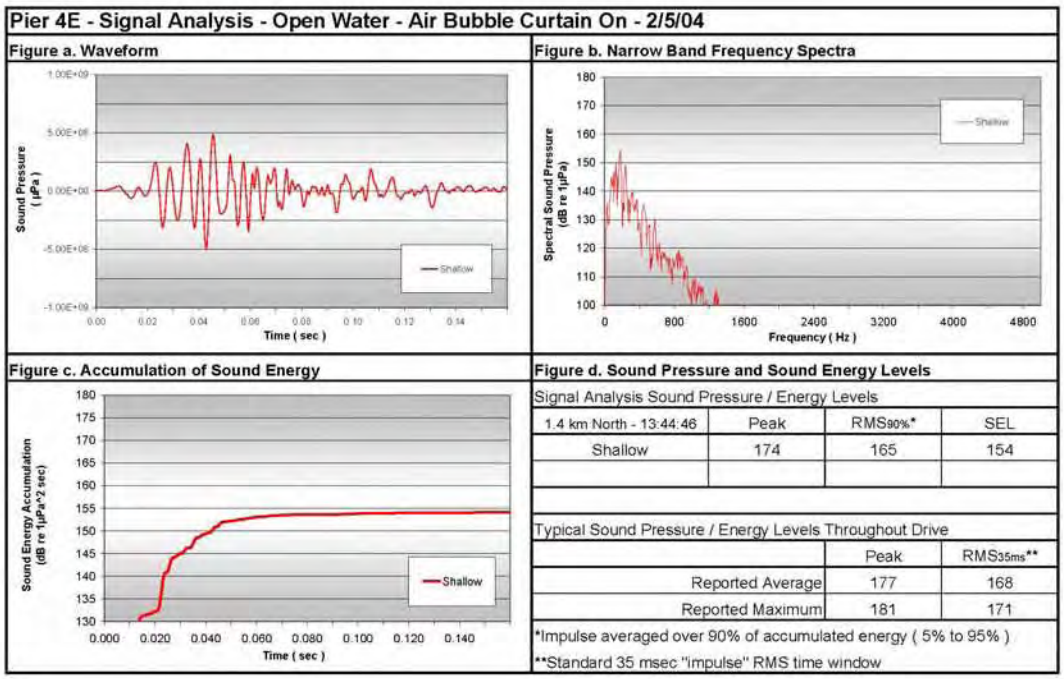


Figure I.9-16. Same as Figure I.9-11, except 1,400 meters from pile. San Francisco-Oakland Bay Bridge East Span Replacement Project

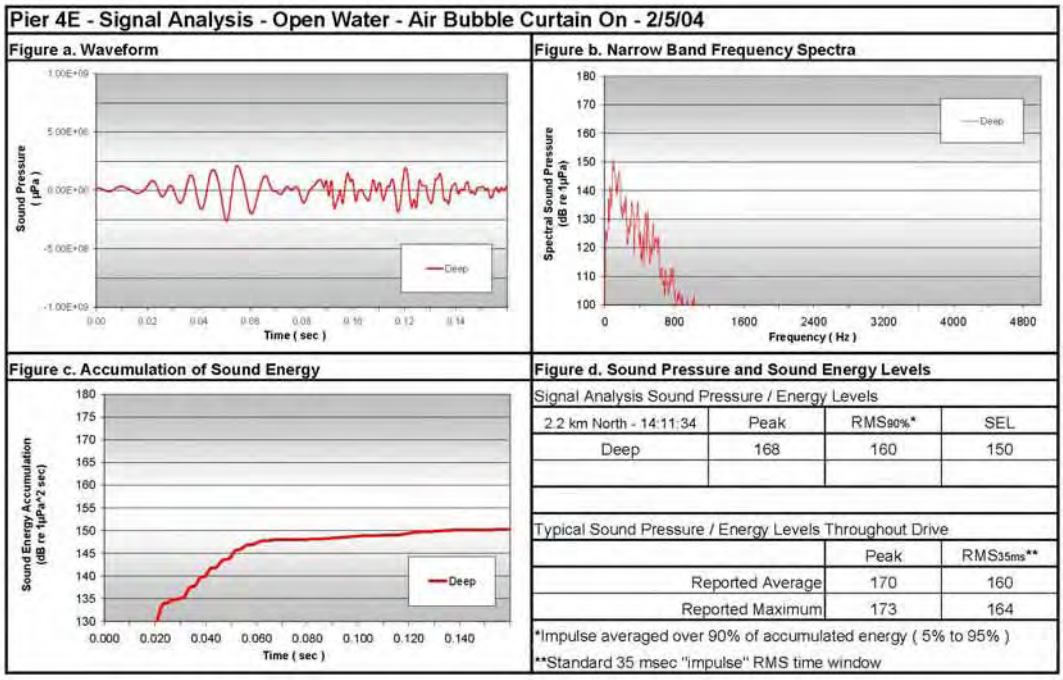


Figure I.9-17. Same as Figure I.9-11, except 2,200 meters from pile. San Francisco-Oakland Bay Bridge East Span Replacement Project

Caged Fish Studies

Fish cage monitoring with hydrophones was conducted in late 2003 and 2004 as part of the *Fisheries Hydroacoustic Monitoring Program*. The fish were exposed to sound pressure levels of up to 209 dB peak, 192 dB RMS and 182 dB SEL at distances as close as 24 meters from the pile. A complete

discussion of the results of this study and associated measured sound pressure data are included in the *Fisheries and Hydroacoustic Monitoring Program Compliance Report*[8] and the addendum to that report[10]. These reports include acoustical signal analyses of the pile-driving sounds measured in the cages containing the fish.

Air Bubble Curtain Tests

Underwater sound measurements conducted when the air bubble curtain was turned on and then off at Piers E6E and E3E indicate a large variation in air bubble curtain performance. The underwater sound measurements obtained from these tests indicated that, in general, peak sound pressures were reduced by about 5 to 20 dB at positions of about 100 meters or closer. The reduction was less for positions further away where the contribution of ground-borne sound was probably substantial and the higher frequency sound was naturally attenuated. Both air bubble curtain tests were conducted under relatively strong currents, which had an effect on the attenuation performance. The bubble curtain performance could be reduced somewhat under relatively strong currents. On the upstream side, the current tends to wash bubbles past that side of the pile, resulting in higher sound pressures. The pier cap appears to provide some attenuation of the sound pulse, since unattenuated sound pressures measured at 100 meters for Pier E6E were lower than unattenuated sound pressures measured during the Pile Installation Demonstration Project or PIDP. The PIDP piles did not include a pier cap and Pier E6E is fairly close to Pile 3 of the PIDP, making a comparison possible.

Table I.9-3 summarizes the sound pressure levels measured at Pier E6E. The air bubble curtain system was turned on and off during the driving of the north and south piles at Pier E6E. A fairly strong north to south flood current was present during these tests. Measurements were made at several positions. Pier E6E was not the ideal pier to conduct the on/off tests since it is in the shallowest water where piles are driven without a cofferdam and the pier box extends about 2/3rds of the way from the water surface to the bay bottom, leaving only 1/3rd of the pile or about 3 to 5 meters exposed to the water. Measurements made at positions 45 meters (148 feet) west, 50 meters (164 feet) north, 100 meters (328 feet) west, 100 meters (328 feet) south and 100 meters (328 feet) north found that sound pressures were 8 to 10 dB higher when the bubble curtain was turned off during the first test. A 1 to 2 dB reduction was measured 500 meters (1,640 feet) south. During the second test, a 2 to 9 dB reduction was measured. The 9 dB difference measured at 100 meters (328 feet) south was consistent with the first test. The 2 dB difference measured at 50 meters (164 feet) north was not consistent with the first test and indicated poorer bubble curtain performance in the upstream side; however, the overall unattenuated level was 3 dB lower than the first test. A 1-2 dB difference was measured at about 500 meters (1,640 feet) south and 400 meters (1,312 feet) west.

Table I.9-3. Summary of measurements - Pier E6E Bubble Curtain ON/OFF Test, 11/21/2003.

Position	Water Depth	ON		OFF	
		RMS	Peak	RMS	Peak
North Pile					
45m West	6m	187	200	196	210
50m North	6m	191	203	196	210
100m West	6m	182	194	188	201
120m North	6m	177	188	184	196
485m South	8m	172	182	174	182
South Pile					

45m West	6m	191	203	196	210
50m North	6m	195	206	197	208
100m West	6m	184	194	190	203
420m West	7m	171	181	173	183
485m South	8m	172	182	173	184

A brief test with the bubble curtain off for one minute of hammer strikes was conducted at Pier E3E. Pier E3E was in about 12 to 15 meter deep water. Measurements were made at 25 m (82 feet) north, south, and west, as well as an additional position 50 meters (164 feet) north. No distant measurements were made during this brief test. A strong flood current (flowing from north to south) was present during the test. At the 25-meter (82-foot) positions, differences of 11 to 18 dB peak (9-15 dB RMS) were measured. At the downstream position (south) the difference was 18 dB (15 dB RMS). At the position normal to the current, the reduction was similar. The upstream positions had differences of 10 dB at 25 meters (82 feet) and 13 dB at 50 meters (164 feet). There was a typical variation of 5 to 7 dB from pulse to pulse (or strike to strike) at the south position when the bubble curtain was on. The variation at the north and west positions was only about 1 to 2 dB. Results are shown in Table I.9-4. The attenuation provided by the air bubble curtain at 50 meters north of the pile is clearly shown in Figure I.9-16.

Table I.9-4. Summary of measurements - Pier E3E Bubble Curtain On/Off Test,

Position	Water Depth	ON		OFF	
		RMS	Peak	RMS	Peak
Center Pile					
50m North	11m	187	199	197	212
25m North	11m	190	201	199	212
25m South	11m	182	193	198	211

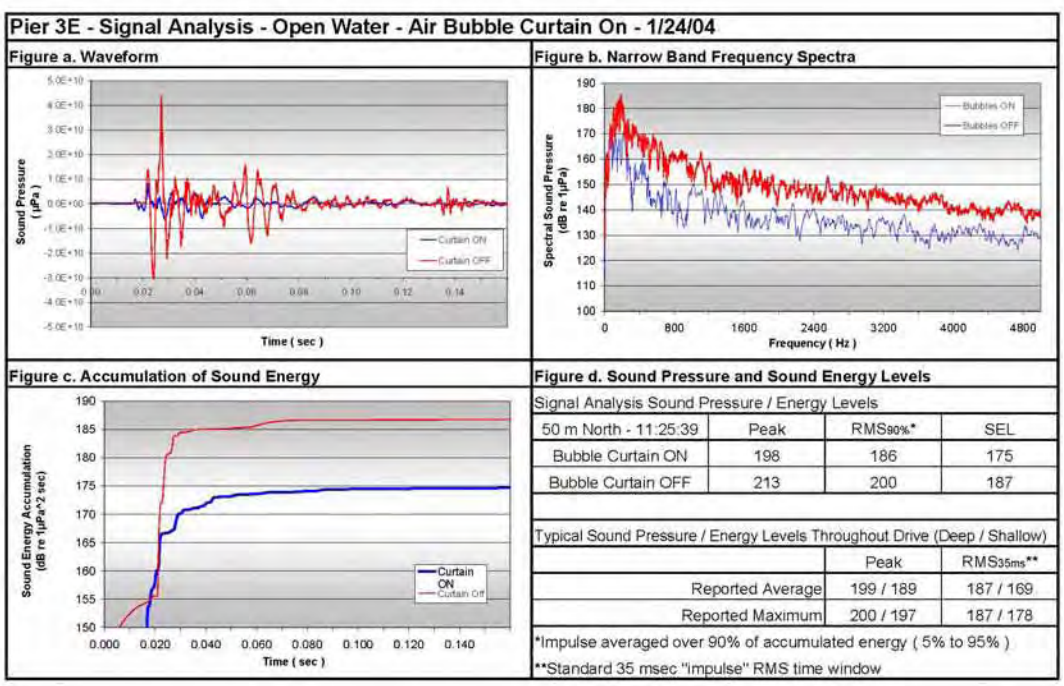


Figure I.9-18. Pulse for attenuated and unattenuated piles strikes during air bubble curtain test at Pier E3E measured 50 meters from Pile. San Francisco-Oakland Bay Bridge East Span Replacement Project

A subsequent air bubble curtain on/off test at Pier E4W indicated much less attenuation and a possible problem with the air bubble curtain. In addition, there were irregular rates of attenuation in different directions. For instance, both peak and RMS sound pressures were lower towards the east than at other positions of similar distance. The underwater sound measurements obtained during the Pier E4W air bubble curtain on/off test indicated that the bubble curtain reduced peak sound pressures by approximately 0 to 8 dB. This was less than the 5 to 20 dB reduction previously measured at Piers E6E and E3E. Measured sound pressures with the air bubble curtain system were generally higher than other in-water piles with the air bubble curtain operating. The subsequent hydroacoustic characterization for Pier E3W indicated much better bubble curtain performance, where peak sound pressures were less than 190 dB at 100 meters (328 feet) from the piles. There is no available explanation for the reduced air bubble curtain performance at Pier E4W during this test.

Although air bubble curtain on and off tests were not conducted at Pier E5E, the close-in measurements describe sound pressure very close to the pile to characterize the air bubble curtain performance in different directions. With ebb current (flowing south to north) underwater sound pressures were found to vary considerably from north to south. This difference is illustrated in the charts that show data 7 m (25 feet) north and 7 m (25 feet) south of the pile. These charts, shown in Figure I.9-17, illustrate the rapid rise time and high peak pressure, as well as the higher frequency noise levels close-in to the bubble curtain system.

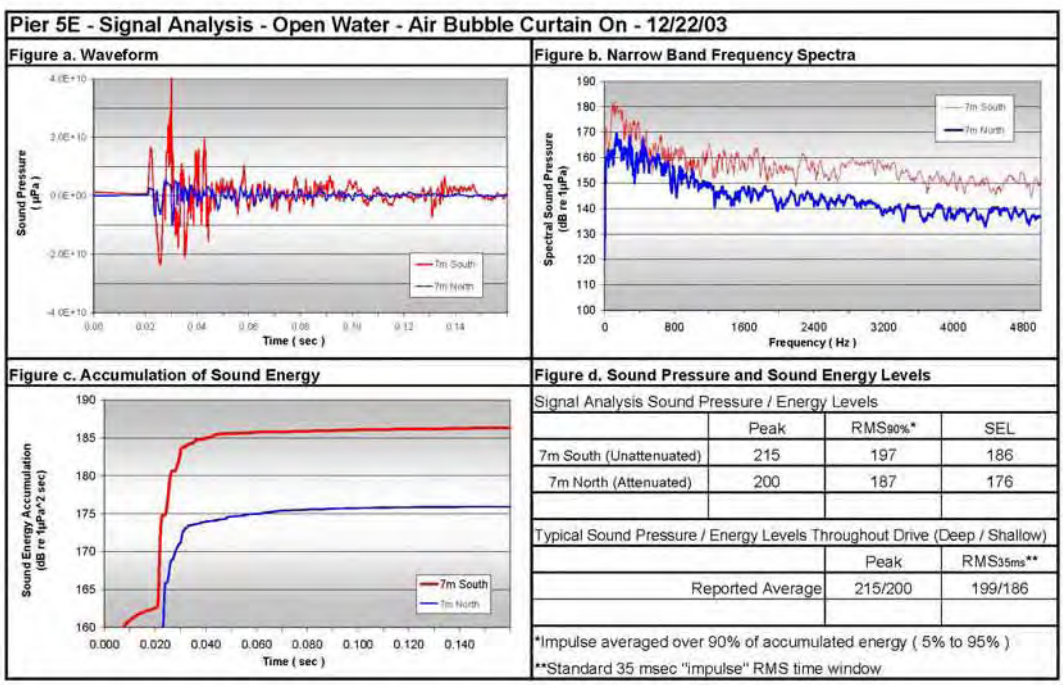


Figure I.9-19. Pulses for attenuated and unattenuated pile strikes at edge of air bubble curtain system, 7 meters from pile. Bubbles to south of pile were being washed away by tidal current. Pier E5E at San Francisco-Oakland Bay Bridge East Span Replacement Project

I.9-5 Greeneridge Sciences Measurements at Pier E6E

Greeneridge Sciences, Inc. also made underwater recordings on during driving of piles at Pier E6E. The piles driven were the top sections of the piles. The Greeneridge Sciences Inc. measurements were conducted independently of the Illingworth & Rodkin, Inc. measurements to provide an independent check, to provide supplemental data, and insights into the data. A comparison of the measured sound pressures at a location approximately 100 meters (328 feet) west and a location about 500 meters (1,640 feet) south are shown in Table I.9-5. The data show excellent correlation between the two separate measurements.

Table I.9-5. Comparison of Greeneridge Sciences, Inc. and Illingworth & Rodkin, Inc. Data Monitored at Pier E6E 11/21/2003 – Deep Sensor Position

Location	Measured Sound Pressure Levels in Db					
	Peak		RMS*		SEL	
	I&R	GS	I&R	GS	I&R	GS
100m west						
MHU 500T Bubble ON	196	196	183	184	--	172
MHU1700T Bubble ON	194	197	184	185	172	174
MHU1700T Bubbles OFF	203	204	190	191	178	180
485-500m south						
MHU 500T Bubble ON	180	181	170	169	160	160
MHU1700T Bubble ON	181	182	171	170	161	161
MHU1700T Bubbles OFF	183	184	173	174	164	164

* Note that GS averages over the duration of the pulse ($RMS_{90\%}$), while I&R averages over a 35-millisecond time constant ($RMS_{impulse}$)

I&R = Illingworth & Rodkin, Inc.

GS = Greeneridge Sciences, Inc.

With the air bubble curtain system operating, Greeneridge Sciences Inc. measured peak sound pressures of 197 dB (SPL of 185 dB) at 100 m (328 feet) at their deep sensor. Sound pressures were 3 to 5 dB lower at their shallow sensor position. The pulse duration (time interval of the arrival of 5% and 95% of the total energy) was about 0.08 seconds. Spectral analyses of the pulses found much of the energy in the frequency range of 160 to 400 Hz, similar to that shown by I&R for Pier E6E at 100m (328 feet) west. Greeneridge Sciences, Inc. found the air bubble curtain system to reduce peak sound pressures by 7 dB at 100 m (328 feet) and 2-3 dB at 500 m (1,640 feet). The corresponding reductions in RMS levels were about 6 and 4 dB, respectively. I&R found reductions of peak pressures of 9 dB at 100 m (328 feet) and 2 dB at 500 m (1,640 feet). The corresponding reductions in RMS levels were 6 and 2 dB.

The complete description of the underwater measurements conducted by Greeneridge Sciences, Inc. is included as Appendix D to this report. The report includes an introduction, a description of their methods, instrumentation, analyses, results and their perspective on these data in comparison to other pile-driving sound measurements conducted by their firm and others.

References

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I.10 Richmond-San Rafael Bridge

Between 2002 and 2004, the California Department of Transportation (Caltrans) performed construction to retrofit the Richmond-San Rafael Bridge (RSRB) to meet current seismic standards. This vital freeway bridge (Interstate 580) crosses the northern portion of the San Francisco bay, connecting Marin and Contra Costa counties. The bridge consists of a cantilever section with stacked roadways that crosses 185 feet over the main channel and the trestle section with side-by-side roadways that crosses the relatively shallow Bay waters near Marin County (see Figure I.10-1).

The seismic retrofit activities included the installation of over 760 cylindrical steel piles over the three-year period using impact pile drivers. The piles ranged in size from 0.3 meters (14 inches) to 3.8 meters (12.5 feet or 150 inches) in diameter. The piles were installed using a variety of pile driving hammers, depending on the size of the pile. Underwater sound measurements were made for different piles driven during the seismic retrofit construction of the Richmond-San Rafael Bridge[1,2,3,4]. These include the following:

- Permanent 0.36m (14in) diameter steel pipe piles (fender piles)
- Temporary 0.76m (30in) diameter steel pipe trestle piles
- Permanent 1.7m (66in) diameter steel pipe trestle piles
- Permanent 3.2m (126in) diameter steel pipe piles
- Permanent 3.8m (150in) diameter steel pipe piles

Figure I.10-1 Richmond-San Rafael Bridge viewed from San Rafael, CA

The 30in and 66in diameter piles were driven along the trestle part of the bridge in relatively shallow water (about 2m to 5m deep). These piles were only driven at night due to the need for traffic control and lane closures. The permanent 14in fender, 126in, and 150in piles were driven to support existing piers of the cantilever sections. Driving of these piles occurred in relatively deep waters (about 13 to 15 meters). Water conditions near the bridge are hazardous due to boat traffic, wind, rough seas, and strong currents. Because of these conditions, optimum measurement positions could not always be accessed. Results of measurements made for each of these piles are described below.

Underwater sound pressure measurements were made during pile driving for the Richmond-San Rafael Bridge Seismic Retrofit. These included measurements for 14- and 30-inch steel pipe piles, 66-inch steel CIDH piles and 126- and 150-inch CISS piles. The performance of an air bubble curtain system was tested (in terms of reducing sound pressures) for the 30-inch steel pipe and 66-inch CIDH piles. The 30in steel pipe and 66-inch CIDH piles along the trestle section could only be measured from the temporary false work that was between the two side-by-side roadways. The 14-inch steel pipe and large CISS piles that were driven in deep water were measured from a boat.

Permanent 0.2-meter (14-inch) Diameter Steel Pipe Fender Piles

Access to the construction area was difficult, so measurements were only conducted in a limited number of positions. Since water was deep, measurements were made at about 10-meter depths. Measurements were conducted for five different driving events. Figure I.10-2 shows a typical pile installation near a bridge pier. Each event was relatively short, some lasting less than a minute. All measurements were made when a Del-Mag D19 hammer was used at energies of about 40 to 45 kilojoules. Measurements were conducted at various distances summarized in Table I.10-1.

Figure I.10-2 14-inch Pile being driven next to pier at Richmond-San Rafael Bridge

Table I.10-1 Typical Range of Sound Pressures Measured for 14-inch diameter steel pipe piles measured for the Richmond-San Rafael Bridge

Position	Sound Pressure Measured in dB		
	Peak	**RMS**	**SEL**
22 meters	190 – 196 max. 198	178-180 max. 182	170
28 meters	185 - 191	169 - 171	--
40 meters	187 – 191	174-178	165
50 meters	185 – 190	173-176	--
195 meters	169 – 172	157-159	--

Sound pressures of up to 198 dB peak, 182 dB RMS, and 170 dB SEL were measured at 22 meters from the pile. The piles were driven adjacent to a pier, and therefore, this pier obstructed sound propagation in some directions. All of the measurements were conducted with the line of sight to the pile unobstructed. The rate of attenuation of sound ranged from 5 to 10 dB per doubling of distance. Figure I.10-3 shows the signal analysis of two representative pulses measured at 22 meters from the pile. The narrow-band frequency spectra for these piles include substantial higher frequency sound content (between 100 and about 5,000Hz). This ringing that occurred, resulted in pulse duration that exceeded 100 milliseconds, and 90% of the acoustical energy was contained within 60 to 80 milliseconds. The high frequency content of this pulse is evident from the waveform.

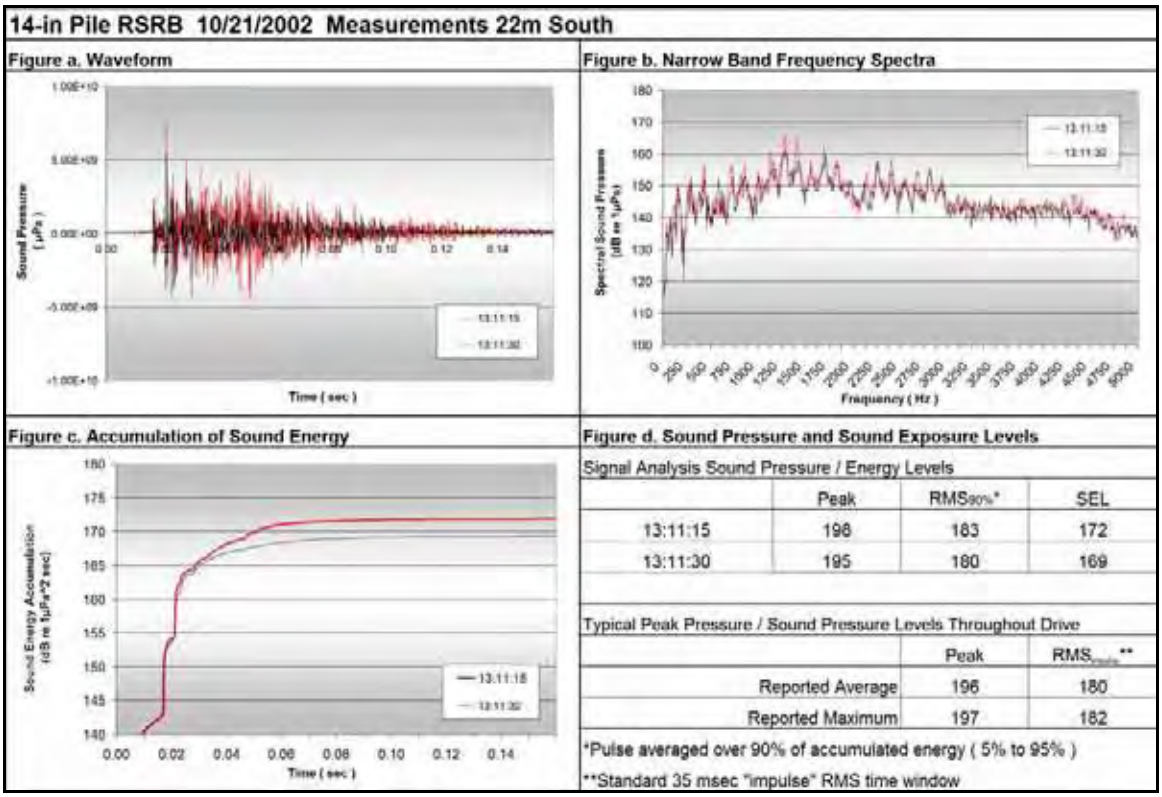

Figure I.10-3 Representative signal analysis for 14-inch diameter pile. Pulse received at 22 meters from the pile at Richmond-San Rafael Bridge

Temporary 0.9-Meter (30-inch) Steel Pipe Trestle Piles

The 30-inch piles were driven to support a temporary construction trestle between the two directional roadways along the trestle portion of the bridge. As a result, measurements were made in a straight line direction east of the pile driving. The piles were driven with a Del-Mag D-30 or D-62 diesel impact hammer. Reported driving energies were 150 to 170 kilojoules. The driving periods for these piles were relatively short, lasting about 2 to 4 minutes of continuous strikes (one strike per 1.5 seconds). The piles were first stabbed using the weight of the pile and the hammer to sink them into the mud. Then "dry" blows were used infrequently to tap the pile. These piles were driven in relatively shallow waters that were 4 to 5 meters deep. A view of the trestle is shown during evening in Figure I.10-4. Note that these piles were driven at night, because road closures were required for safety reasons. Two lanes of traffic are located immediately adjacent of the plywood barriers along the trestle. At most, two piles were driven at night, sometime between 10:00pm and 4:00 am. Measurements were conducted at various distances in the easterly (deeper) direction and are summarized in Table I.10-2.

The driving of four piles was measured on two separate nights. Measurement depths were 2 to 3 meters. The continuous driving events were relatively short, lasting 2 to 4 minutes or less. During two of the events, there were periods of several minutes prior that included sporadic hits to the pile. These sporadic hits resulted in relatively low sound pressure levels. Sound pressures ranged from 205 dB peak and 190 dB RMS at 10m to 195 dB peak and 169 dB RMS at 60 meters. Measurements for all four pile driving events were made at 20 meters, which all indicated unattenuated peak pressures of 200 dB. The measurements were made in relatively shallow water (about 3m deep), and therefore, levels lower than those from deeper-water piles were expected.

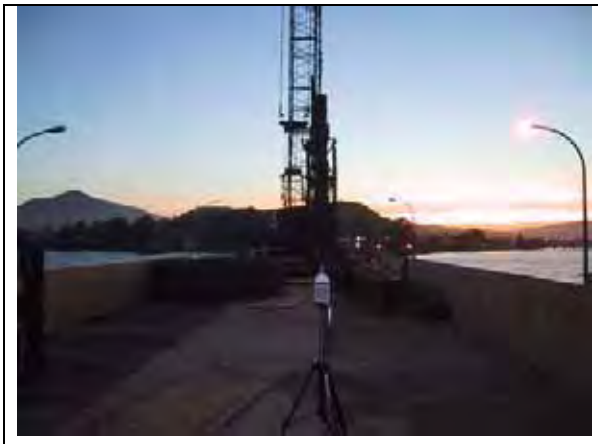

Figure I.10-4 30-inch Pile being driven for temporary trestle at Richmond-San Rafael Bridge

Table I.10-2 Typical Sound Pressures Measured for 30-inch diameter steel pipe piles – Unattenuated. Richmond-San Rafael Bridge

Position	Sound Pressure Measured in dB		
	Peak	**RMS**	**SEL**
10 meters	205 max 210	190 max 192	--
20 meters	200	185	--
30 meters	199	181	170
40 meters	194	178	--
60 meters	195	169	--

Signal analysis was provided for measurements made at 30 meters from the pile (see Figure I.10-5). These signals contained relatively high frequency content, but most of the acoustical energy was contained in the bands between 125 and 1,000 Hz. Much of the event lasted about 35 to 40 milliseconds. The ringing of the pile is evident in both the waveform and frequency spectra. The ringing of the pile followed the initial low frequency pulse from the hammer impact. The change in the rate of accumulated energy shows the additional energy caused by the ringing pile.

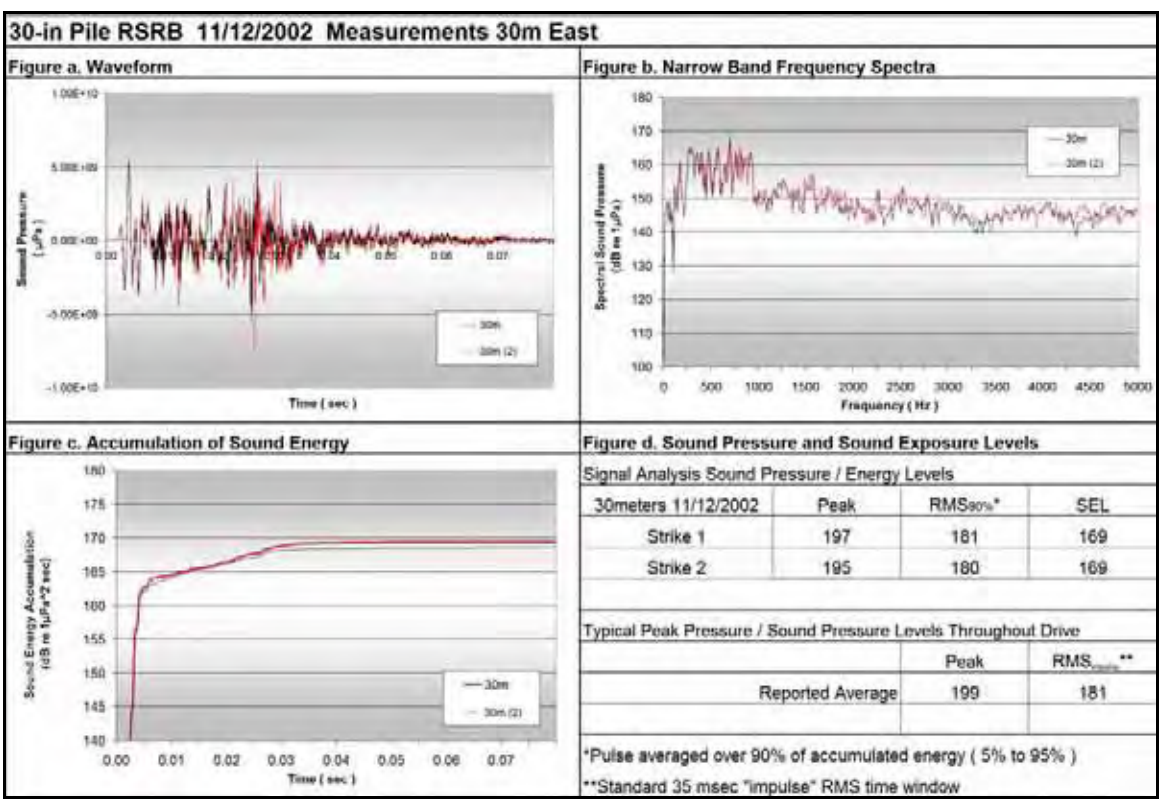

Figure I.10-5 Representative signal analysis for 30-inch diameter pile. Unattenuated pulse received at 30 meters from the pile at Richmond-San Rafael Bridge

An air bubble curtain system was used for piles driven in 2003. The unconfined air bubble curtain consisted of a simple 2-meter diameter ring that was placed at the mud line around the pile (supported from the pile driving crane). A compressor, using a firehouse, supplied the air. This system was tested for two piles, with measurements made at four different positions between 10 and 40 meters from the pile. Two of the positions were at 20 meters, but in different directions. Pile driving occurred with the system on, then off, and finally on. Results, presented in Table I.10-3, show about 10 dB of reduction was provided. In two of the tests, peak sound pressures were reduced below 190 dB at 20 meters.

Table I.10-3 Results of Air Bubble Curtain Test for 30-inch diameter piles at the Richmond-San Rafael Bridge

Position	Sound Pressure Measured in dB		
	Peak	**RMS**	**SEL**
10 meters			
Unattenuated	205	190	--
Attenuated	196	180	--
20 meters			
Unattenuated	200	185	--
Attenuated	191	175	--
40 meters			
Unattenuated	194	178	--
Attenuated	184	169	--

Figure I.10-6 Simple air bubble curtain system used to attenuate sounds for 30-inch piles

Permanent 1.7-meter (66-inch) diameter CIDH Trestle Piles

The 66-inch piles were cast in drilled steel hole piles (CIDH) that were used to support the new trestle section. These piles were driven from the temporary trestle that was supported by the 30-inch piles. Following pile driving, the piles were cleaned out and drilling was conducted to construct the supports for the new trestle bents. The piles were driven with a Del-Mag D-62 or D-100 diesel impact hammer. Reported driving energies were about 270 kilojoules. Pile driving of a 66-inch diameter pile through the temporary trestle is shown in Figure I.10-7. These piles were also driven at night and are located immediately adjacent of the plywood barriers along the trestle. At most, two piles were driven at night, sometime between 10:00pm and 4:00 am. Measurements were conducted at various distances between 4 and 80 meters in the easterly (deeper) direction. Water and measurement depths were similar to those for the 30-inch piles. Results are summarized in Table I.10-4.

Figure I.10-7 66-inch CIDH Pile being driven at Richmond-San Rafael Bridge

Table I.10-4 Typical Sound Pressures Measured for 66-inch diameter CIDH piles – Unattenuated. Richmond-San Rafael Bridge

Position	Sound Pressure Measured in dB		
	Peak	**RMS**	**SEL**
4 meters	219	202	--
10 meters	210 max 211	195 max 197	--
20 meters	205	189	--
30 meters	203	185	173
40 meters	198	180	--
60 meters	187	169	158
80 meters	187	170	--

Signal analysis was provided for measurements made at 30 meters from the pile (see Figure I.10-8). These signals were comprised of mostly lower frequency content, with most of the acoustical energy contained in the bands between 125 and 1,500 Hz. Much of the event lasted only 30 to 40 milliseconds, with most energy contained within 20 milliseconds (very fast). Analyses of strikes further away showed longer durations. The ringing of the pile is evident in both the waveform and frequency spectra, but not as pronounced as it was for the 30-inch piles. The ringing of the pile followed the initial low frequency pulse from the impact of the hammer (about 10 milliseconds into the event). SEL accumulates quickly with this pulse.

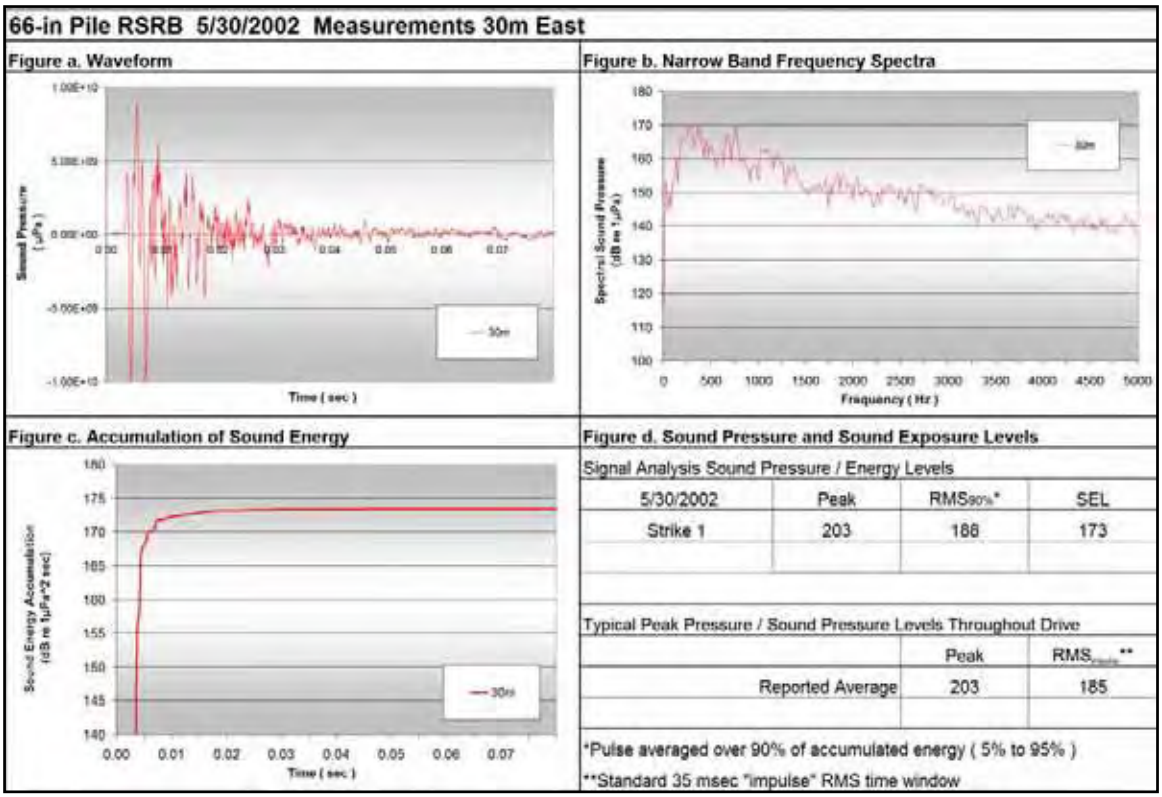

Figure I.10-8 Representative signal analysis for 66-inch diameter CIDH pile. Unattenuated pulse received at 30 meters from the pile at Richmond-San Rafael Bridge

An air bubble curtain test was also performed for these piles, similar to the test conducted for the 30-inch piles. This system was tested for two of the 66-inch piles, with measurements made at four different positions between 10 and 80 meters from the pile. The first test was conducted under slack tide conditions with little current. A current was present during the second test, which affected the bubble curtain surrounding the pile. This was clearly evident from observations that showed an elliptical pattern of bubbles at the surface, with part of the pile unshielded (see Figure I.10-9). Measurements at 10 meters mostly reflected the reduced bubble coverage. Pile driving occurred with the system on, then off, then on, and finally off. Results, presented in Table I.10-5, show 10 to 15 dB of reduction provided under light current conditions. Only the 10-meter position was compromised by the current effects on the second bubble curtain test. A 5 to 10 dB reduction occurred at that position, while other measurements at other positions were similar to the previous test. In two of the tests, peak sound pressures were reduced to almost 190 dB at 20 meters.

Table I.10-5 Results of Air Bubble Curtain Test for 30-inch diameter piles at the Richmond-San Rafael Bridge

Position	Sound Pressure Measured in dB		
	Peak	**RMS**	**SEL**
10 meters			
Unattenuated	208	195	--
Attenuated - Slack	192	177	--
Attenuated – Curr.	203	185	--
20 meters			
Unattenuated	204	189	--
Attenuated	191	173	--
40 meters			
Unattenuated	196	181	--
Attenuated	183	165	--
80 meters			
Unattenuated	196	181	--
Attenuated	183	165	--

Figure I.10-9 Bubble pattern around the 66-inch CIDH pile during tidal currents.

Permanent 3.2-meter Diameter (126-inch) CISS Piles

These 126in piles were driven immediately adjacent to existing bridge piers. Underwater noise levels associated with these piles were measured on only one occasion. The driving of these piles involves a submersible hydraulic hammer, where driving begins with the top of the pile and hammer above the water surface. A follower between the pile and hammer is used so the pile can be driven to a precise tip elevation at the mud line. When driving is complete both the pile and hammer are underwater near the bottom. These piles were driven with an IHC hydraulic hammer that provided typical maximum driving energies of about 350 to 400 kilojoules. Because the piles were located immediately adjacent to the existing bridge piers, attenuation systems were not used. Pile driving durations were about 40 minutes, over a one and one-half hour period. The hammer strikes the pile frequently at the beginning (about once per second), but less frequent as the stroke increases. The frequency of pile strikes was about once every two seconds through much of the driving event. Figure I.10-10 shows the pile driving operation as the hammer was becoming submerged. Due to the relatively rough water conditions and amount of boat traffic, measurements were made primarily at two locations. Two other spot measurements were briefly made near the end of the pile driving event. Measurements results are presented in Table I.10-6.

Figure I.10-10 126-inch CISS Pile being driven underwater at Richmond-San Rafael Bridge

Table I.10-6 Typical Range of Sound Pressures Measured for 126-inch diameter CISS piles – Unattenuated. Richmond-San Rafael Bridge

Position	Sound Pressure Measured in dB		
	Peak	RMS	SEL
10 meters	218 to 208	206 to 197	--
55 meters	?? - 198	?? – 185	--
95 meters	195 - 192	185 – 180	170
230 meters	190 - 187	177 – 175	165

Note: At positions close to the pile, sound pressures were highest when pile extended through the water column and decreased as pile was driven closer to the mud line. This variation was less at distant positions.

Pile driving lasted less than 45 minutes. The two primary measurement locations were from the barge at 10 meters and from a mooring buoy at 230 meters. The entire pile-driving event was measured at the 10-meter location, while most of the event was also measured at the 230m location. There were no mooring buoys that were closer to the pile, and boat traffic was restricted due to the presence of a dive boat (driving was temporarily halted at times while a diver was sent down to check the pile tip elevation). Most measurements were made at a depth of about 10 meters in 15-meter deep water.

Underwater sound levels associated with the driving of this pile varied considerably at the close-in location (10 meters) but were fairly constant over much of the driving period at the distant location (230 meters). The variation of about 5 to 10 dB that occurred close in appeared to be related to the position of the pile and hammer. The highest noise levels occurred during the early part of the driving when the pile extended all the way through the water column and the hammer was above the water. In this case, more pile was available to radiate acoustic energy into the water. This variation was on the order of about 2 dB at the distant location (230 meters), indicating the primary sound source was through the substrates.

Interpolations of the data are difficult since measurements were made at only 4 distances and two of those were made late in the driving period when close in levels were lower. The data does indicate that the maximum peak levels of 190 dB and RMS levels of 177 dB occurred at 230m from the pile. A rough interpolation of the data indicates that peak levels of 195 dB and RMS levels of about 185 dB occurred at about 100 meters.

Evaluations of the acoustic waveforms indicate that these pulses from a pile strike lasted approximately 100 millisecond (see Figure I.10-11). The rise time from the initial disturbance to the peak (or near peak) pressure was about 3-5 milliseconds close in, at 10 meters. The rise time at 230 meters was about 6-7 milliseconds; however, the peak pressure occurred about 10 milliseconds into the disturbance. Most energy, which makes up the RMS level, occurred during the first 45 to 50 milliseconds. Reflections, probably due to the adjacent bridge pier, are apparent in the signal characteristics. The frequency spectra were dominated by low frequency energy (i.e., less than 1,000 Hz). The rate that the SEL accumulates over the duration of the pulse is relatively slow.

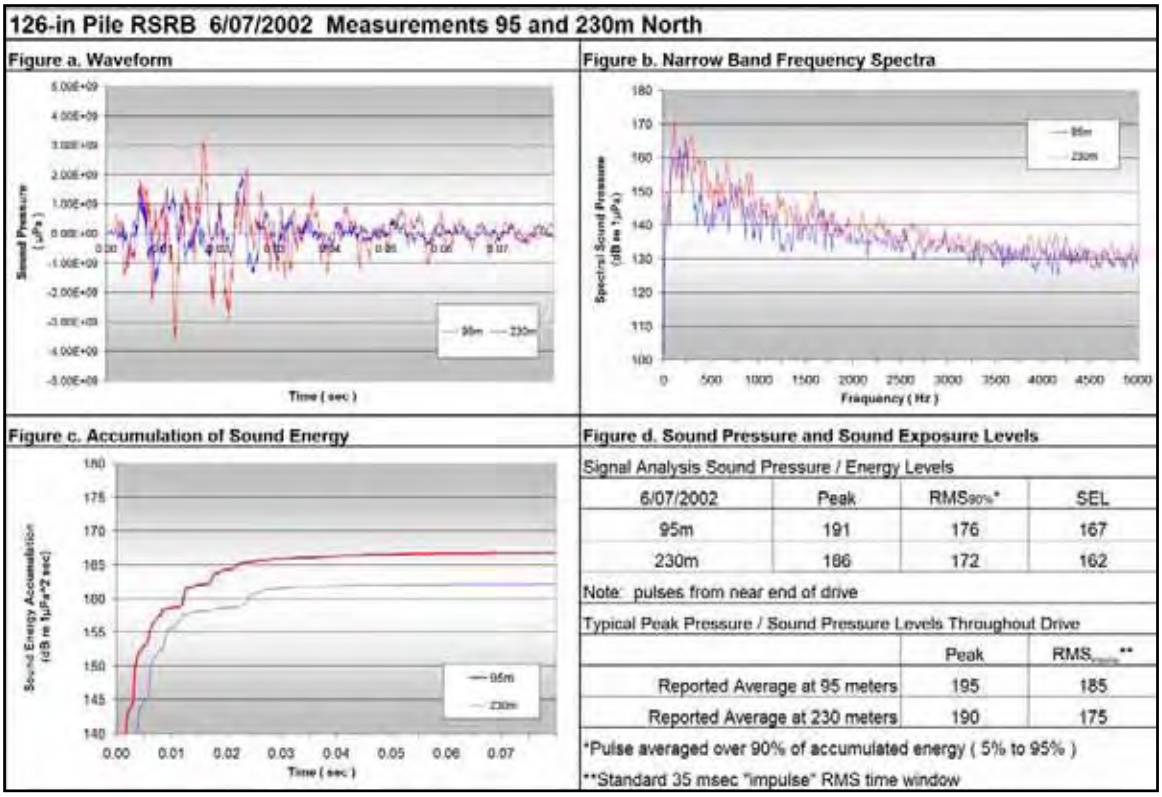

Figure I.10-11 Representative signal analysis for 126-inch diameter CISS pile. Unattenuated pulse received at 95 and 230 meters from the pile near end of driving event at Richmond-San Rafael Bridge

Permanent 3.8-Meter Diameter (150-inch) CISS Piles

These piles were similar to the 126-inch diameter piles and were also driven immediately adjacent to existing bridge piers with tip elevations near the mud line. Driving energies were up to 450 kilojoules. Figure I.10-12 shows the driving operation with the hammer mostly submerged. Driving durations were also about 45 minutes over a 1- to 2-hour period. Table I.10-7 summarizes the measurements for two different piles driven. For one of the events, sound pressures were measured continuously at 22m from the pile along with spot measurements. Only spot measurements were conducted for the other event, but most of the measurements were made 60 to 65m from the pile.

Figure I.10-12 156-inch CISS Pile being driven underwater at Richmond-San Rafael Bridge

Table I.10-7 Typical Range of Sound Pressures Measured for 156-inch diameter CISS piles – Unattenuated. Richmond-San Rafael Bridge

	Sound Pressure Measured in dB		
Position	Peak	RMS	SEL
20 meters	215 to 205	206 to 197	--
55 meters	205-202	193- 188	--
95 meters	194	181	--
160 meters	191	175	--
230 meters	192	178	--
~1,000 meters	169	157	--

Note: At positions close to the pile, sound pressures were highest when pile extended through the water column and decreased as pile was driven closer to the mud line. This variation was less at distant positions.

At 20 meters from one of the piles, sound pressures were measured continuously and ranged from 215 dB peak and 200 dB RMS at the beginning of the drive to 205 dB peak and 193 dB RMS at the end of the drive. At 230 meters, sound pressures were typically 192 dB to 189 dB peak and 178 dB to 180 dB RMS. For the other pile, peak sound pressures were about 203 dB at 50m. Underwater sound levels were generally similar to those measured for the 126-inch pile.

Figure I.10-13 shows the signal analyses for two pulses recorded at 20 meters from the pile. The first pulse was recorded midway through the driving event, while the second was recorded near the end of the event. Much of the acoustic energy for both pulses are relatively low frequency, similar to the 126-inch piles measured at 95 meters. The events last over 80 milliseconds, with much of the energy contained in 60 milliseconds.

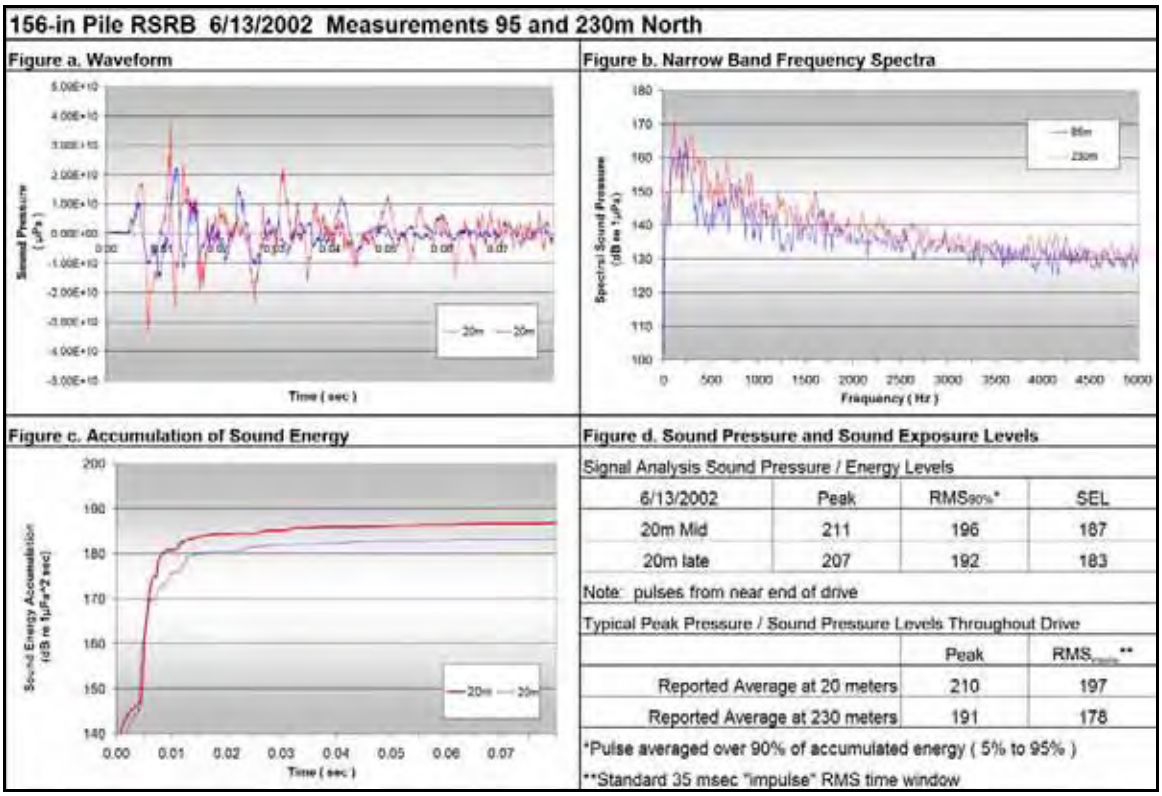

Figure I.10-13 Two representative signal pulses for 156-inch diameter CISS pile. Unattenuated pulse received at 20 meters midway and near the end of the driving event at Richmond-San Rafael Bridge

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2. Reyff, J. A. 2003. Memo to Mike Scott and Tim O'Hearn of Caltrans, Subject *Richmond—San Rafael Bridge 30in Pile Bubble Curtain Test*. May 14, 2003.
3. Reyff, J. A. 2003. Memo to Mike Scott and Tim O'Hearn of Caltrans, Subject *Richmond—San Rafael Bridge 66in Pile Bubble Curtain Test*. May 19, 2003.
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I.11 Humboldt Bay Bridges

Construction for Humboldt Bay Seismic Retrofit Project on State Route 255 between the City of Eureka and the Samoa Spit in California required the driving of steel shell and CISS piles of various sizes. This project consisted of seismically retrofitting the existing bridge substructure of the State Route 255 Eureka Channel, Middle Channel, and Samoa Channel bridges, which collectively span Humboldt Bay and are called the Humboldt Bay Bridges (see Figure I.11-1). The project included the installation of 0.65-meter (24-inch) diameter steel pipe piles for the construction of a temporary construction trestle, 0.91-meter (36-inch), and 1.52-meter (60-inch) steel shell piles for the foundation of the three bridges. All piles were driven to a specified tip elevation. An isolation casing with an air bubble ring or a dewatered cofferdam was used to reduce the underwater sound pressures associated with the driving of the larger permanent piles, the temporary 24-inch temporary piles were driven without any attenuation. The project tested various sound attenuation systems.

Figure I.11-1 Humboldt Bay Bridges, Eureka,, CA

Noise measurements were conducted for the Humboldt Bay Bridges project, as underwater noise attenuation was required for all in-water permanent piles. Results presented in this chapter were collected for pile driving at four different piers. The first set of data was collected at Pier 8 in the Eureka Channel when different attenuation systems were tested. Strong tidal currents compromised the performance of unconfined air bubble curtain systems. Therefore, systems that were unaffected by currents were developed. Measurements were made at Pier 12 of the Samoa channel when 60-inch diameter piles were driven with a isolation casing/air bubble curtain. Finally, measurements were made at Pier 2 on the Middle Channel Bridge, and Pier 3 of the Samoa Channel.

I.11.1 36-inch CISS Piles at Pier 8, Eureka Channel – Attenuation System Testing

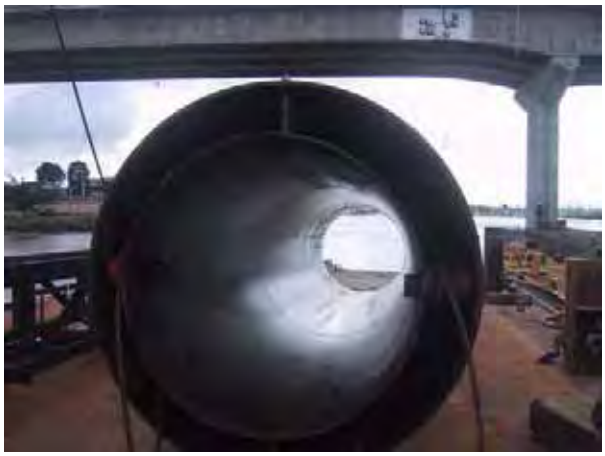
Several tests were conducted in February 2004 at Pier 8 in the Eureka Channel to analyze the sound levels associated with various attenuation devices on the characteristics and intensity of the underwater sound[1]. Piles at Pier 8 in Eureka channel, which were fully inserted prior to testing, were re-struck to perform the various tests. Un-attenuated strikes were also done to confirm the changes in sound pressure due to the attenuation devices. The goal was to determine the best attenuation system available for this specific project. A Delmag D36-32 diesel impact hammer was used, providing about 95 kilojoules of energy.

Figure I.11-2a-c show the various underwater sound measurement tests conducted for Pier 8. The piles had been driven almost to their tip elevation and then left for several days prior to the tests. As a result, the piles resisted movement when driven during these tests. Nine tests were conducted. Water depth varied by about 2 meters due to tidal changes. In general, water depth was about 8 to 10 meters. Hydrophone depth was about 5 meters. Currents were strong during some of the tests.

Figure I.11-2a Driving 36-inch pile in a 5-foot casing with inside bubble ring. Humboldt Bay Bridges, Eureka,, CA

Figure I.11-2b Unconfined air bubble curtain used at slack tide

Figure I.11-2c Double walled attenuator



The first test used the double-walled attenuator that was developed for this project (see Figure I.11-2c). The attenuator was placed around the 36-inch CISS pile. Because of the high tide at the time tests began, the attenuator was flooded. A bubble ring was placed at the bottom of the double walled attenuator so the water could be aerated. The test was repeated as Test 2. When the tide went out and water levels lowered, water was pumped out of the double walled attenuator for Test 3 and repeated for Test 4. Unattenuated tests were conducted as Test 5 and Test 6. A 1.5-meter (5-foot) diameter single-walled pile casing and air bubble curtain was used for Test 7 and 8 (see Figure I.11-2a). The air bubble curtain was placed inside the casing. The air bubble curtain was operated at reduced compressor flow for Test 7 and maximum flow for Test 8. Finally, Test 9 used an unconfined air bubble curtain during slack tide (Figure I.11-2b)

Table I.11-1 summarizes results of underwater the sound measurements. Primary measurements were made at 10 meters in three different directions. Levels were similar with about a 2 dB variation (5 dB maximum) for all of the tests. Measurements were also made at 50 meters for all but Tests 7 and 8. Measurements were made at 100 meters for Tests 7, 8, and 9. In terms of peak sound pressure, the

unconfined air bubble curtain operating during slack tide conditions resulted in the lowest levels at 10 and 50 meters. However, it was not practical to drive piles only at slack current condition. The 5-foot diameter single walled casing with air bubbling was adopted as the new sound control method since peak pressures were lower than the dewatered double walled attenuator used previously. The tests indicated that only 10 to 15 dB of attenuation could be achieved from the attenuation devices for these piles. Maximum unattenuated sound levels were 210 dB peak, 193 dB RMS, and 183 dB SEL at 10 meters. Based on additional measurements at 50 meters, these levels dropped off at a rate of 5 to 6 dB per doubling of distance.

Table I.11-1 Sound Pressures Measured for 36-inch CISS Piles during attenuator testing. Humboldt Bay Bridges, Eureka, CA

Pile	Position	Sound Pressure Measured in dB		
		Peak	RMS	SEL
Test 1 - Flooded double-wall attenuator with bubble ring inside	10 meters	195	182	170
	50 meters	185	174	--
Test 2 - Repeat of Test 1	10 meters	196	183	171
	50 meters	184	173	--
Test 3 - De-watered double-wall attenuator flooded with bubble ring	10 meters	199	188	176
	50 meters	187	176	--
Test 4 - De-watered double-wall attenuator dewatered	10 meters	199	188	176
	50 meters	188	177	--
Test 5 - No attenuation, bare pile	10 meters	210	193	183
	50 meters	198	182	--
Test 6 – No attenuation, but water pumped out of the pile	10 meters	205	191	180
	50 meters	195	179	
Test 7 & 8 - 5-foot diameter single-walled isolation casing bubbled*	10 meters	196	185	174
	100 meters	178	165	153
Test 9 - Un-confined air bubble curtain at slack tide with maximum air flow	10 meters	192	180	170
	50 meters	183	172	--
	100 meters	179	168	155

* Test 7 was bubbled at reduce rate, while Test 8 was bubbled at maximum flow. There was no difference in sound levels measured.

Signal analysis for the unattenuated pile strikes recorded at 10 meters are shown Figure I.11-3. These signals were characterized as having a fairly short duration of about 40 milliseconds with a rapid rise time, which is indicated by the fast rate that SEL accumulates. The frequency spectra indicates relatively high frequency sound content, but most sound energy was in the 125 to 1,000 Hz range. Figure I.11-4 shows the different signals and associated frequency spectra associated with the various attenuation tests recorded at 10 meters. Each of the systems were effective at reducing sounds at frequencies above about 500 Hz, with the unconfined air bubble curtain most effective at reducing higher frequency sounds (i.e., above 1,000 Hz); however, these sounds did not contain much of the unattenuated energy.

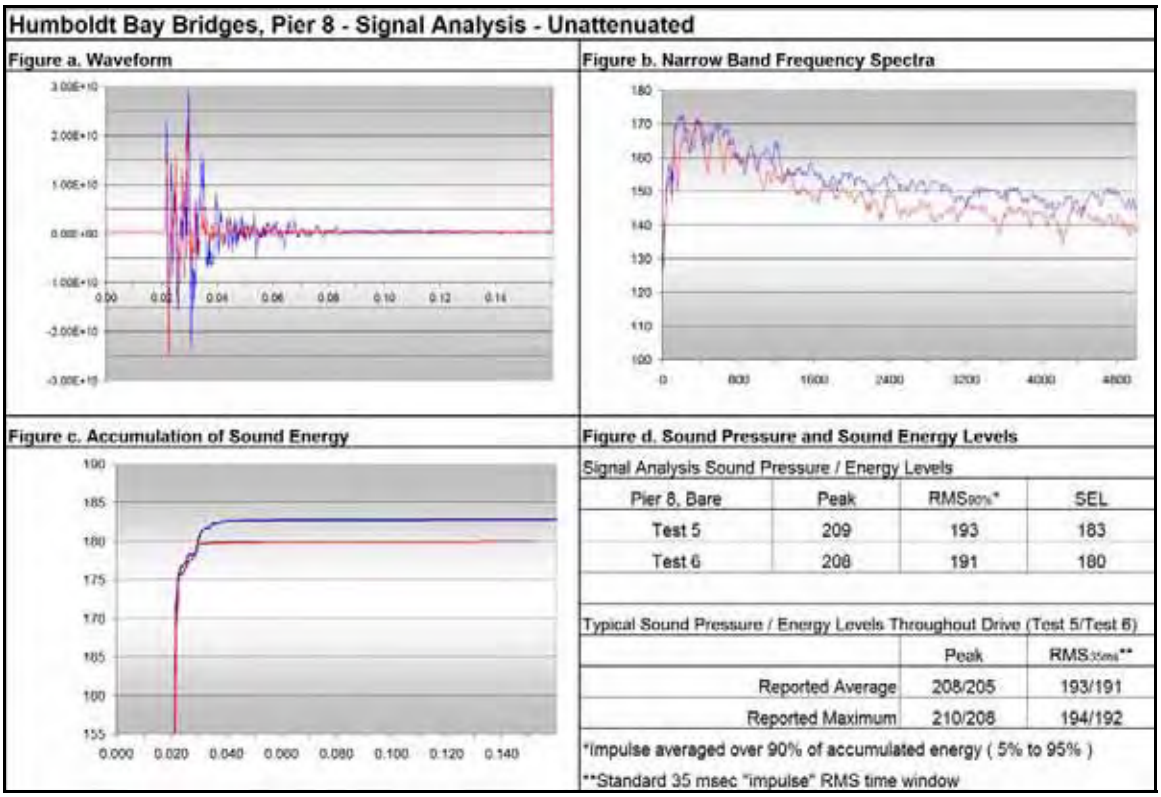


Figure I.11-3 Representative signal analysis for unattenuated 30-inch pile at 10 meters. Humboldt Bay Bridges – Eureka, CA

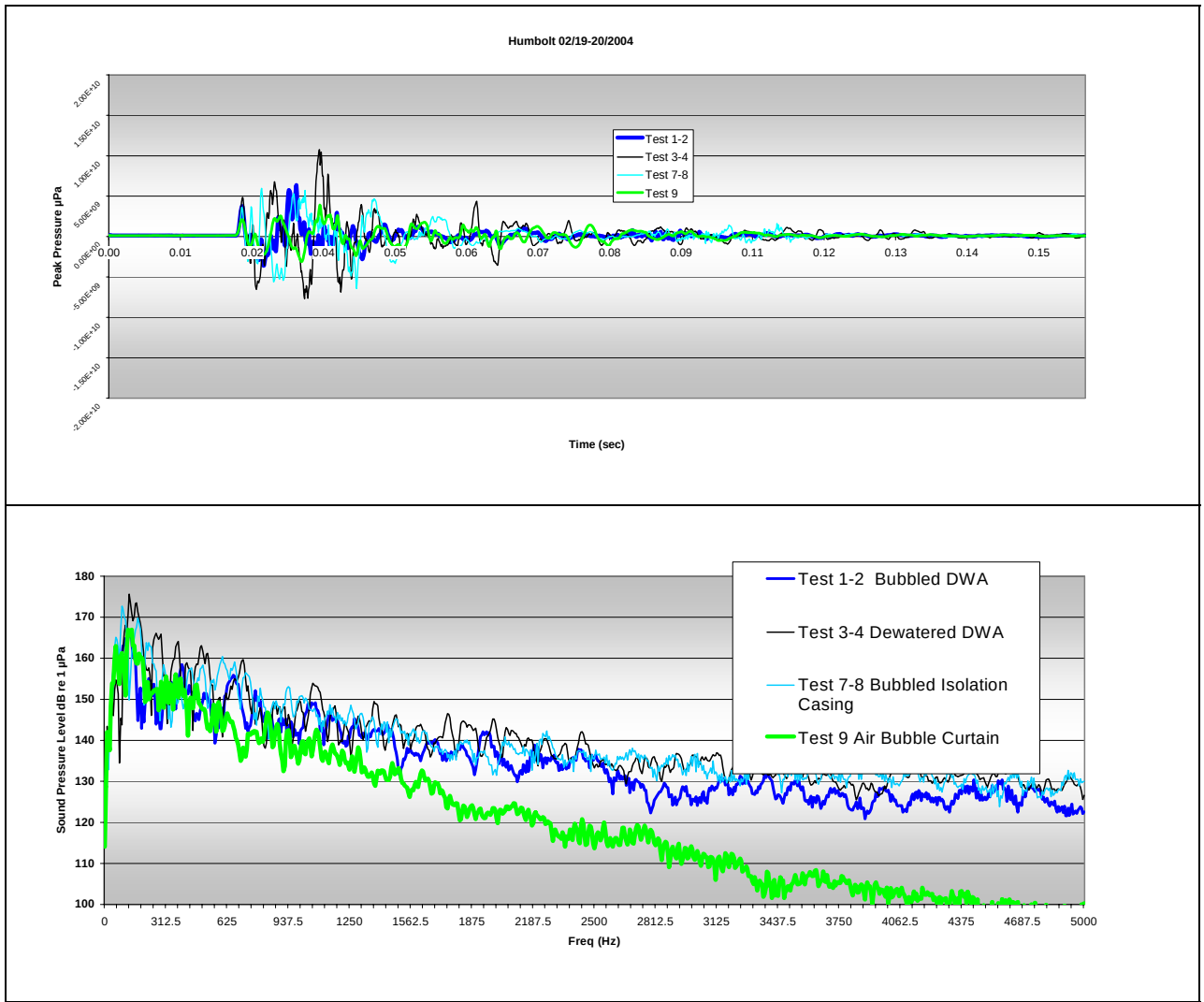


Figure I.11-4 Representative signal analysis for attenuated 30-inch pile at 10 meters. Humboldt Bay Bridges – Eureka, CA

I.11.2 60-inch CISS Piles at Pier S12, Samoa Channel – Production Driving

Measurements were made during the driving of two 60-inch diameter CISS piles at Pier S12 in the Samoa Channel of Humboldt Bay (see Figure I.11-5)[2]. These piles were driven through a large diameter isolation casings that were bubbled, as described in Chapter I.11-1. These were the first sets of piles driven after the attenuation tests previously described. Measurements were made during the driving of one pile.

Table I.11-2 summarizes the measured sound levels at each position. Measurements were made at two different positions 10 meters from the pile and one position down the channel at 125 meters from the pile. At the 10-meter positions, measurements were made at depths of 5 meters, where water depth was only about 7 meters deep. Water depth at 125 meters in the channel was 10 meters, and the hydrophone was placed 7 meters deep. Measurements at 10 meters from the pile were similar for both positions.

Figure I.11-5 Driving 60-inch piles at Pier S12, Samoa Channel at Humboldt Bay, Eureka, CA

Sound levels varied by about 4 dB throughout the driving event. Figure I.11-6 shows the trend in measured sound pressure levels over the course of the pile-driving event. Sound pressures were highest at the beginning of pile driving and lowest at the end. For the most part, measurements at 10 meters east and west were similar, except during the second part of the driving where the peak pressures varied by 3 dB. However, RMS sound pressure levels only varied by 1 dB. Interestingly, there was only 5 dB of attenuation with distance from 10 meters to 125 meters. The attenuated levels were higher than expected.

Table I.11-2 Sound Pressures Measured for 60-inch CISS Piles at Pier S12, Samoa Channel, Humboldt Bay Bridges, Eureka, CA

Condition	Position	Sound Pressure Measured in dB		
		Peak	RMS	SEL
1st Part of Pile Driving ~4 minutes	10 meters West	203	188	177
	10 meters East	202	188	--
	125 meters	197	185	172
2nd Part of Pile Driving ~7 minutes	10 meters West	201	198	174
	10 meters East	198	176	--
	125 meters	194	181	169
3rd (last) Part of Pile Driving <2 minutes	10 meters West	199	186	--
	10 meters East	199	186	--
	125 meters	194	181	--

The signal analysis presented in Figure I.11-7 show that the sounds at 10 meters were attenuated at frequencies of about 500 Hz and above (compared to the unattenuated pulse shown in Figure I.11-3 for a 30-inch pile). However, the attenuation system was probably compromised somewhat because the pile was not centered in the attenuator. The high sound levels measured at 125 meters indicate that there was a substantial ground borne component of underwater sound. This is evident from the frequency spectra that show little or no attenuation between 10 and 125 meters at frequencies below 600 Hz and substantial attenuation of 20 to 25 dB for frequencies above 1,200 Hz. The high sound levels were theorized to be associated with the dense sand layers in the substrate. These types of dense sand layers were also present at parts of the Port Of Oakland where shore-based piles resulted in higher sound levels (see Chapter I.5.5). The 60-inch unattenuated piles measured at Richmond-San Rafael Bridge (see Chapter I.10) were about 8 to 10 dB louder at 10 meters, but similar at 80 meters to the levels at 125 meters presented above.

Figure I.11-6 Trend in measured sound levels for driving of one attenuated 60-inch pile at 10 and 125 meters. Pier S12, Humboldt Bay Bridges – Eureka, CA

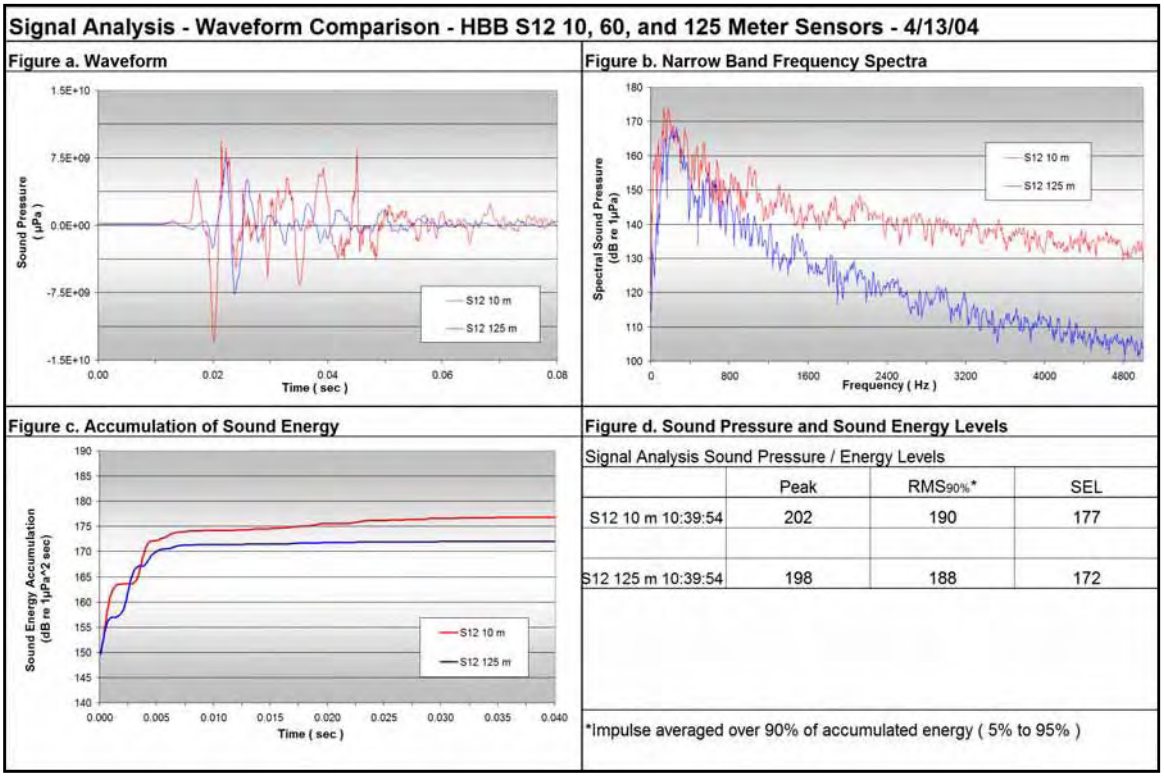


Figure I.11-7 Representative signal analysis for attenuated 60-inch pile at 10 and 125 meters. Pier S12, Humboldt Bay Bridges – Eureka, CA

I.11.3 36-inch CISS Piles at Pier M2, Middle Channel – Production Pile Driving

In June 2005, 1.1-meter (36-inch) diameter CISS piles were driven at Pier M2 in the Middle Channel of Humboldt Bay[3]. These piles were driven inside an isolation casing with a bubble ring placed inside the casing (see Figure I.11-8). Pile driving was performed using an APE 9.5 Hydraulic Hammer mounted on an excavator. This hammer provides about 43,000 foot pounds or 58 kilojoules of energy. The actual driving time four each pile was approximately 6 to 12 minutes. Piles 3 and 4, located on the east side of Pier M2, were measured the first day. The piles on the west side of Pier M2 (Piles 1 and 2) were measured the next day. The water depth was 4 meters and the hydrophone was set 3 meters deep. Measurements were made at 10, 20, and 40 meters from the pile. Results are summarized in Table I.11-3.

Figure I.11-8 Driving 36-inch piles at Pier M2 with isolation casing and bubble curtain, Middle Channel at Humboldt Bay, Eureka, CA

Table I.11-3 Sound Pressures Measured for 36-inch CISS Piles at Pier M2, Middle Channel, Humboldt Bay Bridges, Eureka, CA

Condition	Position	Sound Pressure Measured in dB		
		Peak	RMS	SEL
Pile 3 ~8 minutes	10 meters	198	183	--
	20 meters	192	180	169
Pile 4 ~6 minutes	10 meters	197	185	--
	20 meters	192	181	169
	40 meters	190	178	164
Pile 1 ~12 minutes	10 meters	196	181	--
	20 meters	195	182	--
Pile 2 ~13 minutes	10 meters	196	182	170
	20 meters	194	182	172
	40 meters	191	180	166

The measured sound levels at 10 meters were consistent with levels measured during testing of the attenuation system (see Chapter I.11.1). The rate of sound attenuation with distance was also quite low. This was not so much the case for Piles 3 and 4, but for Piles 1 and 2. Measurements at 20 meters for these piles were similar to those at 10 meters, but higher in some cases. Signals for pulses recorded during the driving of Pile 4 are shown in Figure I.11-9. The attenuation provided by the bubbled isolation casing is evident in both the waveform and frequency spectra when comparing to the unattenuated signals shown in Figure I.11-3.

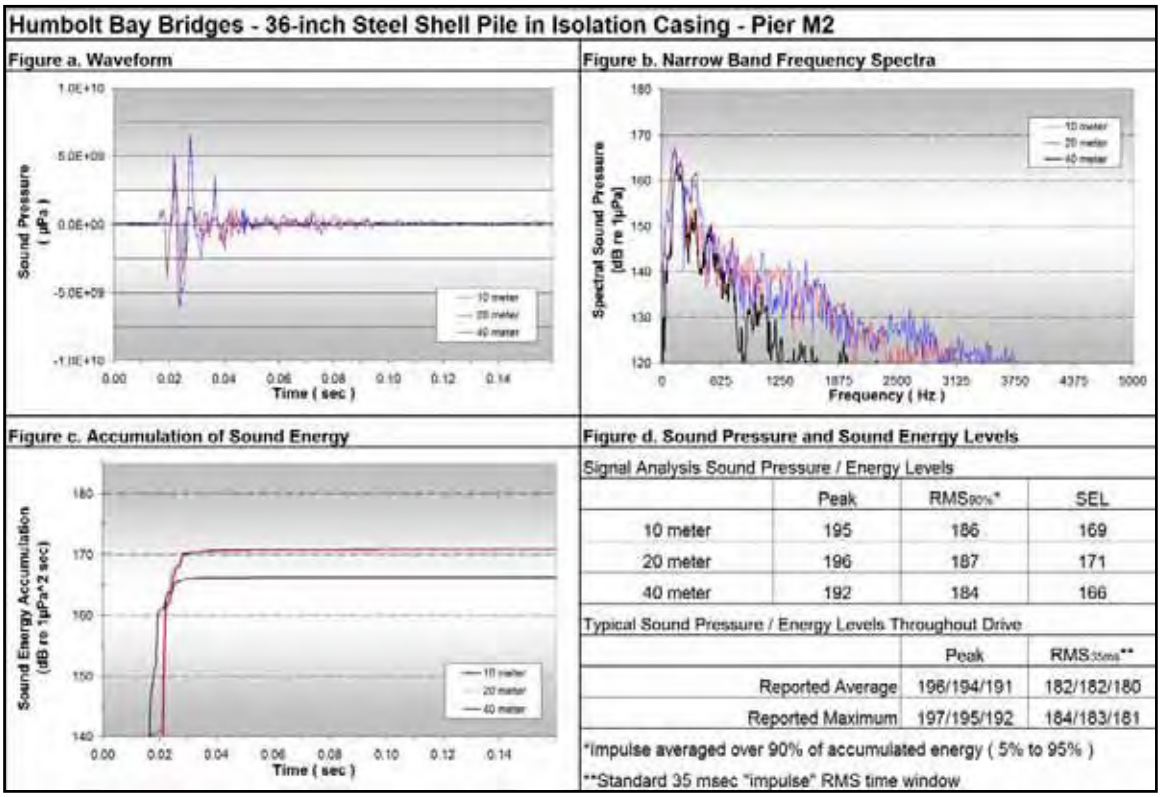


Figure I.11-9 Representative signal analysis for pulses at 10, 20, and 40 meters from a 36-inch pile at Pier S12, Humboldt Bay Bridges – Eureka, CA

I.11.4 36-inch CISS Piles at Pier S3, Samoa Channel – Production Driving

Measurements were made during the driving of 36-inch diameter CISS piles at Pier S3 in the Samoa Channel of Humboldt Bay for the Humboldt Bay Bridge Seismic Retrofit project[4]. Piles at Pier S3 were driven through an unconfined air bubble curtain. The APE 9.5 Hydraulic Hammer was used, similar to Pier M2. Water depth was 6 meters and the hydrophone was 5 meters deep. Measurements were made at 10 and 20 meters and are summarized in Table I.11-4. Results indicate slightly lower levels than measured at Pier M2, especially at 20 meters. There was about a 7-dB variation in sound levels during the roughly 7-minutes of pile driving.

Table I.11-4 Sound Pressures Measured for 36-inch CISS Piles at Pier S3, Middle Channel, Humboldt Bay Bridges, Eureka, CA

Condition	Position	Sound Pressure Measured in dB		
		Peak	RMS	SEL
Pile at S3 ~7 minutes	10 meters	Avg. 194 max. 200	Avg. 182 max. 186	--
	20 meters	Avg. 190 max. 193	Avg. 178 max. 182	168

The signal analysis was only performed for pulses captured at 20 meters. The signals shown in Figure I.11-10 are comparable to those in Figure I.11-9. They show a pulse of longer duration with higher frequency content (above 1,000 Hz). Pulses measured at Pier M2 contained most energy in about 20 to 25 milliseconds, while the pulses at Pier S3 had most energy in about 40 milliseconds. The amplitude of the Pier S3 pulses was generally lower.

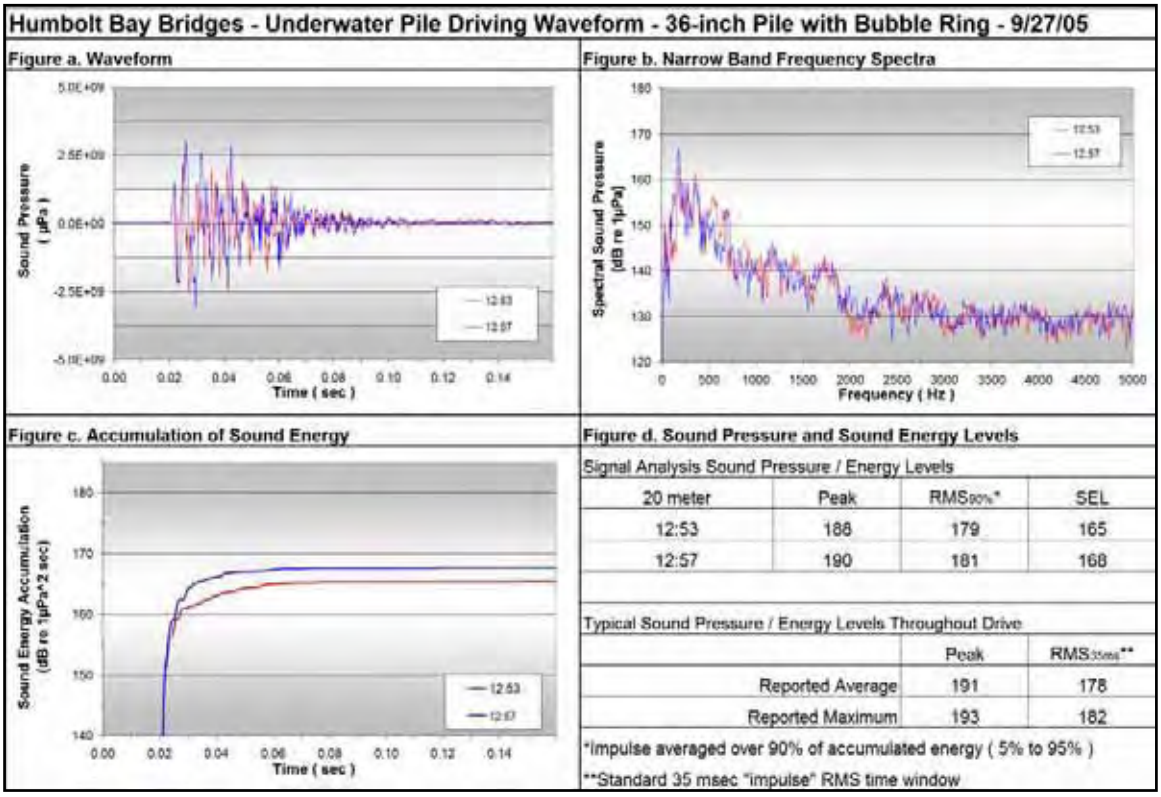


Figure I.11-10 Representative signal analysis for pulses at 20 meters from a 36-inch pile at Pier S3, Humboldt Bay Bridges – Eureka, CA

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2. Illingworth & Rodkin, Inc. *Data files of unpublished measurements for pile driving at Pier S12, Humboldt Bay Bridges on February 13, 2004*.
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