Final

Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish

Prepared for:

California Department of Transportation
1120 N Street
Sacramento, CA 94274
Contact: Jim Andrews

Prepared by:

ICF Jones & Stokes
630 K Street, Suite 400
Sacramento, CA 95818
Contacts: Rick Oestman, Dave Buehler

And:

Illingworth and Rodkin, Inc
505 Petaluma Blvd. South
Petaluma, CA 94952
Contacts: James Reyff, Rich Rodkin

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List of Acronyms

AIP	Agreement in Principal for Interim Criteria for Injury to Fish from Pile Driving Activities
BA	Biological Assessment
BCDC	San Francisco Bay Conservation and Development Commission
BMP	best management practice
BO	Biological Opinion
c	speed of sound
CCC	California Coastal Commission
CEQA	California Environmental Quality Act
CESA	California Endangered Species Act
CISS	cast-in-steel shell
Corps	U.S. Army Corps of Engineers
CZMA	Coastal Zone Management Act
CZMP	Coastal Zone Management Plan
dB	decibel(s)
DCH	designated critical habitat
Delta	Sacramento/San Joaquin Delta
Department	California Department of Transportation
DFG	California Department of Fish and Game
DPS	distinct population segment
EFH	essential fish habitat
ESA	federal Endangered Species Act
ESU	evolutionarily significant unit
FHWA	Federal Highway Administration
FHWG	Fisheries Hydroacoustic Working Group
ft-lbs	foot-pounds
g	gram(s)
Hz	hertz
I	intensity
λ	wavelength of the sound waves
L_{PEAK}	peak sound pressure level
msec	milliseconds

List of Acronyms (Continued)

MSFMCA	Magnuson-Stevens Fisheries Management and Conservation Act
NEPA	National Environmental Policy Act
NOAA Fisheries	National Oceanic and Atmospheric Administration National Marine Fisheries Service
PFMC	Pacific Fishery Management Council
PTS	permanent threshold shift
ρ	density
ρc	characteristic impedance
RMS	root mean square
SEL	sound exposure level
$SEL_{cumulative}$	cumulative sound exposure level
$SEL_{single\ strike}$	single-strike sound exposure level
SER	Standard Environmental Reference
Services, the	U.S. Fish and Wildlife Service and NOAA Fisheries
SPL	sound pressure level
State	state of California
TEF	total energy flux
Tf	final time
Ti	initial time
TTS	temporary threshold shift
USFWS	U.S. Fish and Wildlife Service

Chapter 1 Introduction and Background

Most estuaries and major streams in California provide habitat for one or more fish species listed as threatened or endangered under the federal Endangered Species Act (ESA) or California ESA (CESA), or species managed under the essential fish habitat (EFH) provisions of the Magnuson-Stevens Fisheries Management and Conservation Act (MSFMCA). The potential for death or injury of fish resulting from driving piles has elevated the public and resource agency concerns relative to effects on listed species populations. Required development of minimization measures to protect fish species listed under the ESA has resulted in costly project delays and has increased project implementation costs for California Department of Transportation (the Department) and other transportation departments and ports on the West coast.

The purpose of this technical guidance manual is to provide Department engineers, biologists, and consultants with guidance related to the environmental permitting of in-water pile driving projects. Specifically, this manual provides guidance on:

- Fundamentals of hydroacoustics;
- Fish hearing and hydroacoustic impacts on fish;
- Environmental documentation and permit applications required for pile driving projects;
- Assessment of potential impacts on fish and their habitat from sound generated from pile driving;
- Measures to avoid or minimize pile driving impacts; and
- Methods to assess impacts, mitigation, and compensation for pile driving impacts on fish.

The chapters and appendices in this guidance manual are briefly described below.

Chapter 2 – Fundamentals of Hydroacoustics provides key information on the generation, propagation, and measurement of underwater sound from pile driving. Key terminology and metrics used to describe and measure underwater sound are provided, along with a discussion of methods used to attenuate underwater pile driving sound.

Chapter 3 – Fundamentals of Hydroacoustic Impacts on Fish discusses the types of impacts that could potentially occur to fish (or their habitat) from the sound generated during pile driving. The chapter also describes how effects might vary depending on the location, species presence, physiological attributes of species, species life history and behavior, timing of activities, and other environmental conditions (e.g., channel morphology, depth of water, and tidal conditions).

Chapter 4 – Framework and Process for Environmental Analysis of Pile Driving Impacts on Fishery Resources for Project Planning, Development, and Implementation provides guidance in preparation of environmental documentation and permit applications for projects involving pile driving. The chapter first explains what documentation, permits, or consultations will be required for projects with pile driving, based on the design and location of the project. The primary focus of this chapter is a description of how to comply with the ESA, CESA, and EFH provisions of the MSFMCA.

The chapter contains the following main sections:

- Applicable Laws,
- Avoidance and Minimization Measures,
- Best Management Practices,
- Performance Standards, and
- Detailed Impact Assessment Methodology.

Appendix I – Compendium of Pile Driving Sound Data provides a summary of measured underwater sound levels for a variety of pile driving situations.

Appendix II – Procedures for Measuring Pile Driving Sound provides guidance in measurement of underwater pile driving sound.

Appendix III – Fish Habitat Types and Distribution provides a synopsis of the fish species that might be present at project sites, their status (whether federally or state listed), and habitat types.

The *Glossary* provides definitions of key acoustical terms used in this manual.

A wide variety of pile types and pile driving methods are used on Department projects. Users of this manual should have a basic understanding of the types of piles and driving methods that are used. Rather than providing a detailed description of this information here, the reader is referred to the Department's Foundation Manual. The manual can be found at: http://www.dot.ca.gov/hq/esc/construction/Manuals/OSCCompleteManuals/Foundation.pdf.

Chapter 2 Fundamentals of Hydroacoustics

This chapter summarizes information about pile driving sound under water. It contains the following main sections:

- Fundamental Principles of Hydroacoustics,
- Underwater Sound Propagation,
- Measurement of Underwater Sound,
- Examples of Underwater Pile Driving Sound Levels, and
- Common Underwater Sound Control Measures.

This chapter is supplemented by *Appendix I (Compendium of Pile Driving Sound Data)*, which provides an extensive summary of measured underwater sound levels at a number of project sites; and *Appendix II (Procedures for Measuring Pile Driving Sound)*, which provides guidance on how to measure underwater sound.

2.1 Fundamental Principles of Hydroacoustics

Sound is defined as small disturbances in a fluid from ambient conditions through which energy is transferred away from a source by progressive fluctuations of pressure (or sound waves). Sound waves are always produced by vibrating objects. In this discussion, the vibrating object is a pile, which has been struck by a pile driver. As the vibrating surface moves, it compresses the molecules in the adjacent medium, creating a high-pressure region. As the object vibrates back to its original position, the molecules in contact with the vibrating surface produce a low-pressure region. These areas are known as "compressions" and "rarefactions," respectively. In fluids (e.g., gases and liquids), sound waves can only be longitudinal. In solids, sound can exist as either a longitudinal or a transverse wave. The pressure fluctuations are expressed in standard units of pressure (e.g., psi, Pascals, and bars).

Sound levels often are expressed in decibels (dB). The decibel is used for many different engineering applications, and it is commonly used to describe the magnitude of a sound pressure. It is a convenient way of expressing sound pressure level (SPL) because the sounds we typically hear result from a very wide range of pressures. A decibel used to describe sound is "a logarithmic measure of the sound strength." The mathematical definition of a decibel is the "base 10 logarithmic function of the ratio of the pressure fluctuation to a reference pressure." This is shown mathematically in the *Calculation of Sound Pressure Level* box. Note that the reference pressure in air is different than the reference pressure in water. It is important to clearly state the reference pressure when expressing sound levels in decibels.

Calculation of Sound Pressure Level (SPL):

$$SPL = 10 \log (p/p_{ref})^2, dB$$

or

$$SPL = 20 \log (p/p_{ref}), dB$$

where p_{ref} is the reference pressure:
for air, $p_{ref} = 20\ \mu Pa$
for water, $p_{ref} = 1\ \mu Pa$

As a result:

$$SPL_{water} = SPL_{air} + 26\ dB$$

For example:

$$1\ psi = 6{,}859\ Pa = 197\ dB\ re{:}\ 1\ \mu Pa$$

Three metrics are commonly used in evaluating hydroacoustic impacts on fish:

- Peak sound pressure level (L_{PEAK}),
- Root mean square (RMS), and
- Sound exposure level (SEL).

Figure 2-1 represents a sinusoidal (single-frequency) pressure wave and the various metrics that are used to describe amplitude. The amplitude of the pressure is shown on the vertical axis, and time is shown on the horizontal axis. The wave is shown to fluctuate around the neutral point. The peak sound pressure (L_{PEAK}) is the absolute value of the maximum variation from the neutral position; therefore, it can result from a compression or a rarefaction of the fluid. The peak-to-peak sound pressure is the absolute sum of the positive and negative peak amplitudes. The average amplitude is the average of the absolute value of all amplitudes over the period of interest. The root-mean-squared amplitude is a type of average that is determined by squaring all of the amplitudes over the period of interest, determining the mean of the squared values, and then taking the square root of the mean of the squared values. SEL is the constant sound level over 1 second that has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. These metrics are discussed in detail later in this section.

Typical sound levels found in underwater environments where pile driving normally occurs are shown in Table 2-1. The sound levels are shown in terms of decibels and Pascals. One can readily see how the range of pressures is reduced by using the decibel scale. **All underwater sound levels referenced in this document are in dB referenced to 1 micro Pascal (1 μPa).**

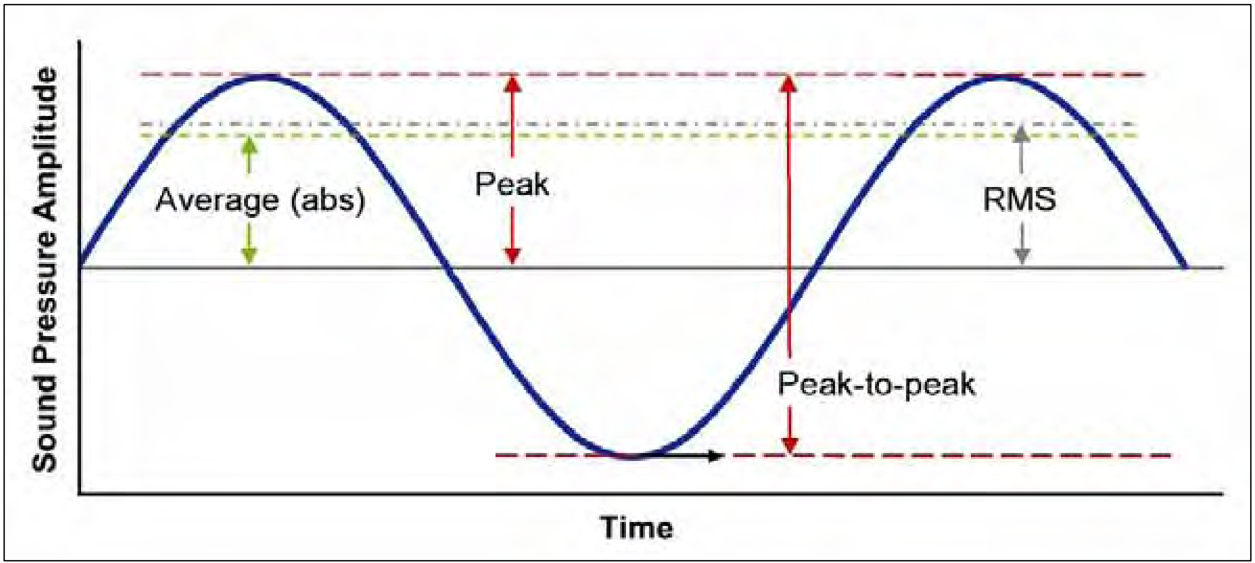

Figure 2-1. Sound Level Metrics

Table 2-1. Typical Sound Levels in Underwater Environments Where Pile Driving Normally Occurs

Sound Source	Sound Pressure Level (dB RMS)	Sound Pressure (pascals)
High explosive at 100 meters	220	100,000
Airgun array at 100 meters	200	10,000
Unattenuated pile strike at 200–300 meters (San Francisco-Oakland Bay Bridge, Benicia-Martinez Bridge)	180	1,000
Large ship at 100 meters	160	100
Fish trawler passby (low speed) at 20 meters	140	10
Background with boat traffic (ranging from quiet estuary to water body with boat traffic)	120	1
	100	0.1
	80	0.01
	60	0.001

The *Acoustic Properties* and *Acoustic Properties Characteristic Impedance* boxes describe several acoustic properties that illustrate the difference between sound in water and sound in air. The speed of sound (c) relates primarily to the temperature and density of a medium. The speed of sound in sea water at a standard temperature of 21º C is equal to 4.4 times the speed of sound in air at standard temperature and pressure. The wavelength of the sound waves (λ), which is the length of one full cycle (i.e., the distance between peaks), is equal to the speed of sound divided by the frequency (i.e., peaks per second expressed as hertz [Hz]). The example in the *Acoustic Properties* box shows that, at a frequency of 250 Hz, the wavelength in water is 6 meters (20 feet), and the wave length in air is 1.4 meters (4.5 feet).

Acoustic Properties:

Speed of Sound

- Function of temperature, salinity, and depth
- For 21°C, $c = 1{,}521$ m/sec
- Relative to air, $c_{water} = c_{air} \times 4.4$

Acoustic Wavelength ($\lambda = c/f$)

- Relative to air, $\lambda_{water} = \lambda_{air} \times 4.4$
- At 250 hz, $\lambda_{air} = 1.4$ m (4½ feet) and $\lambda_{water} \approx 6$ m (20 feet)

Acoustic Properties Characteristic Impedance (ρc):

- $\rho_{water} \approx \rho_{air} \times 811, \quad \rho c_{water} \approx \rho c_{air} \times 3{,}570$
- For a constant volume displacement source in air and water:
  - Acoustic pressure is 60 times greater than in air (~36 dB)
  - With the difference in references, SPL_{water} would be 62 dB greater than SPL_{air}
- Because $\rho c_{water} >> \rho c_{air}$, the transmission loss between them is about 30 dB

Another important acoustical property is the characteristic impedance (ρc), which is the product of the density (ρ) and speed of sound (c) of a material. The *Acoustic Properties Characteristic Impedance* box illustrates the relationship between acoustic pressure in air and water**.** Because the characteristic impedance of water is much greater than that of air, a sound source located above the water surface (in the air) has less effect under the water. The difference in the characteristic impedance values in air vs. water causes a sound transmission loss between air and water of about 30 dB.

The preceding discussion has focused on simple signals at a single frequency. The following discussion addresses pile driving strikes and other examples of waveforms.

Figure 2-2 shows a waveform for a typical pile driving pulse displayed over a period of 0.18 second. It can be seen that the peak pressure occurs early in this sample waveform.

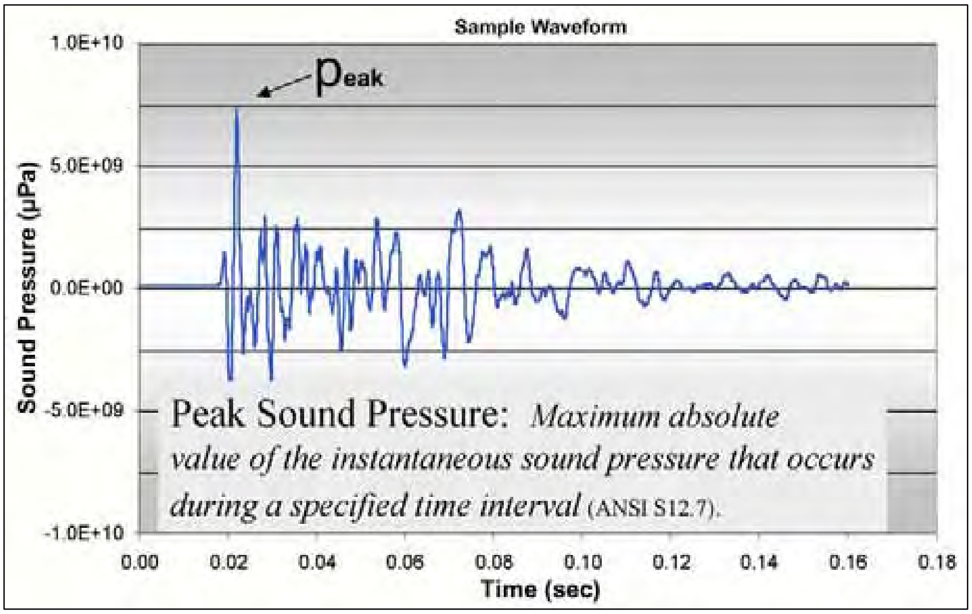

Figure 2-2. Peak Sound Pressure

Figure 2-3 illustrates the "rise time," the time interval a signal takes to rise from 10 to 90 percent of its highest peak value.

Figure 2-4 illustrates an acoustical impulse. This is often referred to in literature in terms of the "psi-millisecond metric" or the "pascal-second metric." This metric has been used by researchers to evaluate the effects of blast signals on fish where the signal is typically characterized by a single positive peak pressure pulse.

Figure 2-5 illustrates how the RMS sound pressure level is determined from a pulse such as a pile strike. This metric has been used in the assessment of the effects of underwater sound on marine mammals and fish. As noted earlier, the RMS is the square root of the sum of the squares of the pressure contained within a defined period from the initial time (Ti) to a final time (Tf).

For marine mammals, the RMS pressure historically has been calculated over the period of the pulse that contains 90 percent of the acoustical energy (the total energy minus the initial 5 percent and the final 5 percent). This is called the "effective pressure," as shown in Figure 2-6. Comparative analysis of pile driving pulses has shown that the "impulse" setting on a precision sound level meter usually provides a good estimate of the effective pressure.

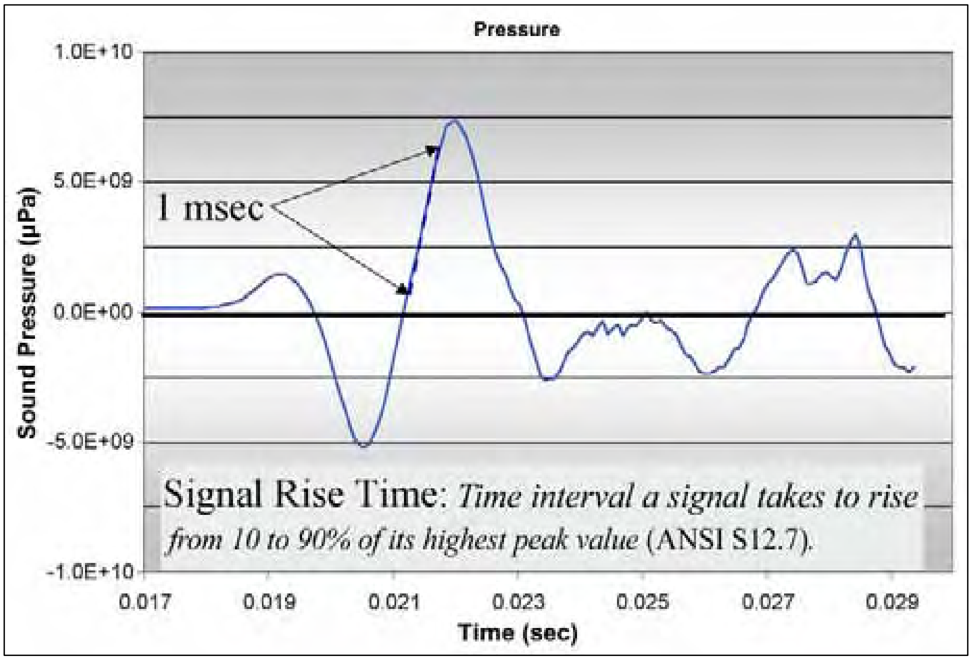

Figure 2-3. Signal Rise Time

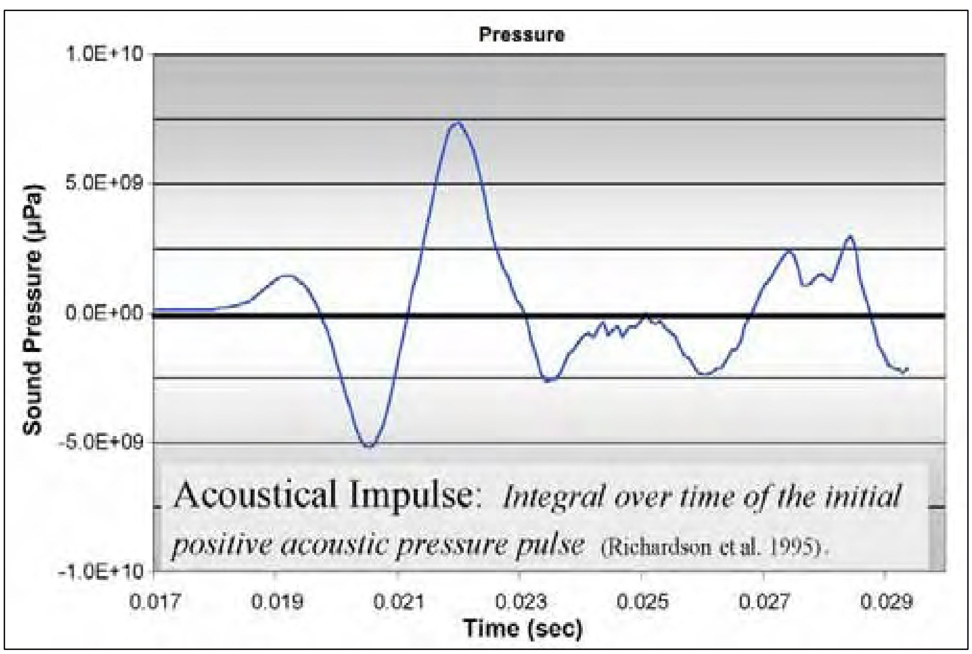

Figure 2-4. Acoustical Impulse

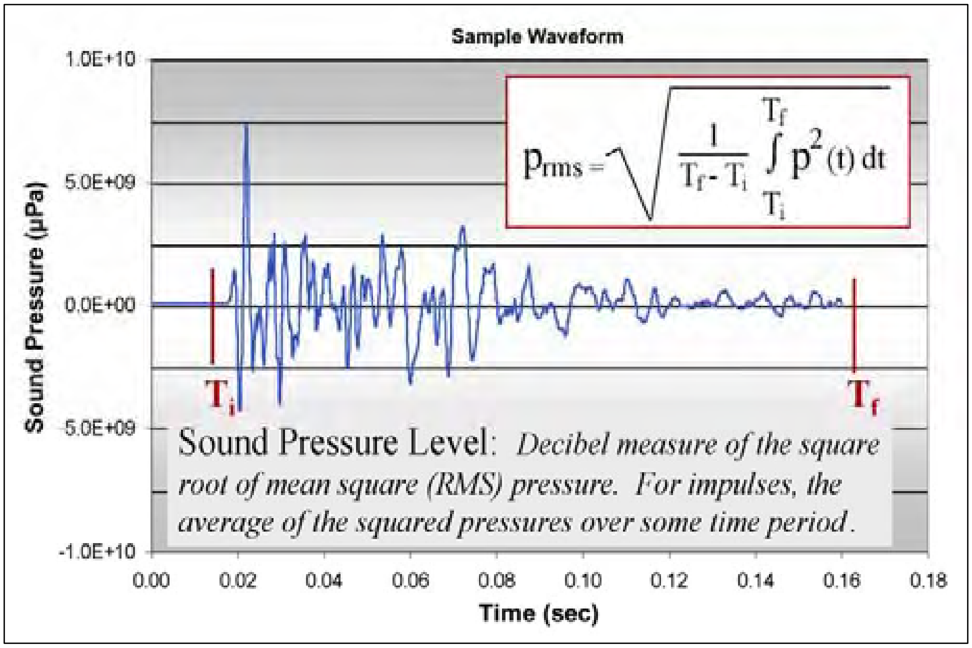

Figure 2-5. RMS Sound Pressure Level

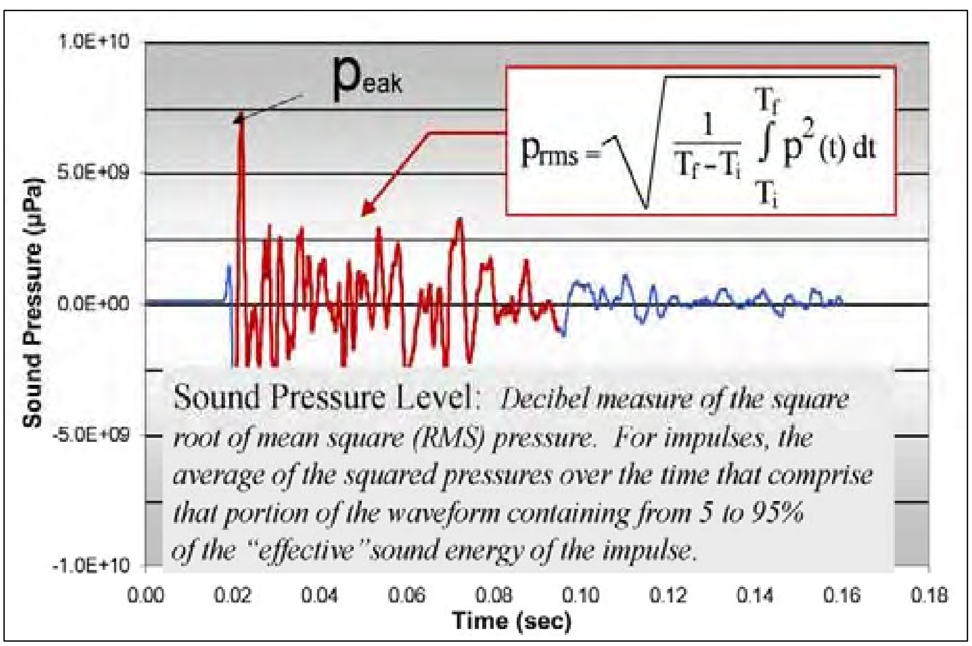

Figure 2-6. Effective Sound Pressure Level

Another way to quantitatively describe the time history of a pressure signal generated by a pile driving pulse is to describe the total sound energy in the pressure signal. In this guidance manual, sound energy associated with a pile driving pulse, or series of pulses, is characterized by the SEL. As noted above, SEL is the constant sound level in one second, which has the same amount of acoustic energy as the original time-varying sound (i.e., the total energy of an event). SEL is calculated by summing the cumulative pressure squared over the time of the event.

Figures 2-7 and 2-8 show the sample waveform and the pressured squares over time, respectively. Figure 2-9 shows the accumulated energy in the pulse, with the resulting level representing the SEL. The same chart with the trailing energy at the end of the waveform removed shows the SEL calculated over the period where 90 percent of the energy in the pulse is contained, excluding the initial 5 percent and the final 5 percent, similar to the effective pressure.

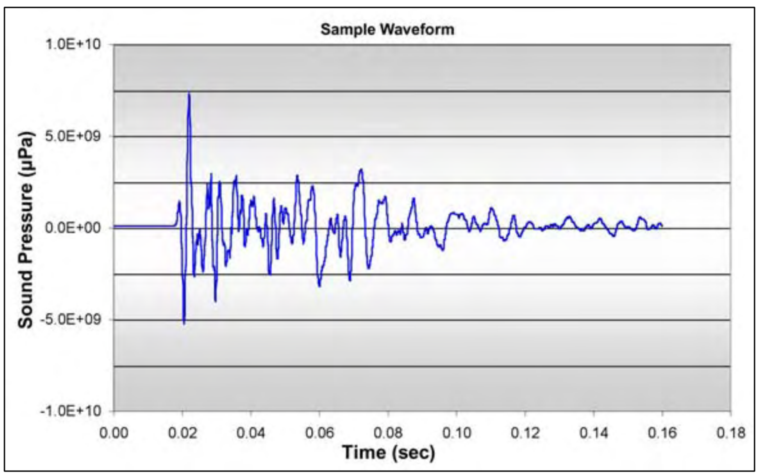

Figure 2-7. Sound Exposure Level for a Single Pile Driving Impulse

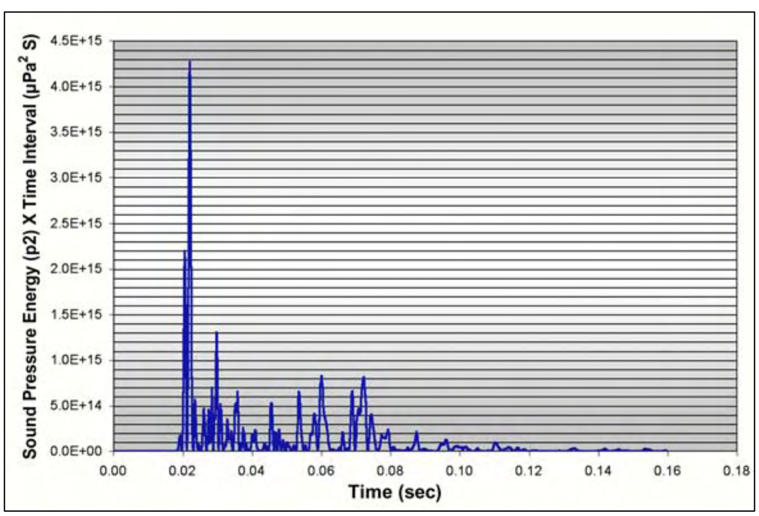

Figure 2-8. Sound Exposure Level Calculation

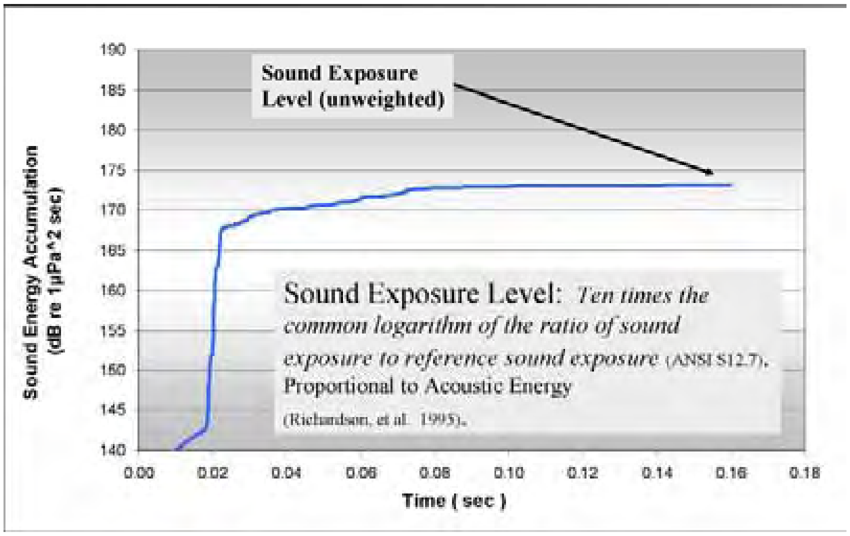

Figure 2-9. Sound Exposure Level

The acoustic energy flux density, or intensity (I), of a sound wave is the product of sound pressure and acoustic particle velocity divided by the acoustic impedance of the medium. To estimate the acoustic energy flux, or total energy flux (TEF) as it is sometimes referred to in literature, most researchers use the assumption that pressure and velocity are in phase with one another. This assumption, however, is only true for conditions approaching plane waves. (A plane wave is a constant-frequency wave whose wavefronts are infinite parallel planes of constant amplitude normal to the velocity vector of the wave). In many environments, particularly in shallow water near shore, pressure and velocity are complex quantities that are not likely to be in phase. This is also true near the sound source in what is called the "acoustic near field." Because of the difficulty in measuring total energy flux in the field, SEL is used as the energy metric in this guidance manual.

Most sounds, including the sound of a pile driving pulse, are composed of many different frequencies. This is referred to as the "frequency spectrum" of the sound. A typical sound pressure spectrum is shown in Figure 2-10. The amplitude of the sound in dB re: 1 micro-Pascal is shown on the vertical axis, and the frequency of the sound is shown on the horizontal axis. Frequency is measured in cycles per second (Hz). When characterizing a sound pressure spectrum for a waveform, the unit of amplitude is normally the RMS pressure, which is measured over a defined frequency bandwidth. The bandwidth can be as narrow as 1 Hz or as wide as 1/3 octave (an octave is a doubling of frequency); therefore, the bandwidth must be specified. Frequency spectra are important because the frequency content of the sound may affect the way the fish responds to and is affected by the sound (in terms of physical injury as well as hearing loss). It also can be important for other species when determining how the sound may interfere with their ability to communicate using sound. From an engineering perspective, the frequency spectrum is important because it affects the expected sound propagation and the performance of a sound attenuation (i.e., reduction) system, both being frequency dependent.

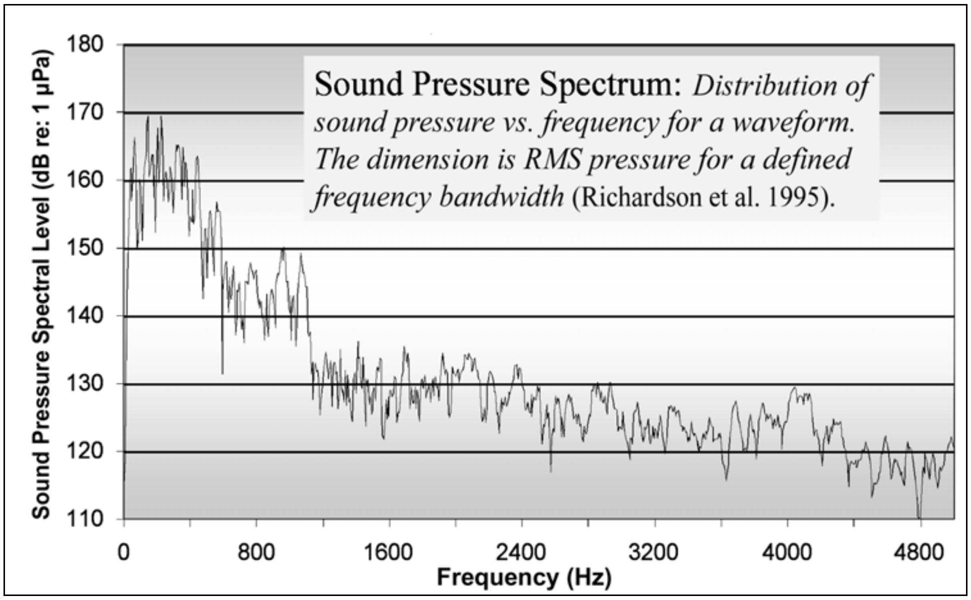

Figure 2-10. Narrow-Band Frequency Sound Pressure Spectrum Level

In an evaluation of pile driving impacts on fish, it may be necessary to estimate the cumulative SEL ($SEL_{cumulative}$) associated with a series of pile strike events. $SEL_{cumulative}$ can be estimated from a representative single-strike SEL value and the number of strikes that likely would be required to place the pile at its final depth by using the following equation:

$$SEL_{cumulative} = SEL_{single\ strike} + 10 \log (\#\ of\ pile\ strikes) \qquad \textit{Equation 2-1}$$

Equation 2-1 assumes that all strikes have the same SEL value and that a fish would continuously be exposed to pulses with the same SEL, which is never actually the case. The equation does, however, provide a reasonable estimation of the cumulative SEL value, given a representative single-strike SEL value and an estimate of the number of strikes.

Although not currently used as a criterion metric, the vector quantity particle velocity may emerge as a useful metric for evaluating the effect of underwater sound on fish. When applied to a sound wave traveling through water, particle velocity would be the physical speed of a water molecule as the wave passes by it.

2.2 Underwater Sound Propagation

Underwater sound propagation is complex but is similar in certain respects to sound propagation through the air. Sound propagation in water is subject to the same governing propagation equations that apply in air. There is the primary direct transmission path between the source and the receiver; there is reflection from extended surfaces, such as the water surface and the bottom; and there are refraction effects and shielding effects. A significant difference between the propagation of sound underwater versus sound in air is that the underwater medium has distinct boundaries (the water surface and the bottom) that can substantially affect propagation characteristics. In addition, when pile driving is the source of noise, there is the potential for the vibration that results from the pile being struck by the hammer to shake the ground, which then re-radiates noise back into the water. Figure 2-11 illustrates these basic propagation concepts.

Generally, underwater sound propagation is divided into two categories: deep water and shallow water (Richardson et al. 1995). For most projects involving pile driving, the conditions shown in Figure 2-12 that describe a shallow-water environment are applicable. There is a direct transmission from the source to the receiver, and there are reflected paths from the surface and the bottom. As described above, with pile driving, there is also the potential for sound energy that is re-radiated from the ground to reach the receiver. Normally, the ground-radiated noise is dominated by low frequencies, which cannot propagate efficiently through shallow water.

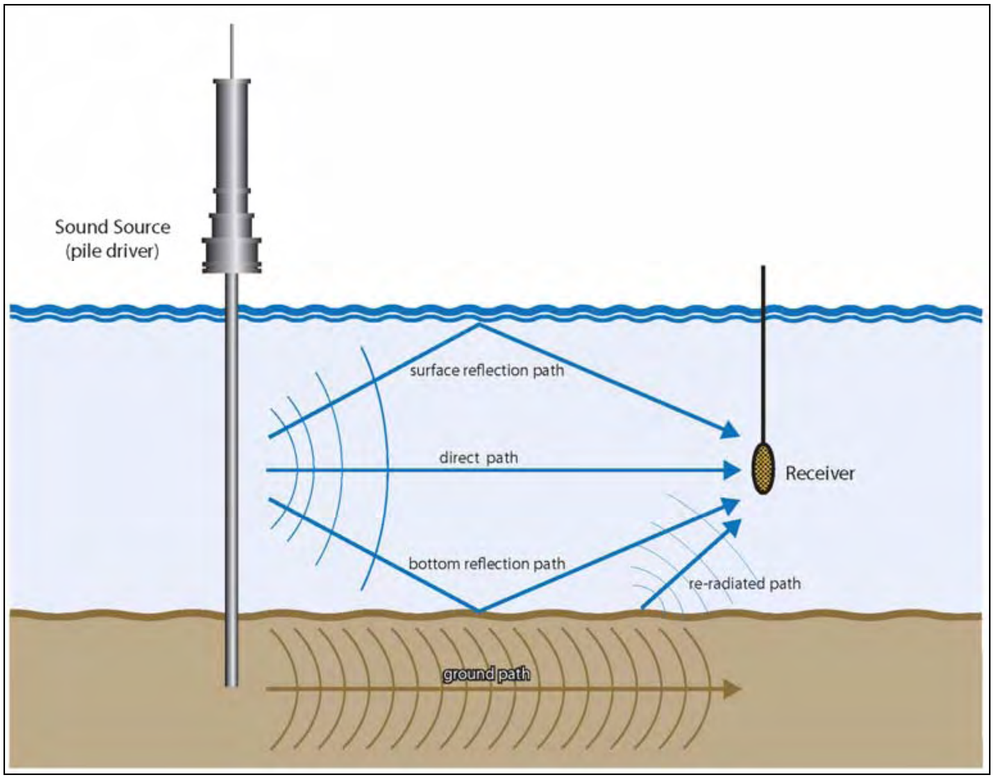

Figure 2-11. Underwater Sound Propagation Paths

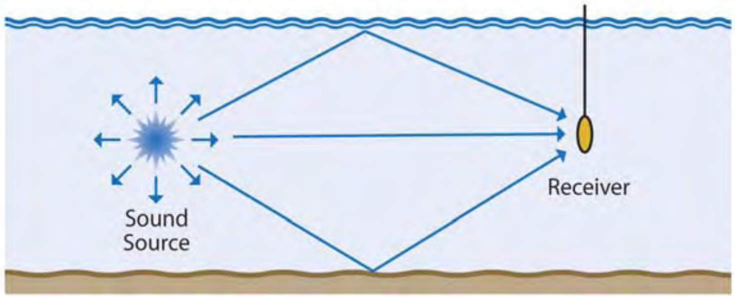

Figure 2-12. Underwater Sound Propagation in Shallow Water

Figure 2-13 shows what happens in shallow water near the surface. At this location, there is a "pressure release," which is a 180-degree shift in the phase of the sound wave. Excess attenuation from wave cancelation effects can occur because of the interaction between the direct and out-of-phase reflected waves near the surface.

The pile segment that is in the water is an extended source (not a point source) that typically extends from the water surface to the mud line. In some cases, the tops of the piles are driven all the way to the mud line using a submersible hammer, as indicated in Figure 2-14. In these situations, when the pile does not extend from the water surface to the mudline, the source and propagation characteristics associated with the pile will change as the top of the pile is submerged.

All pile driving projects for which data are available are in shallow-water environments that exhibit all of the propagation complexities previously described. Normally, the geotechnical conditions below the mud line are not completely known. As previously noted, the potential for the direct transmittance of energy through the bottom substrates below the mudline complicates the prediction of sound propagation to any point in the water. In addition, obstructions such as barges, other piles, and other structures (e.g., existing bridges) and channel characteristics such as the narrowness of the channel and the slope of side of the channel can modify how sound propagates in water.

Because of these complications, empirical data rather than mathematical models are used to predict sound propagation effects. On several projects, sound levels have been measured at varying distances. This information is documented in Appendix I, and the methodology for applying these data sets is described in Chapter 4.

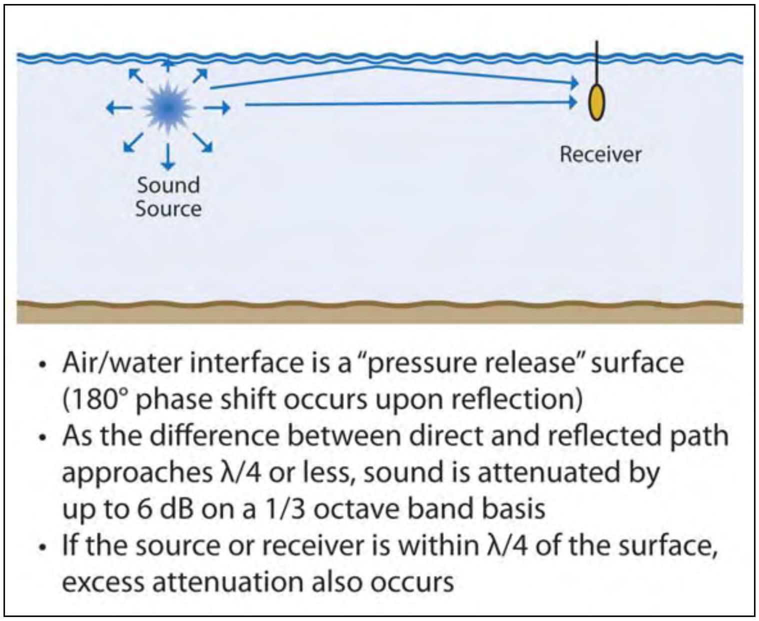

Figure 2-13. Underwater Sound Propagation in Shallow Water near the Surface

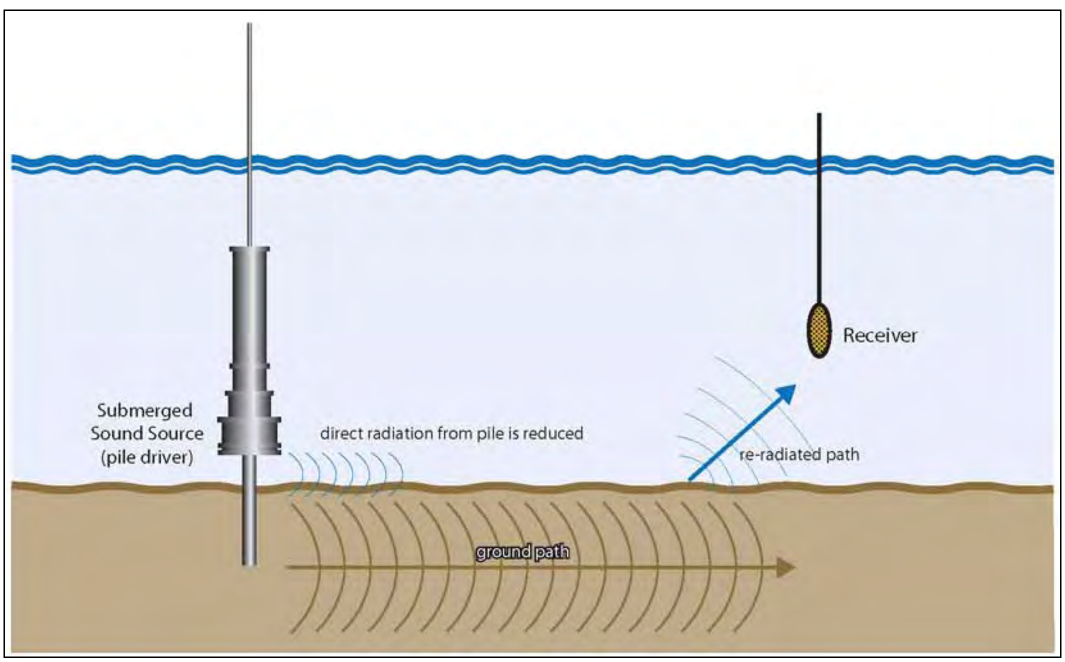

Figure 2-14. Underwater Sound Propagation with Submerged Hammer

Analytical methods for evaluating the attenuation of underwater sound over distance are discussed in Chapter 4, Section 4.6.3.

2.3 Measurement of Underwater Sound

This section provides an overview of measuring underwater sound resulting from in-water pile driving. Example data are provided. Appendix II provides a detailed procedure for conducting measurements of noise generated during pile driving events.

The basic measurement system consists of a hydrophone, like a microphone, that is waterproof and connected via cables to recording devices. Usually, specialized signal conditioners and power supplies are required. This equipment system is shown in Figure 2-15. Figure 2-16 shows an actual measurement system. The equipment shown in the photograph includes a hydrophone; a thermometer used to measure water temperature; cables; and a field case that includes power supplies, signal conditioners, a two-channel digital audio tape recorder, and data loggers. In this application, the signal from the hydrophone is transmitted separately to a field data logger, which is a precision sound level meter, and the digital audio tape recorder for subsequent laboratory analysis. This measurement system allows the person conducting the measurements to determine the approximate L_{PEAK}, RMS, and SEL values directly in the field.

The hydrophone sensor is normally placed in a water column at least 1 meter deep, with the sensor located at a depth of 0.5 meter above bottom of the water column. Monitoring plans typically specify the minimum water column depth and the depth of the hydrophone sensor.

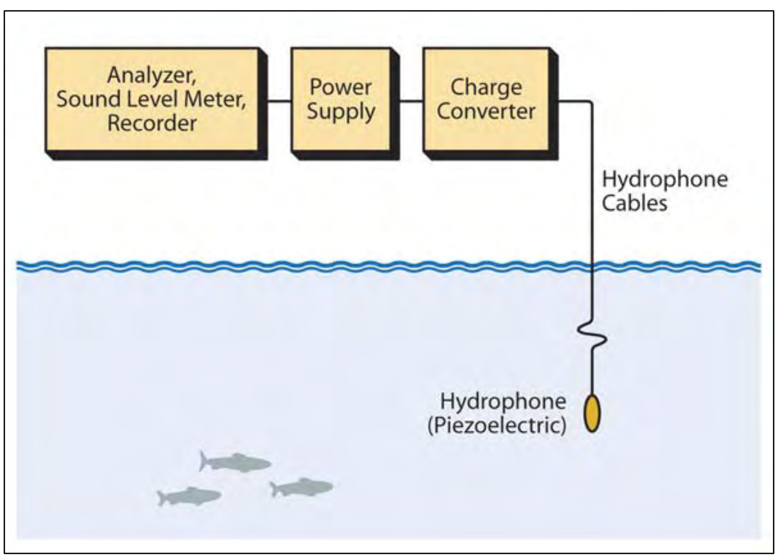

Figure 2-15. Basic Hydrophone System

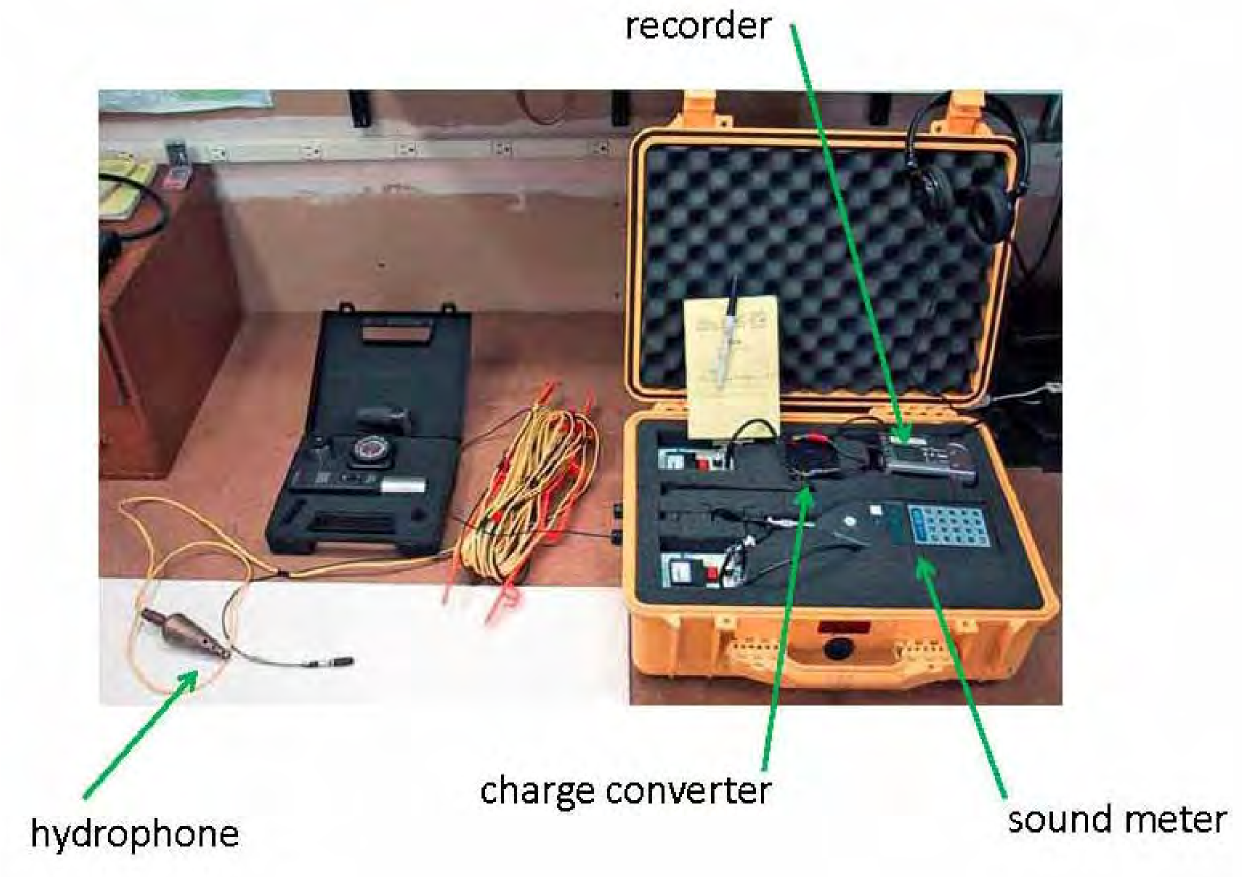

Figure 2-16. Measurement System

Figure 2-17 shows three representative hydrophones with differing sensitivities. The selection of the appropriate sensor is based on the anticipated amplitude of the signal. Where signal levels are low, a sensitive hydrophone is used to detect the low signals; where signals are expected to be very high, a sensor such as the blast transfuser can be used. If the wrong sensor is selected, the signal can be below the minimum signal that the sensor can measure or it can exceed the capability of the sensor, thereby saturating the measurement system and invalidating the measurement.

The instrumentation must be calibrated so that the correct levels can be determined from the recorded data. Figure 2-18 is a photograph of a field calibration system. The various methods for achieving calibration are described in Appendix II.

Figure 2-17. Pressure Sensors

Figure 2-18. Calibration in the Field

2.4 Examples of Underwater Pile Driving Sound Levels

Typical sound levels associated with different types of piles are shown in Table 2-2. Reference sound levels from pile driving normally are reported at a fixed distance of 10 meters. **In this document, all underwater peak and RMS decibel levels are referenced to 1 μPa, and the SEL is referenced to 1 μPa^2-sec.** These data show that different types of piles result in different sound pressures. The data also illustrate the relationship between the peak pressure, the RMS sound pressure, and the SEL. A typical waveform, frequency spectrum, accumulation of energy curve, and data summary from a 96-inch-diameter cast-in-shell steel (CISS) pile are shown in Figure 2-19. Additional data on a wide variety of pile sizes and pile driving conditions are provided in Appendix I.

Table 2-2. Single-Strike Sound Levels Associated with Different Piles (Measured at 10 Meters from Pile)

Pile	Peak Pressure (decibels)	RMS Sound Pressure (decibels)	Sound Exposure Level (decibels)
Timber (12-inch) drop	177	165	157
Cast-in-shell steel (CISS) (12-inch) drop	177	165	152
Concrete (24-inch) impact	193/183	175/171	160
Steel H-type impact	190	175	Not available
CISS (12-inch) impact	190	180	165
CISS (12-inch) impact	200	184	174
CISS (30-inch) impact	208	190	180
CISS (96-inch) impact (at 25 meters)	212	197	188

Note: Dual values for 24-inch concrete represent the range of measured levels.

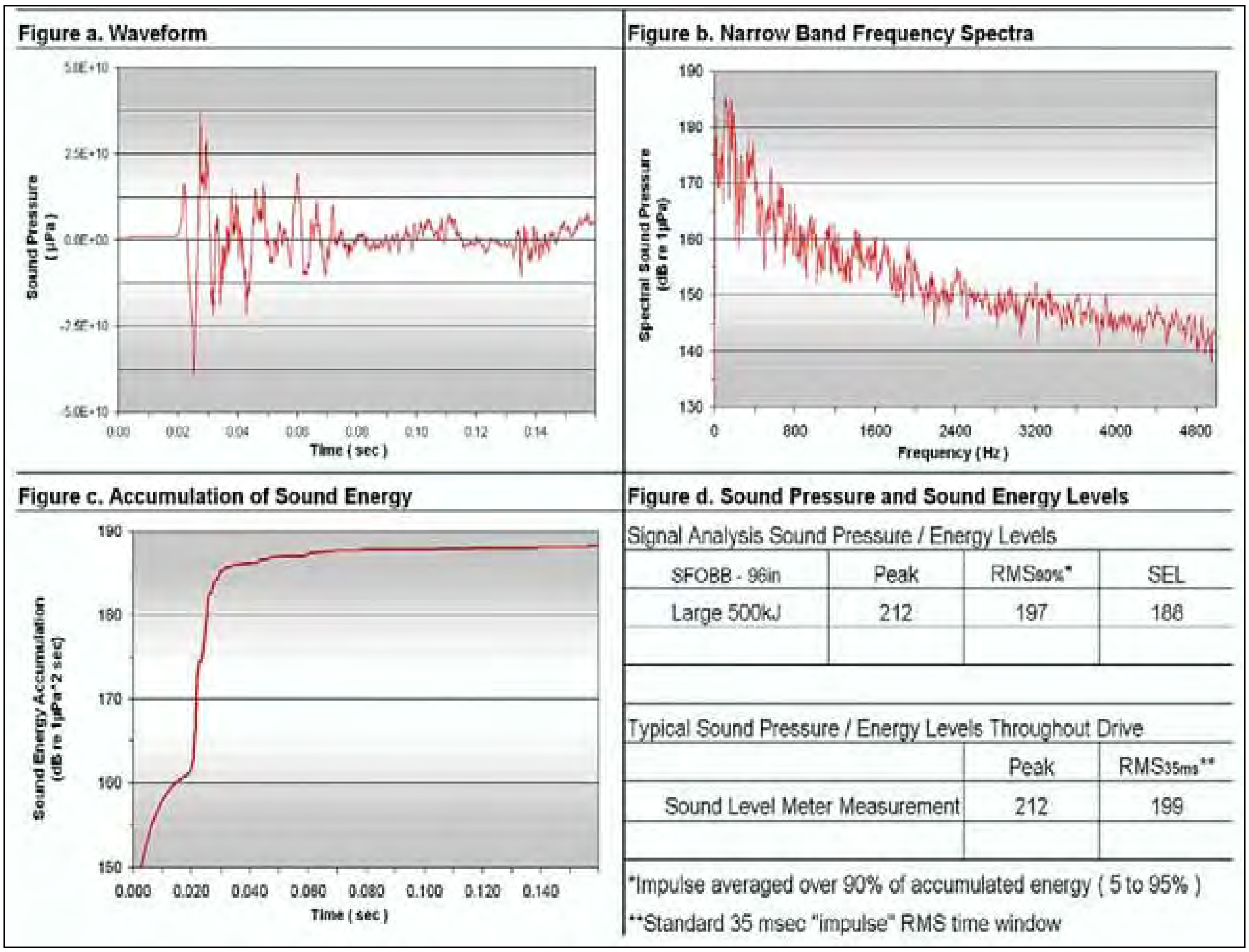

Figure 2-19. Representative Pile Strike at 25 Meters from a 96-Inch-Diameter CISS Pile with a 500-Kilojoule Hydraulic Hammer

As discussed above, it may be necessary to estimate $SEL_{cumulative}$ for a given pile driving scenario. Such an estimate requires an estimate of the single-strike SEL at a fixed distance from the pile and an estimate of the number of pile strikes needed to place the pile at its final elevation. The number of strikes needed to install a pile depends on many factors, such as the size and type of the pile, the type of substrate, and the size of the hammer. It may also be necessary to estimate the total number of strikes that may occur in a day if multiple piles are driven in the same location on the same day.

Data from past projects on the actual number of pile strikes per pile and per day are limited. Table 2-3 summarizes available typical strike data for a range of pile types. The data reported in Table 2-3 are based on examples of past projects and may not be representative of other projects that use different construction techniques (e.g., pile driving from barge vs. trestle).

Table 2-3. Summary of Typical Strike Data

Pile Type, Size, and Shape	Typical Use	Typical Installation Duration	Typical Strikes per Pile
Concrete, 24-inch hexagon	Wharf construction projects	1 to 5 piles per day	580
Thin steel H, small	Temporary construction projects	6 piles per day	550
Steel pipe, 40-inch diameter	Permanent construction projects	1 to 5 piles per day	600
Cast-in-steel shell (CISS) pipe, 30-inch diameter	Permanent construction projects	2 to 4 piles per day	1,600 to 2,400 per day
CISS pipe, 96-inch diameter	Permanent construction projects	1 to 3 pile sections per day	7,000 per day

2.5 Common Underwater Sound Reduction Measures

Various measures have been developed to reduce underwater sound generated by in-water pile driving. These measures fall into two general categories:

- Treatments that reduce the transmission of sound through the water, and
- Treatments to reduce the sound generated by the pile.

The first category includes simple unconfined air bubble curtains, multiple-stage unconfined air bubble curtains, confined air bubble curtains, and cofferdams. The second category includes alternative hammer types, such as vibratory hammers and oscillating, rotating, or press-in systems. The use of wood, nylon, and micarta pile caps also would fall in the second category. Information is currently available on the general effectiveness of various air bubble curtain systems and cofferdams. Limited data are available on the effectiveness of vibratory hammers and other treatments intended to reduce the noise generated by the pile. Vibratory hammers are generally much quieter than impact hammers, at least in terms of sound amplitude. However, the accumulated SEL could be higher if the vibratory hammer requires considerably more time to install the pile. In general, vibratory hammers are not used because they cannot drive the pile to the specified depth or resistance.

As more measurement data become available for other pile installation methods, the data will be added to this document and the compendium of underwater sound data presented in Appendix I.

2.5.1 Bubble Curtains

The underlying mechanism of bubble curtains is changing the local impedance in the area where the bubbles are introduced. This can have two effects:

- To act as a barrier for the sound to pass through once the sound is radiated from the pile; and
- To reduce the radiation of sound from the pile into the water by having the low-density bubbles very close to the pile.

The first effect is assessed by modeling the attenuation as a simple sound transmission problem through multiple media (i.e., transmission from water, through a water/air mix, and back to water). For the water/air mix, consider the local density as a function of the percent of air, or bubbles. The two parameters are then the bubble percentage and the thickness of the bubble curtain. Basically, attenuation increases with more bubbles and (to a point) a thicker curtain. There was success in Canada using a relatively narrow curtain produced by a 50-millimeter-wide bubbler (Frazier River Pile and Dredge undated). Studies on blast pressure attenuation by the U.S. Army Corps of Engineers have indicated some, but not complete, success in reducing fish mortality using a lower air flow rate per hole and a wider bubbler. Using this system, there was still mortality of approximately 6 percent of the fish evaluated. This would be expected because attenuation is generally more affected by the percentage of bubbles than by the curtain thickness.

Figure 2-20. Unconfined Air Bubble Curtain Systems

For the San Francisco-Oakland Bay Bridge Pile Installation Demonstration Project, achieved from 0 to 2 dB of attenuation. For other various pile driving projects, achieved from 0 to 5 dB of attenuation.

For the second effect (changing the radiation from the pipe), the sound power radiated by the pile is directly proportional to the characteristic impedance of the media it is radiating into. The impedance for water is almost 4,000 times greater than for air. This means, in the extreme, that the potential exists for reductions up to 36 dB as the impedance of air is approached. But other factors would affect this result. An assessment of the actual potential effect must take into account the effects of the different densities of water and air on the vibration of the pile, and the change in radiation efficiency in water due to the change in coincidence frequency in water.

Air bubble curtains can be confined or unconfined. In a confined system, the bubbles are confined to the area around the pile with a flexible material (plastic or cloth) or a rigid pipe. The material of the confining casing does not affect the overall sound reduction provided by the system (i.e., steel or cloth would work equally as well). Confined systems are most often used when there is potential for high water-current velocities to sweep the bubbles away from the pile. Unconfined systems have no such system for restraining the bubbles. The first known unconfined air bubble curtain system in California was used on the San Francisco-Oakland Bay Bridge Pile Installation Demonstration Project. This system is shown in Figure 2-20. Because the diameter of the air bubble curtain system was large with respect to the pile, the bubble screen that was generated by this system was not immediately adjacent to the pile. This type of bubble screen has the disadvantage of allowing the sound pulse to propagate into the water. It also was affected by the currents, which swept the bubbles away from the pile. Although this system provided only a minimal measured attenuation of from 0 to 2 dB, similar systems used on various other pile driving projects have resulted in from 0 to 5 dB of attenuation in high current situations. In low current situations, from 5 to 15 dB of noise reduction has been achieved.

Figure 2-21 shows another bubble ring system used during construction on the Richmond- San Rafael Bridge. This system used a smaller diameter ring and was utilized only in light current conditions. A similar system has been used on concrete piles on wharf repair projects in the San Francisco Bay region. This system has been shown to provide from 5 to 15 dB of attenuation in the overall pressure where currents are light or non-existent. Figure 2-22 shows the dual-stage (with an upper and lower bubble ring) unconfined air bubble curtain system used on the San Francisco-Oakland Bay Bridge when the piles were re-struck to assess their resistance to forces about a year after they were originally driven. This system provided from 5 to over 20 dB of attenuation but was found to provide different levels of attenuation, depending on the direction from the pile. This directional characteristic was likely due to the current or ground-borne vibration propagation. Figures 2-23 and 2-24 show the waveforms and frequency spectra with this system turned on and turned off. The waveforms show the significant reduction in the peak pressure realized with this air bubble curtain system. The frequency spectra in Figure 2-24 show that the reduction in sound provided by the attenuation system varies as a function of frequency.

Figure 2-21. Bubble Ring

For the Richmond-San Rafael Bridge, provided from 5 to 15 dB of attenuation in light to nonexistent current for 30- to 66-meter piles driven in shallow water.

Figure 2-22. Dual-Stage Unconfined Air Bubble Curtain

For the San Francisco-Oakland Bay Bridge Pile Installation Demonstration Project re-strike, provided from about 5 to 20 dB of attenuation.

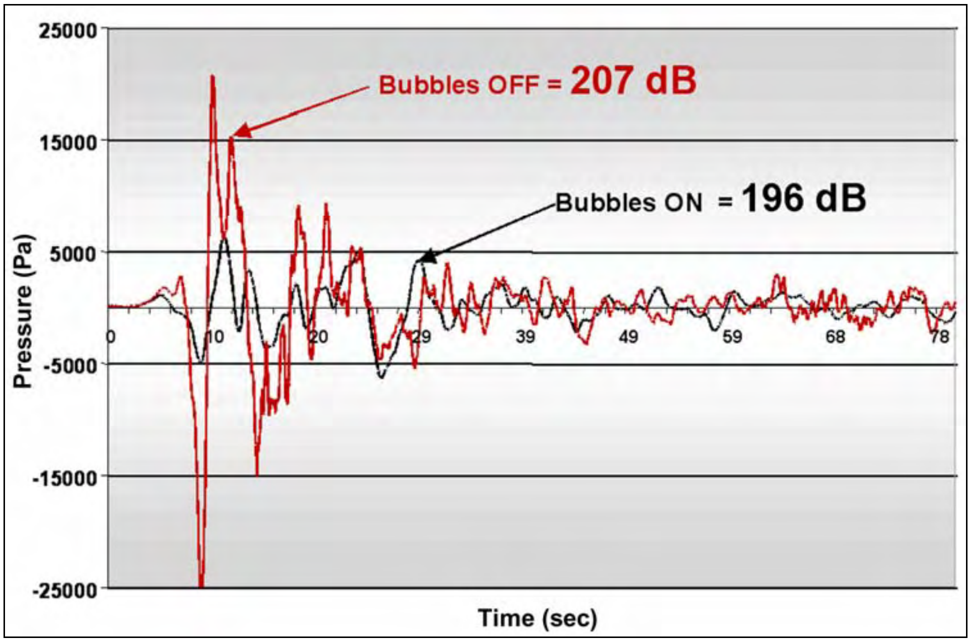

Figure 2-23. San Francisco-Oakland Bay Bridge Re-Strike Air Bubble Curtain Waveforms

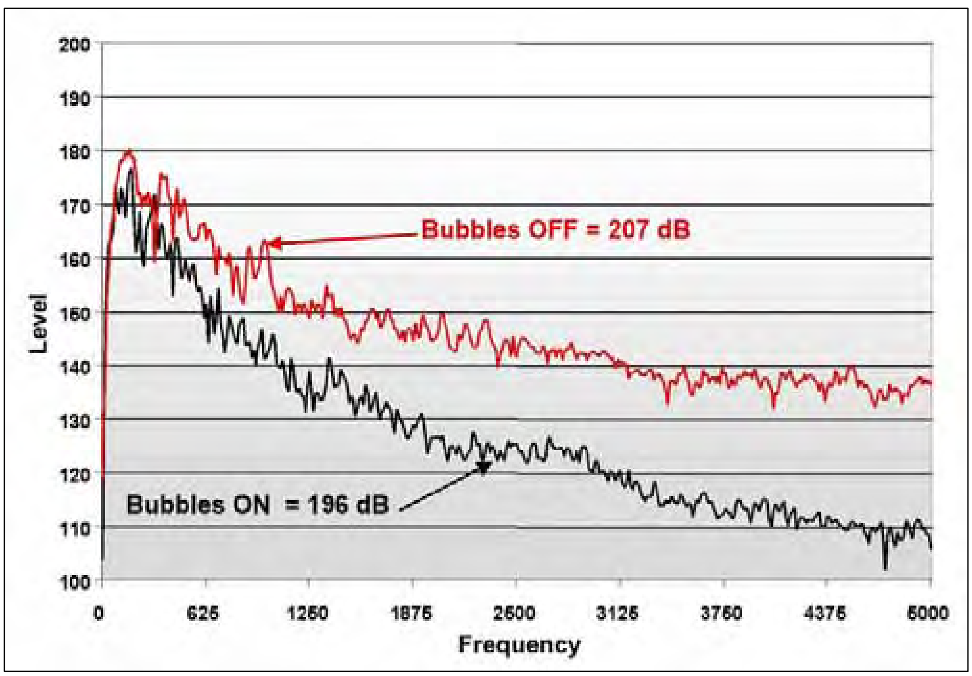

Figure 2-24. San Francisco-Oakland Bay Bridge Re-Strike Frequency Spectra

Construction of the Benicia-Martinez Bridge provided additional complications primarily due to deep water and strong currents. To deal with these factors, an attenuator was developed consisting of nine different bubble rings (nine stages) stacked vertically, as shown in Figure 2-25. Five stages were typically operational. This system provided outstanding performance, with attenuation in the range of 15 to more than 30 dB across the entire frequency spectrum. Figures 2-26 and 2-27 show waveforms and frequency spectra for this system.

Figure 2-25. Multiple-Stage Unconfined Air Bubble Curtain System

For the Benicia-Martinez Bridge, achieved from about 15 to more than 30 dB of attenuation.

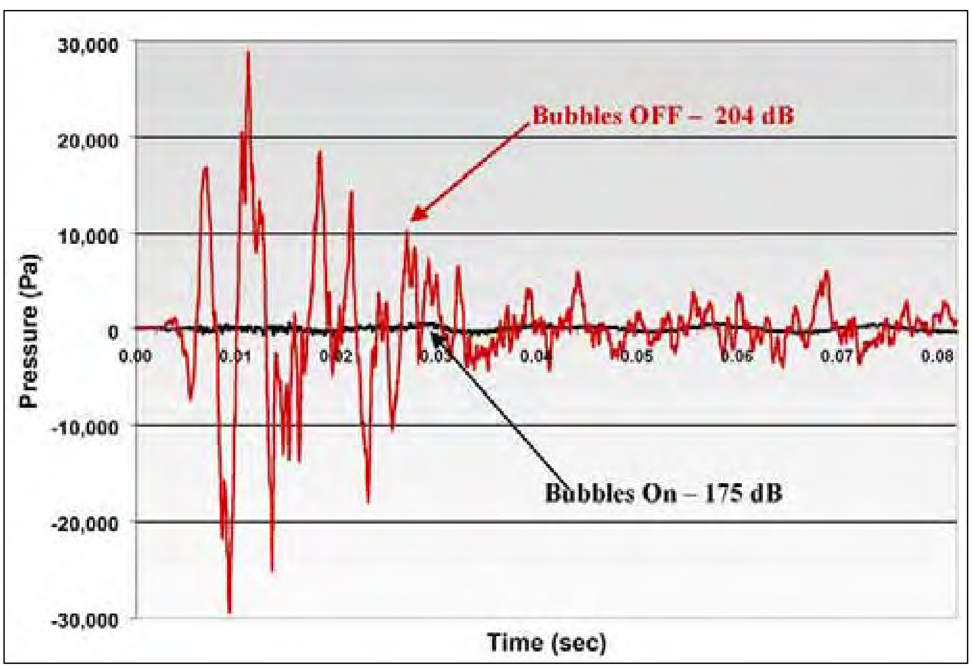

Figure 2-26. Benicia-Martinez Bridge Waveforms

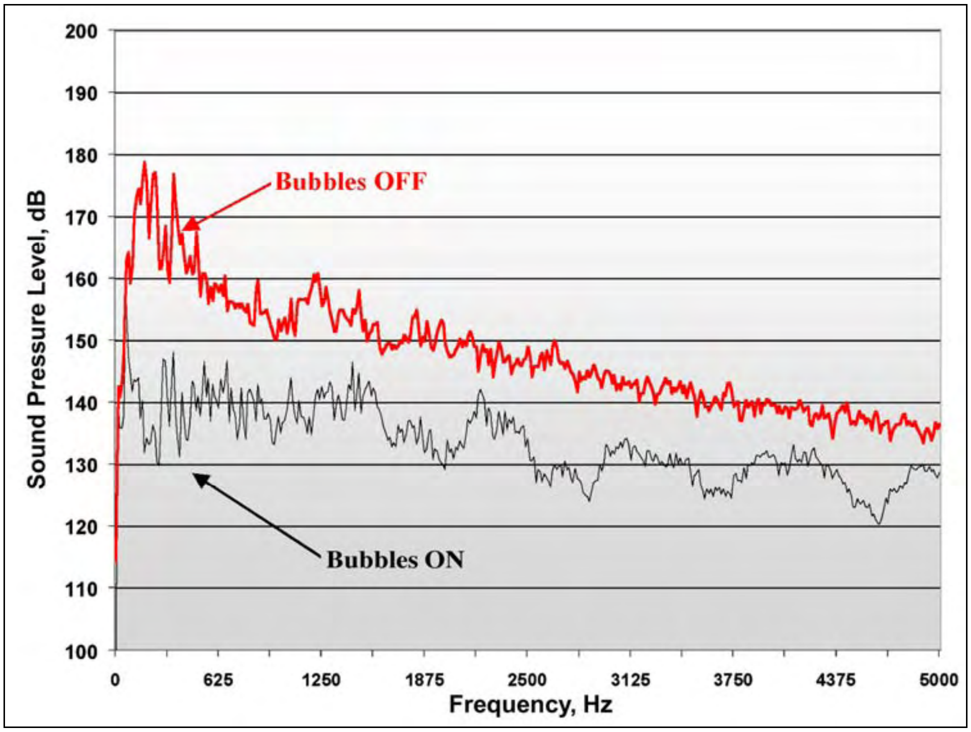

Figure 2-27. Benicia-Martinez Bridge Bubble Curtain Sound Pressure Reduction

Proprietary confined air bubble curtain systems have been developed by several manufacturers, in consultation with Caltrans and independently. Figure 2-28 shows the proprietary bubble curtain system that was used for the San Francisco-Oakland Bay Bridge for the Pile Installation Demonstration Project. The system achieved from 5 to 10 dB of attenuation. Although they can be effective, in some cases proprietary systems can be more costly than non-proprietary systems without significant benefit over non-proprietary systems.

Figure 2-28. Proprietary Confined Air Bubble Curtain System

For the San Francisco-Oakland Bay Bridge Pile Installation Demonstration Project, achieved from about 5 to 10 dB of attenuation.

Figures 2-29 and 2-30 show the isolation casing used on the Benicia-Martinez Bridge. The isolation casing provided attenuation similar to the nine-stage bubble curtain.

Figure 2-29. Confined Air Bubble Curtain System Used in an Isolation Pile at the Benicia-Martinez Bridge

For Benicia-Martinez Bridge Pier 9, achieved from about 20 to 25 dB of attenuation—either with bubbles or no water.

Figure 2-30. Confined Air Bubble Curtain System Used in an Isolation Pile at the Benicia-Martinez Bridge

For Benicia-Martinez Bridge Pier 9, an oversized-diameter pipe was used to decouple the pile from the water column.

Figure 2-31 shows a simple confined air bubble curtain system. This system proved to be very effective when properly deployed and operating, and achieved from about 15 to 30 dB of attenuation. Several confined and unconfined systems were tested for the Humboldt Bay Bridges Project. In this situation, the best attenuation system could provide only from 10 to 15 dB of attenuation, because the ground-radiated sound appeared to dominate the attenuated received level. As a general rule, sound reductions of greater than 10 dB with attenuation systems cannot be reliably predicted.

Figure 2-31. Simple Confined Air Bubble Curtain System

For the Humboldt Bay Bridges Project, the system achieved from about 15 to 30 dB of attenuation.

2.5.2 Coffer Dams

Cofferdams are sometimes used during in-water and near-water pile driving. A cofferdam may be used for acoustic or non-acoustic reasons. Cofferdams full of water provide only limited attenuation. Sometimes bubble curtains are used within a watered cofferdam if dewatering is not practical. Cofferdams that have been dewatered down to the mud line substantially reduce underwater pile driving sound. This is the best isolation that can be provided. The sound, however, is not eliminated because some of the energy is transmitted through the ground (as previously discussed).

2.5.3 Vibratory Hammers

Vibratory hammers are routinely used on smaller piles. Although peak sound levels can be substantially less than those produced by impact hammers, the total energy imparted can be comparable to impact driving because the vibratory hammer operates continuously and requires more time to install the pile. To meet pile resistance requirements for some projects, piles need to be struck multiple times with an impact hammer; this can preclude the use of vibratory hammers in many cases.

2.5.4 Other Sound Reduction Systems

Other sound reduction systems utilize mechanisms for oscillating, rotating, or pressing in the pile. These systems have limitations on pile size and type, and pile resistance. No acoustical data are known to exist for these alternative systems. They are, however, expected to generate substantially lower sound pressures than either impact or vibratory hammers. Pre-drilling the hole for the pile also can serve as a means to reduce the number of pile strikes needed to place a pile.

2.6 References

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Chapter 3 Fundamentals of Hydroacoustic Impacts on Fish

3.1 Introduction

Sound generated by percussive pile driving has the potential to affect fish in several ways. The range of effects potentially includes alteration of behavior to physical injury or mortality, depending on the intensity and characteristics of the sound, the distance and location of the fish in the water column relative to the sound source, the size and mass of the fish, and the fish's anatomical characteristics (Yelverton et al. 1975—cited in Hastings and Popper 2005).

Because little was known about the effects of underwater pile driving noise on fish, the Department commissioned the preparation of several white papers to collect and evaluate literature, which could be used to establish interim criteria for the analysis of pile driving impacts to fish. Hastings and Popper (2005) reviewed the literature on the effects of sound on fishes, and identified data gaps and potential studies that would be needed to address areas of uncertainty relative to the measurement of sound and the response of fishes to sound. This paper concluded that duel interim criteria were warranted, including criteria for single-strike peak pressure and criteria for single-strike accumulated pressure (i.e., SEL).

The need to further research the applicability and application of the dual interim criteria led to the publication of two additional white papers, Popper et al. (2005) and Carlson et al. (2007), which ultimately led to the interagency Agreement in Principal for Interim Criteria for Injury to Fish from Pile Driving Activities (FHWG 2008). (This agreement is contained in *Appendix IV*; also see Chapter 4.) Refer to the Caltrans website for copies of these studies and additional related information: http://www.dot.ca.gov/hq/env/bio/fisheries_bioacoustics.htm.

This chapter summarizes the discussions of the anatomy and physiology of fishes from those papers that are fundamental to understanding the types of impacts that could potentially occur to fish from sound generated during pile driving.

3.2 Types of Fishes

More than 29,000 fish species have been identified worldwide (Froese and Pauly 2005). With such a large and diverse group, there are many ways to classify fish species. One categorization is to distinguish between cartilaginous and bony fishes. Cartilaginous fishes include sharks and rays, while bony fishes compose the vast majority of fish species—including the more advanced family of teleosts (e.g., salmon, tuna, perch, sturgeon, and most commercially important species). Research completed thus far on hearing in fish has been based primarily on bony fishes.

Fish also can be categorized by the way they hear. All fish fall into two hearing categories: hearing generalists (such as salmon and trout) and hearing specialists (such as herring and shad). Hearing generalists sense sound directly through their inner ear but also sense sound energy from the swim bladder. Hearing specialists are more complex. Many of the hearing specialists have evolved any one of a number of different mechanisms to couple the swim bladder (or other gas-filled structure) to the ear. The swim bladder is stimulated by the pressure of sound waves and serves as a transducer that re-radiates energy in the form of particle motion that is detected by the inner ear. This increases hearing sensitivity compared to hearing generalists and therefore makes them more susceptible to loud noises.

Most teleost fishes maintain their buoyancy by inflating and deflating their swim bladder with air. Fish with swim bladders can be categorized into two groups. Physostomes are fish with ducted swim bladders (e.g., salmon, trout, pike, sturgeon, and catfish, among others). In physostomous fish, the swim bladder is directly connected to the esophagus by a thin tube, allowing the fish to expel air from the swim bladder through this tube and out of the mouth. The second group, called physoclists (e.g., perch and tuna, among others), have non-ducted swim bladders. Physoclistous fish fill their swim bladder by the forcible excretion of oxygen from an area rich in arterial and venous blood vessels called the gas gland and reabsorb gas into their bloodstream at a site called the oval. Some physostomous fish also have a gas gland or resorbant area in addition to the pneumatic duct, but these tend to be weakly developed in comparison to physoclistous fish. This distinction has the potential to inform how fish are impacted by underwater noise. Tissue damage can occur when sound passes through a fluid tissue (e.g., muscle) into a gas void (swim bladder) because gas is more compressible. When a fish is exposed to a sound wave, gas in the swim bladder expands more than surrounding tissue during periods of underpressure and contracts more than surrounding tissue during periods of overpressure. This can cause the swim bladder to oscillate and result in tissue damage, including rupture of the swim bladder (Alpin 1947, Coker and Hollis 1950, Gaspin 1975, Yelverton et al. 1975—all cited in Hastings and Popper 2005). Yelverton et al. (1975—cited in Hastings and Popper 2005) found that physostomous fish were just as vulnerable to injury and death due to underwater sound impulses created by blasts as physoclistous fish. However, Hastings and Popper (2005) note that fish with ducted swim bladders may be able to respond to other types of sound with longer rise and/or fall times that would allow them more time to respond to the change in pressure by releasing air from the swim bladder.

3.3 Fish Hearing

Fish live in highly complex acoustic environments that appear to require the animals to perform “auditory scene analysis” in essentially the same manner as other vertebrates. Moreover, because of how sound propagates in water, fish are able to extract the direction of a sound source by directly sensing the motion of the sound particles traveling through the water. Fish are also able to use sound to communicate, locate prey, avoid predators, and gain an understanding of their physical environment.

Two independent but related sensory systems in fish are used for “hearing,” the inner ear and the lateral line system. The primary auditory structures in a fish’s inner ear are sensory hair cells and otoliths. Otolithic organs are dense calcified structures that overlie a tissue layer containing numerous sensory hair cells. Because the body of a fish contains mostly water, and otoliths are stiffer and denser than the rest of the body, sound will penetrate the otoliths more slowly than the rest of the fish. The difference between the motion of sound through the fish and the otoliths stimulates the sensory hair cells, resulting in detection of sound in the brain. Otolithic organs contain thousands of these sensory hair cells and can be damaged by exposures to loud sounds. However, these hair cells continue to be produced throughout much of the fish’s life (Hastings and Popper 2005). There is also evidence that fish can replace or repair sensory hair cells that have been damaged in both the inner ear and lateral line (Meyers and Corwin 2008). Lombarte et al. (1993—cited in Meyers and Corwin 2008) showed that, when damaged by exposure to certain drugs, fish were able to produce new hair cells to replace the ones lost. More recently, Smith et al. (2006) demonstrated that goldfish with hair cells damaged by sound exposure were able to produce replacement hair cells to a level similar to the recovery seen in earlier studies regarding hair cell damage by drug treatment.

Organs in the lateral line (neuromasts) can detect the relative motion of water past these organs when hair cells are stimulated by this movement. These cells detect water motion relative to the fish within a few body lengths of the animal (Coombs and Montgomery 1999, Popper et al. 2003—all cited in Hastings and Popper 2005). Sound passing through water creates particle motion, which is detected by the neuromasts and transmitted via neurons to the brain.

Data on hearing capabilities exist for perhaps only 100 of the 29,000 or more extant species of fish (Popper et al. 2003—cited in Hastings and Popper 2005). Consequently, any extrapolation of hearing capabilities between different species, and especially those that are taxonomically distant must be done with the greatest caution.

3.4 Potential Effects of Pile Driving Noise on Hearing in Fish

Exposure to low levels of sound for a relatively long period of time, or exposure to higher levels of sound for shorter periods of time, may result in auditory tissue damage (damage to the sensory hair cells of the ear) or temporary hearing loss—referred to as a "temporary threshold shift" (TTS). The level and duration of exposure that cause auditory tissue damage and TTS vary widely and can be affected by factors such as repetition rate of the sound, pressure level, frequency, duration, size and life history stage of the organism, and many other factors. Both peak sound pressure level and SEL can affect hearing through auditory tissue damage or TTS. TTS will occur at lower levels than auditory tissue damage. Vulnerability to non-auditory tissue damage increases as the mass of the fish decreases. Therefore, non-auditory tissue damage criteria differ depending on the mass of the fish. Carlson et al (2007) proposed separate peak and SEL interim criteria for auditory tissue damage and TTS for both hearing generalists and hearing specialists (see Chapter 4 for a complete description of proposed interim thresholds for pile driving).

By definition, hearing recovers after TTS. The extent (how many dB of hearing loss) of TTS depends on the variables listed above, among others. Recovery from TTS may occur minutes to days following exposure. Popper et al. (2005) found that both hearing specialists and generalists were able to recover from varying levels of substantial TTS in less than 18 hours post exposure.

An additional possible effect on hearing from loud underwater sound is referred to in the literature as a "permanent threshold shift" (PTS). PTS is a permanent loss of hearing and is generally accompanied by death of the sensory hair cells of the ear. There is only a small body of peer-reviewed literature showing that exposure to extremely high sound pressure levels can destroy the sensory cells in fish ears (Enger 1981, Hastings et al. 1996, McCauley et al. 2003—all cited in Hastings and Popper 2005).

Indirect effects of hearing loss in fish may relate to the fish's reduced fitness, which may increase the animal's vulnerability to predators and result in the fish's inability or reduced success in locating prey, inability to communicate, or inability to sense their physical environment.

3.5 Potential Effects of Pile Driving Noise on Fish Anatomy and Physiology

Compared to data for the effects of exposure to sound on fish hearing capabilities and the ear, there are even fewer peer-reviewed data regarding effects on other aspects of fish anatomy and physiology. It is widely known that exposure to sounds at high levels can alter the physiology and structure of terrestrial vertebrates (e.g., Fletcher and Busnel 1978, Saunders et al. 1991—all cited in Hastings and Popper 2005). Effects may include cellular changes, organ system changes, or stress level effects caused by exposure to sound. However, these effects have not been observed at the lower sound frequencies generated by impact pile driving.

As described above, gas oscillations induced by high sound pressure levels can even cause the swim bladder in fishes to tear or rupture, as has been indicated in response to explosive stimuli in several gray literature reports (e.g., Alpin 1947, Coker and Hollis 1950, Gaspin 1975, Yelverton et al. 1975—all cited in Hastings and Popper 2005). Similar results have been seen from pile driving (Caltrans 2001 and 2004—cited in Hastings and Popper 2005). Carlson et al (2007) found that the literature does not show a correlation between non-auditory tissue damage and peak sound pressure level, but is related to the mechanical work (or force) exerted on tissue, which can be estimated by $SEL_{cumulative}$. The effect of the accumulated sound energy to a fish is dependent on the mass of the fish (See Chapter 4 for a complete description of proposed interim thresholds for pile driving).

Other non-auditory damage to fish caused by sound have been explored in studies by Hastings 1990 and 1995, Turnpenny et al. 1994, Caltrans 2001 and 2004—all cited in Hastings and Popper 2005. These include capillary rupture in skin, neurotrama, eye hemorrhage, swim bladder rupture, and in some cases death.

Sound at sufficiently high pressure levels can generate bubbles from micronuclei in the blood and other tissues such as fat (ter Haar et al. 1982—cited in Hastings and Popper 2005). Because blood vessels in fish are particularly small in diameter, if bubbles are forced to come out of solution at low frequencies, they could cause an embolus or clot and burst small capillaries. This also can occur in the eyes of fish, where tissue might have high levels of gas saturation (Gisiner 1998, Turnpenny et al. 1994—all cited in Hastings and Popper 2005).

Because traumatic brain injury can be caused by high-level transient sound, it is suspected that fish with swim bladder projections or other air bubbles near the ear could be susceptible to neurotrauma when exposed to high sound pressure levels. In humans, effects can include instantaneous loss of consciousness or sustained feelings of anxiety and confusion, or amnesia, and may result in death (Elsayed 1997, Knudsen and Oen 2003—all cited in Hastings and Popper 2005). In several studies, Hastings (1990 and 1995—cited in Hastings and Popper 2005) reported “acoustic stunning” in four blue gouramis (*Trichogaster trichopterus*). The loss of consciousness exhibited by these fish could have been caused by neurotrauma, especially since a bubble of air in the mouth cavity located near the brain enhances the hearing capability of this species (Yan 1998, Ladich and Popper 2004—all cited in Hastings and Popper 2005).

It is important to note that no studies have examined the longer term effects of exposure to pile driving sounds that may lead to delayed death or, perhaps, to other alteration in behavior that could affect the survival of individuals or of populations of fishes. Non-mortality effects may include temporary injury that heals, injury that leads to a slow death (e.g., breakdown of tissues in some organ system), temporary or permanent hearing loss, movement of fish away from feeding grounds, and—as discussed above—

effects such as reduced fitness, vulnerability to predators, inability or reduced success in locating prey, inability to communicate, inability to sense the physical environment, and many other possible scenarios. Thus, future investigations must not only examine immediate mortality to fish from pile driving noise exposure but they must also consider longer term effects on physiology and behavior—as well as effects on fishes that are at some distance from the source.

It is also important to consider the effects of cumulative exposures on mortality, physiology, and behavior, including the effects of exposure to multiple impacts from pile driving and their intermittency (e.g., one strike every few seconds to several per second). One issue in this regard is whether there are any physiological differences when an animal is exposed to a very frequent sequence of high-level sound exposures vs. there being some "recovery" time between exposures. Another aspect of cumulative exposure that needs consideration is the potential effect on a fish that is in an area and exposed to pile driving and then exposed again to pile driving noise several hours, days, or weeks later.

3.6 Life History Considerations

Key variables that appear to control the physical interaction of sound with fishes include the size of the fish relative to the wavelength of sound, mass of the fish, anatomical variation, and location of the fish in the water column relative to the sound source (Yelverton et al. 1975—cited in Hastings and Popper 2005; Carlson et al. 2007).

Whereas it is possible that some (although not all) species of fish would swim away from a sound source, thereby decreasing exposure to sound, larvae and eggs are often found at the mercy of currents or move very slowly. Eggs also can be stationary and thus could be exposed to extensive human-generated sound if it is presented in the surrounding water column or substrate. Data are limited concerning the effects of sound on developing eggs and larvae. Although in a study by Banner and Hyatt (1973), increased mortality was found in eggs and embryos of sheepshead minnow (*Cyprinodon variegates*) exposed to broadband noise (100–1,000 Hz) that was about 15 dB above ambient sound level, hatched fry of sheepshead minnow and fry of longnose killifish (*Fundulus similes*) were not affected by the same exposure.

3.7 Behavioral Effects

Little is known about the effects of pile driving on fish behavior. Currently, data are lacking on behavioral responses to pile driving, such as a startle response to noise or movement away from highly utilized habitats impacted by sound (Hastings and Popper 2005). Field studies by Engås et al. (1996—cited in Hastings and Popper 2005) and Engås and Løkkeborg (2002—cited in Hastings and Popper 2005), while not actually observing the behavior of fish, showed that there was a significant decline in the catch rate of haddock and cod that lasted for several days after termination of air gun use, after which time the catch rate returned to normal. The authors concluded that the catch decline resulted from fish moving from the area because of the sound of the air guns, although there were no direct data to support this conclusion. Again, in 2004, this same group (Slotte et al. 2004—cited in Hastings and Popper 2005) showed parallel results for several additional pelagic species that included blue whiting and Norwegian spring spawning herring. Slotte et al. (2004—cited in Hastings and Popper 2005) found that fishes in the area of air guns appeared to go to greater depths compared to their vertical position prior to the air gun usage. A non-peer reviewed report by Gausland (2003—cited in Hastings and Popper 2005), however, suggests that the declines in the catch rate observed in these studies may have resulted from other factors and are not statistically different than the normal variation in catch rates over several seasons. Another study completed on a coral reef found no permanent changes in behavior, and no animals appeared to leave a reef when subjected to air guns (Wardle et al. 2001—cited in Hastings and Popper 2005). The studies raise questions on how territorial fish may react to high sound levels.

As discussed above, pile driving sound has the potential to produce longer term impacts on behavior, such as the inability of fish to reach quality habitat upstream of a continuous noise source or difficulty in locating mates or food due to continuous sounds from pile driving. These longer term potential impacts to behavior have not been studied.

3.8 Environmental Factors to Consider in Analysis

Effects of sound on fish hearing and physiology likely will depend in part on the local environment, such as channel morphology, depth of water, or tidal conditions. Hastings and Popper (2005) state that one of the unknowns that needs to be investigated is determining the characteristics of the underwater sound field. Underwater sound propagation models need to be developed for locations of interest and be integrated with pile structural acoustics models to estimate received levels of sound pressure and particle velocity in the vicinity of pile driving operations. This will help to define zones of impact on fishes. These results need to be verified with field measurements of underwater sound pressure measurements.

Chapter 4 addresses framework and process for the analysis of pile driving noise impacts based on current research and information.

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Chapter 4 Framework and Process for Environmental Analysis of Pile Driving Impacts on Fishery Resources for Project Planning, Development, and Implementation

4.1 Introduction

Projects that involve driving piles in water typically require a number of federal, state, and local permits. Acquisition of these permits requires evaluation of the project to ensure its compliance with the laws and regulations pertaining to the type of environment and the geographical area of the project. This chapter focuses on one element of the permitting process: the environmental analysis that can be required by the permitting agencies to evaluate the effect on fish of underwater noise generated by pile driving. This chapter describes the permitting and regulatory requirements for pile driving activities and the approaches and information necessary to evaluate potential project-related adverse effects. Best management practices (BMPs), avoidance and minimization measures, and performance standards are addressed. In addition to discussing the process for preparing an impact analysis, the chapter presents empirical data from projects involving pile driving and lessons learned from impact analyses conducted for prior projects.

4.2 Permits and Regulatory Requirements for In-Water Pile Driving Activities

Table 4-1 identifies the permits and approvals that typically require an evaluation of underwater noise generated by pile driving and the types of information that are included in the analysis and documentation. For a complete discussion of permits and approvals required for Department projects and associated regulatory procedures, please refer to the Department Standard Environmental Reference (SER) at: http://www.dot.ca.gov/ser.index.htm.

4.3 Information Needed to Evaluate Impacts

The following discussion addresses the information needs for and approaches to evaluating impacts on fish caused by underwater sound generated from pile driving. The permit application and documentation process used by the Department is outlined in the SER. Table 4-2 outlines the information needs and the level of detail required to evaluate the effects on fish from in-water pile driving activities.

Table 4-1. Federal and State Authorizations Permits and Authorizations Typically Required for Projects Resulting in Underwater Noise from Pile Driving

Permit or Authorization	Relation to Noise Impacts on Fish
Federal Permits and Authorizations	
National Environmental Policy Act (NEPA) (federal lead agency)	For actions that may adversely affect environmental resources. NEPA mandates that federal[a] agencies evaluate projects for adverse effects on environmental resources. This includes a summary evaluation of the significance of impacts of pile driving noise on fish and fish habitat, and on threatened and endangered species.
Clean Water Act Section 404 (U.S. Army Corps of Engineers [Corps])	For actions that dredge or fill waters of the United States. Temporary and permanent piles placed in waters of the United States are considered fill, and projects that include pile driving in waters of the United States require a Section 404 permit. The Corps must consult with the U.S. Fish and Wildlife Service (USFWS) and the National Marine Fisheries Service (NOAA Fisheries) (collectively, the Services) to ensure that issuance of a Section 404 permit is in compliance with the federal Endangered Species Act (ESA) (see below).
Endangered Species Act (NOAA Fisheries and USFWS)	For actions that may adversely affect federally listed species. The ESA requires that all federal[a] actions avoid and minimize potential take of listed species or the adverse modification of critical habitat. "Take" includes harm and harassment of listed species. Noise from pile driving and other sources needs to be evaluated to determine the potential for effects on species that could result in take. This includes effects that result in injury or death and effects that modify the behavior of the fish (an action that is likely to injure wildlife by annoying it to such an extent as to significantly disrupt normal behavior patterns such as breeding, feeding, or sheltering). If listed species or their habitat may be affected, informal or formal consultation with the Services is required. The analysis for underwater noise impacts would be included in the Biological Assessment prepared for the consultation. The Services then determine whether the action would jeopardize the continued existence of listed species or destroy or adversely modify designated critical habitat (DCH). The Services can require terms and conditions to further minimize or avoid take.
Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) essential fish habitat (EFH) (NOAA Fisheries)	For actions that may adversely affect EFH. The federal lead agency must consult with NOAA Fisheries on all federal[a] projects that may adversely affect EFH (defined as those waters and substrate necessary to fish for spawning, breeding, feeding, or growth). The MSFCMA addresses effects on habitat (not on individuals of the species). Underwater noise generated by pile driving can be considered a temporary impact on EFH.
Coastal Zone Management Act (CZMA) (delegated to state and local agencies)	(See "State Permits and Authorizations" below)

Table 4-1. (Continued)

Permit or Authorization	Relation to Noise Impacts on Fish
Federal Permits and Authorizations (Continued)	
Fish and Wildlife Coordination Act (FWCA)	For actions that involve modifications of waters. The federal lead agency of all federal[a] projects that include impoundment, diversion, deepening, or other modification of waters must coordinate with the federal and state fish and wildlife agencies (USFWS, NOAA Fisheries, and California Department of Fish and Game [DFG]). The fish and wildlife agencies review the proposed federal project (through the NEPA or Section 404 permit processes) and can recommend measures to prevent loss of or damage to fish and wildlife resources. This can include recommendations for non-listed species.
State Permits and Authorizations	
California Environmental Quality Act (CEQA) (state lead agency)	For state[b] projects that may adversely affect environmental resources. CEQA ensures that projects do not result in significant avoidable impacts by requiring analysis of alternatives and mitigation. In addition to other resources, the Act requires an evaluation of all potential effects on aquatic resources, including all federally and state-listed fish species. The underwater noise analysis generally is based on the discussion of such effects evaluated as part of the ESA or California Endangered Species Act (CESA) documentation (depending on the federal[a] or state[b] funding or authorities).
Lake or Streambed Alteration Agreement (DFG Section 1602 Authorization)	For any project that would divert, obstruct, or change the natural flow or bed, channel, or bank of any river, stream, or lake. In-water pile driving is included in the above categories. Potential noise impacts from pile driving would need to be addressed but generally would involve a summary and reference to the ESA or CESA documentation. If the project would result in substantial adverse effects on existing fish or wildlife, DFG is required to propose reasonable project changes to protect the resource.
California Endangered Species Act (DFG Section 2081 Permit)	Roughly parallels the federal ESA in providing protection to state-listed species. CESA does not officially identify "harm and harass" (non-lethal effects) as the ESA does; however, adverse modification of habitat is considered take if the modifications would be a proximate cause of death. Concerning underwater noise, CESA requires an evaluation of physical injury to state-listed species but not behavioral effects that do not result in death. CESA also requires mitigation for the take (death or proximate cause of death) of state listed species, in contrast to the ESA.
Coastal Development Permit California Coastal Commission (CCC) Consistency Determination (CCC and San Francisco Bay Conservation and Development Commission [BCDC])	For any project located in a coastal zone with the potential to affect coastal resources. The CCC or BCDC reviews proposed projects with the potential to affect coastal resources to ensure their consistency with the Coastal Zone Management Plan (CZMP) and California's federally approved Coastal Management Program (i.e., the Coastal Act). The Consistency Determination would include compliance with the ESA and CESA.

[a] "Federal" in this table means any project that is funded, permitted, or otherwise approved or carried out by a federal agency.

[b] "State" in this table applies to projects or programs proposed to be funded, carried out, or approved by California state and local public agencies.

Table 4-2. Information Needed for Evaluation of In-Water Pile Driving Effects on Listed and Other Fish Species

Information Needed	Level of Detail
Project Description	
Describe the project	Briefly describe the location of, purpose and need, and basic design concepts of the project. Identify the alternatives that were considered and rejected.
Environmental Setting	
Describe the drainage in the vicinity of the project	Indicate the drainage width; depth; approximate flow; whether tidally influenced; whether freshwater, salt water, or estuarine conditions; and the types of habitat present and cover within the project action area, particularly if there are areas where fish could congregate.
Description of Piles and Pile Driving Activities	
Type(s) and number of piles	Specify the number, composition, size, and location of the piles (e.g., in water, within 25 meters of water, away from water). Catalog and identify the locations of both temporary and permanent piles.
Location of piles in the channel	Provide scaled drawings that include the water depth in profile view and the channel width in plan view. Illustrate the approximate locations of temporary and permanent piles. Indicate the location and distance of piles not driven in water to ordinary high water.
Type(s) of pile driver(s) to be used	Identify whether impact hammer, vibratory, or other type of hammer would be used to drive piles. Identify whether pre-drilling would be used. Specify the approximate size of hammer, if the information is available.
Overall project phasing and pile driving schedule	Indicate the total project schedule, as well as construction phases and the pile driving schedule (discuss for all phases: what piles would be driven, when piles would be driven, the size of piles to be driven during each phase, and any actions such as the need for splicing or welding pile sections). For bioacoustic analyses, the pile driving schedule should be specific to the duration of all in-water and near-shore (within 25 meters of shore) pile driving activity.
Number of strikes per pile by type	Estimate the number of strikes per pile by pile type/size (engineer's estimate)
Number of piles driven each day and total pile driving days	Provide a conservative estimate of the number of piles that are anticipated to be driven in a day (i.e., estimate the number on the high side) and how many hours of pile driving are expected in a day. Include a discussion of the duration of activities between each pile drive (e.g., does the driver need to be repositioned between each drive; do pile sections need to be welded before continuing the driving?) The time between driving events can affect sound exposure level calculations.

Table 4-2. (Continued)

Information Needed	Level of Detail
Description of Piles and Pile Driving Activities (Continued)	
Cofferdams installed?	Cofferdams are sometimes constructed to isolate pile footings. If so, provide detailed information (e.g., when, where, and how they would be constructed; what type of hammer would be used for installation, when the cofferdam would be removed, and how that would be accomplished). Identify whether cofferdams would be dewatered.
Sound attenuation used?	Identify the type of attenuation anticipated to be used (e.g., bubble curtain, isolation casing, cushion block, or dewatered cofferdam). Indicate which piles these would be used for (if any). State the anticipated decrease in transmitted sound pressure level from the sound attenuation device. See Chapter 2 and *Appendix I*.
Methodology	
Methodologies for evaluation	Describe the methodologies used to evaluate the potential effects on fish of pile driving noise. Section 4.6.3 describes the calculation of noise transmission loss used to evaluate noise attenuation through water. Note any site conditions that could block or attenuate noise (e.g., river bends and existing in-water structures); the transmission loss calculations in Section 4.6.3 do not account for effects of structures on attenuation.
Results	
Pile driving-generated sound	Estimate the sound generated from each pile type/size with attenuation (if used). Sound monitoring has been conducted for numerous pile driving projects. Data in *Appendix I* can be used to estimate source sound pressure levels for underwater sound generation by pile size and composition. See Section 4.6.2 and Chapter 2.
Project action area	Define the project action area for pile driving-generated noise. See Section 4.6.6.1. The distance at which the generated underwater sound attenuates to the ambient noise level is generally considered the project action area for pile driving noise, even though the distance that the noise is attenuated to the injury threshold (see Section 4.6.4) is a much smaller area.
Acoustic impact area	Estimate the attenuation of sound through water to the ambient sound pressure level and to the injury threshold (see Section 4.6.4). See Section 4.6.6.2.
Special-Status Species	
Special-status species in the project action area	Identify the special-status species that could occur in the project action area. Contact U.S. Fish and Wildlife Service (USFWS), National Marine Fisheries Service (NOAA Fisheries), and California Department of Fish and Game (DFG) to identify federally and state-listed species that could occur in the project action area. Also document whether the project action area occurs in designated critical habitat.

Table 4-2. (Continued)

Information Needed	Level of Detail
Special-Status Species (Continued)	
Fish presence, life history stages, and habitat type	Describe historical and current fish presence, their life history stages, and habitat type in the project action area. If pile driving would occur in water, both federally and state-listed species need to be addressed. Indicate the listed species that could occur in the vicinity of the project and their life history traits (e.g., spawning, rearing, and migration). Include documented migration periods and in-water work windows approved by NOAA Fisheries, USFWS, and DFG.
Consultation History	
Agency consultation	Provide documentation of all interactions with USFWS and (NOAA Fisheries) regarding the project, including the initiation of the consultation process (documentation of meetings, calls, decisions, and prior written documentation). Describe any changes to the proposed project required or requested by these agencies.
Impact Assessment	
Effects on listed and other species and habitats	Estimate the number or habitat area of listed and other species possibly affected by pile driving-generated noise (include sound attenuation if included in the project). See Section 4.6.7.
Mitigation	
Proposed mitigation	Identify other mitigation to avoid and minimize impacts on listed species and their habitats. This may include pile type or placement, types of pile drivers used, and project timing.
Best management practices	Identify any best management practices included in the project. This may include attenuation devices such as air bubble curtains, cofferdams, isolation casings, and cushion blocks.
Performance measures	Identify any performance measures. This may include the maximum allowed underwater sound pressure levels.
Mitigation for take of listed species	Identify potential mitigation for take of state-listed species. Under the California Endangered Species Act, the State requires mitigation for take of listed species. The amount of mitigation required must offset the loss of individuals due to the project, including any fish taken from fatal exposure to noise from pile driving.
Essential Fish Habitat Analysis	
Essential fish habitat (EFH)	Identify EFH within the project action area. The EFH analysis typically is included as an appendix to the Biological Assessment. In California, there are three EFH: Pacific Coast Groundfish, Coastal Pelagic Species, and Pacific Salmon (see *Appendix III*). The Pacific Salmon EFH in California includes only Chinook and coho salmon habitats.

As noted in Table 4-2, most analyses will require a detailed project description that identifies the purpose and need of the project and the alternatives that were considered and rejected.

The project components should be described in sufficient detail to support the discussion of pile driving activities that would be required for the project. Typically, this information is collected by the noise analyst in coordination with the project engineers. This initial description should include all pile driving activities associated with the project and define which piles (e.g., permanent and temporary piles, and cofferdams) would be located in or near surface waters. Description of the construction methods that may be used (e.g., construction site isolation from water [cofferdams or water bladders], dewatering of the isolation structure, construction of footings, methods of demolition of the structure being replaced, temporary bridges or trestles, temporary fill, use of barges or tugs, and use of explosives) is important because they would contribute to the level, attenuation, or duration of underwater sound generation.

The information gathered for the Description of Piles and Pile Driving Activities (in Table 4-2) is required to estimate the underwater sound that is expected to be generated during the project. The pile size and type and pile driver type are factors for estimating the unattenuated peak sound pressure level and single-strike SEL. These metrics are further refined if some method of sound attenuation is used (e.g., a bubble curtain, cofferdam, isolation casing, or cushion blocks). The information about number of piles, number of strikes per pile, and phasing of pile driving activities is used to estimate the underwater sound pressure level that a fish might be exposed to through a pile driving event (e.g., 1 day of pile driving), which has been referred to as accumulated SEL ($SEL_{ACCUMULATED}$).

Information on the consultation history typically refers to any consultation with USFWS, NOAA Fisheries, or California Department of Fish and Game (DFG) regarding project-related potential effects on federally or state-listed species and their habitat. It is particularly important to discuss any modifications to the project design or timing in response to federal, state, or local agency requirements or recommendations.

A description of special-status fish species is required to determine which species and life histories may be exposed to underwater sound during pile driving. *Appendix III* provides information on special-status species that generally may occur throughout the state and within isolated habitats. The project biologist should contact NOAA Fisheries, USFWS, and DFG to determine which species to address for the watershed in which the project occurs. The discussion would address federally and state-listed species and the potential presence of other fish species in the project action area. EFH needs to be identified (see Section 4.5.4.).

To assess the species and number of fish potentially affected, a description of the habitat types in the area and the life history phases potentially present is required. Many of the listed species addressed are anadromous, which means that spawning and some duration of juvenile rearing occurs in freshwater, the juvenile fish migrate to the ocean to rear to adults, and the adults then return to their natal freshwater to spawn. The location of the project in the watershed and the timing of the project are important factors in determining the species and numbers of fish that could be exposed to pile driving noise. NOAA Fisheries, USFWS, and DFG staff should be contacted to determine the approved in-water work windows during which pile driving can occur. The agencies have established these timing windows to minimize the potential for anadromous fish (particularly salmon and steelhead) to be present in the project area during construction activities that could disturb them.

In some locations, sensitive fish species are present year-round. For instance, rearing coho salmon and steelhead can be present throughout the year, particularly in coastal streams. Green sturgeon is considered present year-round in the Bay Delta and Sacramento River (and potentially the lower reaches of the San Joaquin River and tributaries of the two rivers). Species of Eulachon, Sacramento splittail, and delta and longtail smelts are present in San Francisco Bay year-round. Territorial species, such as tidewater gobies, also may be present year-round in specific estuaries. Other listed species occur year-round in restricted habitats throughout the state. (See *Appendix III.*)

The timing and duration of pile driving activities and the life history phase of fish exposed to noise generated by pile driving are important factors in determining effects on the various species of fish that could be present during pile driving activities. The following section describes a suite of measures that can be incorporated into the design phase to avoid or minimize potential effects on species, BMPs that can be implemented in the field, and performance measures that can be used to ensure that potential project effects are minimized.

4.4 Avoidance and Minimization Measures, Best Management Practices, and Performance Standards

4.4.1 Avoidance and Minimization Measures

Avoidance and minimization measures are incorporated into the project during the design phase; they include design and timing elements to avoid or minimize the potential exposure of fish to sound generated by pile driving. The following discussion addresses how project timing, pile placement, equipment used, pile type, and pile size could avoid or minimize impacts on fish and their habitat.

4.4.1.1 Project Timing

Resource agencies typically set in-water work windows to avoid or minimize the effects of construction on fish species. The in-water work windows represent the periods with the least potential for a species, or a particular life history stage of a species, to be present in areas that might be affected by a project. The most common in-water work window relates to the migratory patterns of salmon and steelhead. Although the explicit timing can vary by drainage or location within a drainage, in-water work windows typically occur between cessation of the outmigration of juvenile salmon (mid-June) and initiation of the upstream migration of adults returning to spawn (September or October). Local DFG and NOAA Fisheries biologists should be contacted to determine the applicable in-water work windows. For larger or more complex projects, it may not be possible to complete pile driving within the work windows. Also, some project areas support listed species year-round (e.g., rearing salmonids, green sturgeon in the Sacramento River and Bay Delta, and tidewater gobies in many coastal estuaries). If in-water pile driving is unavoidable outside of the established in-water work window, the project description should clearly state why it is not feasible to limit construction activities to the established window. In these cases, additional BMPs typically would be required to minimize construction-related effects and generation of underwater noise (see Section 4.4.2).

4.4.1.2 Pile Placement

In-water work is defined as the placement of piles within the ordinary high water mark or in saturated soils adjacent to the reach. For some projects, it may be possible to design the project to avoid in-water work (i.e., where in-water reaches can be avoided by placing piles outside of ordinary high water or adjacent saturated soils). This may not be feasible due to engineering considerations. In such cases, limiting the number of piles that need to be placed in water also could be considered. If in-water pile driving is unavoidable, the project description should clearly state why alternative designs that eliminate or minimize the number of piles placed in water are not feasible. The determination to limit the number of piles that need to be placed in water would need to be made by the project engineer, and this approach should not be suggested as an avoidance or minimization measure unless the engineer has verified its feasibility.

4.4.1.3 Pile Driving Equipment

In some instances, it may be possible to use non-impact pile driving equipment that does not produce as loud of a sound signature. This would include the use of vibratory hammers or push or press-in pile installation. The potential for use of these non-impact methods depends on a number of factors, including pile size (length and diameter) and composition, the bearing capacity necessary for the pile, and the substrate conditions. Even if these methods are feasible, piles typically need to be proofed (i.e., tested for bearing capacity and structural integrity) with an impact pile driver. The project engineer would need to determine the feasibility of using non-impact pile driving equipment, and this approach should not be suggested as an avoidance or minimization measure unless the engineer has verified its feasibility.

4.4.1.4 Pile Type

Piles used for construction can be composed of wood, steel, or concrete. Piles also come in various shapes, including tube, H-type, and I-type steel piles and square, octagonal, or circular cross-section concrete. Permanent structural pilings for bridges are typically CISS (cast-in-shell-steel) piles. Pile size, composition, and, shape depend on a number of factors, including necessary bearing capacity, pile length and diameter, the function of the pile, and cost.

Alternative pile types can be used to reduce underwater noise levels from individual pile strikes. For example, driving concrete or wood piles instead of steel piles, or driving H-type piles instead of CISS piles results in less noise from individual pile strikes [see Chapter 2 and *Appendix I*]). The use of an alternative pile type must be reviewed by the project engineer for engineering feasibility before any alternative method is suggested as an avoidance or minimization measure.

4.4.1.5 Pile Size

Use of smaller piles can be considered for construction in or close to sensitive habitats, as long as engineering constraints do not limit their feasibility. For instance, if an over-water structure is constructed near an occupied sensitive habitat (e.g., high-quality occupied salmonid rearing habitat), reduction in the pile size may reduce peak sound pressure levels, which would attenuate to non-injurious levels before entering the habitat of concern. However, care should be taken in determining whether using smaller piles would be more protective than using larger ones. Use of smaller piles often requires that more piles be driven—resulting in a larger number of pile strikes compared to use of larger piles. Therefore, even though peak sound pressure values may be reduced by using smaller piles, accumulated SEL values during a pile driving event could be greater with smaller piles than with larger ones. In addition, the project engineer must verify that use of smaller piles as a noise reduction strategy is feasible before this strategy is proposed to the resource agencies.

4.4.2 Best Management Practices

BMPs are actions incorporated into the project during the construction phase, such as the use of sound attenuation devices, to avoid or minimize exposure of fish to noise generated during pile driving. Various measures have been developed to attenuate underwater noise generated by pile driving, such as air bubble curtains, cofferdams, isolation casings, and use of smaller piles. These measures are discussed in detail in Chapter 2 and are summarized below.

4.4.2.1 Air Bubble Curtains

Air bubble curtains infuse the area surrounding the pile with air bubbles, creating a bubble screen that inhibits the propagation of sound from the pile. Results on the effectiveness of air bubble curtains in reducing sound pressure waves are varied. Reyff (2003 cited in WSDOT 2006) reviewed reports on the effectiveness of air bubble curtains in reducing sound and found a 0- to 10-dB reduction in RMS sound pressure levels. In his own study, Reyff (2003 cited in WSDOT 2006) found that air bubble curtains reduced peak pressures from 6 to more than 20 dB (3–10 dB RMS). Thorson and Reyff (2004 cited in WSDOT 2006) found similar results with reductions in the range of 5 to 20 dB, while Vagle (2003 cited in WSDOT 2006) reported reductions between 18 and 30 dB. The confined bubble curtain strategy was found to reduce peak pressures by 23 to 24 dB (Reyff et al. 2002 cited in WSDOT 2006). *Appendix I* provides additional information on the effectiveness of air bubble curtain systems. The data generally indicate that an air bubble curtain used on a steel or concrete pile with a maximum cross-section dimension of 24 inches or less will provide about 5 dB of noise reduction. For a mid-sized steel pile (with a dimension greater than 24 but less than 48 inches), the data indicate that an air bubble curtain will provide about 10 dB of noise reduction. For larger piles (with a dimension of greater than 48 inches) about 20 dB of noise reduction is indicated. Proper design and implementation of the air bubble curtain are key factors in the effectiveness of this strategy. For example, use of a bubble curtain in a channel with substantial current would be not effective without a sleeve around the pile to confine the bubbles to the area around the pile.

4.4.2.2 Cofferdams

Cofferdams are temporary structures used to isolate an area generally submerged underwater from the water column. Cofferdams are most commonly fabricated from sheet piling or inflatable water bladders. Other types of cofferdams are also used, albeit less frequently, such as earthen cofferdams (e.g., sandbags and earthen dams). Cofferdams can be used to isolate the piling from the surrounding water column. Cofferdams typically are dewatered to isolate the piling from the water, which attenuates sound by providing an air space between the exposed pile and the water column. If the cofferdam is dewatered, DFG-approved dewatering and fish salvage protocols need to be implemented. Cofferdams that are not dewatered also can be used, but they provide only limited attenuation. Additional attenuation can be achieved by using a bubble curtain inside a cofferdam, if the cofferdam cannot be effectively dewatered. The project engineer must verify that use of a cofferdam as a noise reduction strategy is feasible before this strategy is proposed to the resource agencies.

Dewatered coffer dams generally can be expected to provide attenuation that is at least as great as the attenuation provided by air bubble curtains.

4.4.2.3 Isolation Casings

Isolation casings are hollow casings slightly larger in diameter than the piling to be driven. The casing, typically a larger hollow pile, is inserted into the water column and bottom substrate. The casing then is dewatered, and the piling is driven within the dewatered isolation casing. Isolation casings are similar to cofferdams in that they isolate the work area from the water column; however, because isolation casings have a smaller footprint, they cannot be used to isolate large areas. In addition, because the air space is smaller between the pile and the casing, isolation casings do not have as much attenuation value as cofferdams. Dewatered isolation casings generally can be expected to provide attenuation that is at least as great as the attenuation provided by air bubble curtains.

4.4.2.4 Cushion Blocks

Cushion blocks are blocks of material that are used with impact hammer pile drivers. They consist of blocks of material placed atop a piling during pile driving to minimize the noise generated while driving the pile. Materials typically used for cushion blocks include wood, nylon, and micarta blocks. Other materials also may be used.

Studies conducted by the Washington State Department of Transportation indicate the following reductions in sound pressure levels with various cushion block types:

- Wood – 11 to 26 dB
- Micarta – 7 to 8 dB
- Nylon – 4 to 5 dB

Cushion blocks can be used in conjunction with other BMPs, such as air bubble curtains, cofferdams, and isolation casings, to provide attenuation that is additive to the noise reduction provided by these systems. However, the durability and practicality of using blocks in marine environments must be considered.

4.4.3 Performance Standards

Performance standards are avoidance and minimization measures that can be used for project elements that are unknown at the time of document preparation. For some project elements that are unknown at the time of the evaluation, it may be necessary to indicate what will not be done or to what degree something will be accomplished—as opposed to what specific project action will take place or how specifically it will be done. For example, if the type of equipment or construction method to be used has not been established, the engineer/biologist can provide assumptions based on performance standards that will be monitored (or verified) during construction. Performance standards may include remedies to be implemented if the standards are not achieved.

In the subsequent section, methods are presented to determine the potential impacts on fish from noise generated by pile driving. In the pre-project analysis, several assumptions are made regarding the duration of activities, the magnitude of sound propagation, natural sound attenuation, and the effectiveness of sound attenuating devices used for pile installation. Performance standards typically required for pile driving can include monitoring the actual pile driving activity and monitoring received sound pressure levels at various distances from the pile driving activity.

The pile driving logs that are compiled during the actual pile driving activity include useful information that can contribute to performance evaluations. Data such as date; location of pile; depth, type, and diameter of pile; type of pile driver; start and completion time for each pile driven; actual drive time; blow counts; blow rates; energy of each blow; type of blow; and downtime can be compiled for an accurate record of activities and sound generation. In combination with noise monitoring (see *Appendix II*), this information is useful for post-project evaluations.

The scope of the noise monitoring studies depends on the specific activities occurring, site-specific environmental conditions, and the type and sensitivity of the species and habitats in the vicinity of the project. *Appendix II* discusses noise monitoring goals and objectives, and methods currently used to monitor noise associated with pile driving.

4.5 Considerations for Assessing Impacts

Fish can be found in nearly any marine, estuarine, and freshwater environment. Therefore, pile driving activities occurring in or near any aquatic environment should be assessed for potential impacts on protected fish species and their habitats and other fish species. Four factors generally should be considered when assessing impacts on different fish populations: habitat, sound sensitivity, behavior and life history, and protected status.

4.5.1 Habitat

The diversity of aquatic habitats found in California is used by an equally diverse assemblage of fish species. California contains a variety of aquatic habitat types—from large bays and mainstem rivers to estuaries, lakes, and small headwater streams. A description of the various habitats and a list of sensitive species likely to be encountered in these diverse environments are included in *Appendix III*. This document does not provide a comprehensive list of all the fish species that may be encountered in California waters but identifies the most common and those that are currently protected by state or federal regulations. The information provided on these species is intended to aid in determining what fish species may be present in a given aquatic habitat. After determining which species or groups of species are likely to occur in the habitat affected, one must consider how each species receives and can potentially react to sound.

4.5.2 Sound Sensitivity

Fish differ in regard to their sensitivity to sound. As discussed in Chapter 3, fish species can be divided into two groups based on their perception of sound: sound specialists and sound generalists. The physical structures of specialist species allow them to detect a wide range of sound; sound specialists are presumed to use sound as part of their behavior. In broad terms, generalist species—which includes most fish that would be encountered during pile driving projects in California—can detect sound but do not have specialized structures or behavior related to sound. In general, species of herring, croakers, and shad are hearing specialists while most other fish are hearing generalists. Sound specialists are likely to be affected by sound to a greater degree than sound generalists, and smaller fish are generally more susceptible to injury from sound than larger fish. Larger fish are generally more susceptible to temporary threshold shift (TTS) (see Section 4.6.4) than smaller fish. *Appendix III* provides basic information on the category of hearing of some fishes, but the effects of underwater sound on most fish species are not known. The most comprehensive reviews of this information were conducted by Hastings and Popper (2005), Popper et al. (2006), and Carlson et al. (2007); these reviews are summarized in Chapter 3.

4.5.3 Behavior and Life History

The behavior and life history of fish affect how they are exposed to sound generated by pile driving activities. Fish display a wide variety of behaviors that can affect their susceptibility to sound exposure and their response to sound and other disturbances. Although not specifically documented, highly mobile species (e.g., salmon, steelhead, sturgeon, eulachon, smelts, and splittail) have the capability of leaving an area when pile driving is occurring and returning when activities cease. Because migration timing for different salmon runs are known, this information can be taken into account when planning pile driving activities. Other species like the tidewater goby are less mobile and are not capable of leaving an area;

consequently, individuals of these species may be exposed for longer periods or at higher levels. Other fish may behave and use habitats differently; these factors must be considered when determining potential effects on fish present in the area of pile driving activities.

4.5.4 Protected Status

Some species have distinct legal status and require special protection. CESA and the ESA regulate actions in aquatic environments as they relate to specific groups of fish. Both federal and state laws may place species into categories of Threatened or Endangered or may propose species as Candidates for federal or state listing. While there is considerable overlap in the species that are listed under the two Endangered Species Acts, the lists do not coincide exactly. Tables III-2 and III-3 in *Appendix III* provide the latest information on species status with respect to CESA and the ESA. It is important to note that the listing status of these species can change at any time; therefore, updated species lists always should be requested from the regulatory agencies (NOAA Fisheries, USFWS, and DFG) when planning a project involving pile driving in or near fish-bearing waters.

For some listed fish populations, legally protected habitat has been designated for the species. The ESA requires designation of critical habitat for listed populations. Designated critical habitat (DCH) refers to areas that are considered necessary for the survival and recovery of a species federally listed as Threatened or Endangered. Tables III-2 and III-3 in *Appendix III* identify species with DCH in California. The USFWS Threatened and Endangered Species System (TESS) database is an excellent source of all regulatory information for federally listed species, including listing and critical habitat information, recovery plans and other recovery documents, habitat conservation plans, candidate conservation agreements, and safe harbor agreements. The data for California species are located at http://ecos.fws.gov/tess_public/StateListing.do?status=listed&state=CA and are updated regularly.

Other habitats for commercially important fish species are protected under the MSFCA. As noted earlier, the MSFCA governs the conservation and management of EFH, or "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity." EFH has been designated for 83 species of Pacific Coast groundfish, three species of salmon (two of which, Chinook salmon and coho salmon, are found in California), and five species of coastal pelagic fish and squid that are managed by the Pacific Fishery Management Council (PFMC). EFH for rockfish, flatfish, skates, and sharks (groundfish) and for sardines, anchovy, mackerel, and squid (pelagic fish) is located along all areas of the California coast—from nearshore marine and estuarine waters to 200 miles offshore at the U.S. Economic Exclusion Zone boundary. EFH in estuarine and marine habitats for salmon includes all coastal areas from Point Conception northward. For locations of Chinook and coho salmon freshwater EFH in California, and for general descriptions of species and recommended conservation and enhancement measures to consider, see the PFMC/EFH website (http://www.nmfs.noaa.gov/habitat/habitatprotection/profile/pacificcouncil.htm) and *Appendix III*.

4.6 Impact Analysis

Once the project has been described and the considerations identified above have been determined, the impact analysis can proceed. This section describes the types of information necessary to assess potential impacts on fish from pile driving noise. The discussion walks the reader through example assessments and the process used to determine anticipated ambient noise-levels, the level of underwater noise generated by pile driving, the potential impact of the noise on fish, and the distance at which pile driving noise will attenuate to ambient noise levels or interim criteria levels for injury. The process of assessing noise impacts on fish from pile driving is complex and requires a high level of expertise and experience. The information in this document is not intended to enable the reader to conduct these analyses; the intent is to educate Department staff on the process so that work conducted by experts in acoustic analysis can be effectively reviewed and evaluated.

The degree of attenuation of noise through a body of water is used to predict the area that would be exposed to direct and indirect effects. This area is referred to as the "project action area" in ESA Section 7 consultations. The methods described below also can be used to evaluate the distance from a pile at which the noise would attenuate to the injury thresholds.

Depending on the species potentially present and the environmental conditions, the information in the following sections can be used to determine the amount of a species habitat affected (in the case of rearing or territorial species—such as rearing salmon or trout, or tidewater gobies, respectively). Concept models and methods for quantifying the number of fish, or percent of a cohort of fish, potentially exposed to noise exceeding the threshold are also discussed.

A spreadsheet model developed by NOAA Fisheries is also presented that can be used to develop a first-order approximation of the habitat area affected or the percent of a cohort of migratory fish (such as salmon) that might be exposed to injurious levels of noise from a pile driving activity. These methods describe the basic process for evaluating underwater water noise impacts and may not be appropriate for all situations.

The discussion of impact assessment factors and methodology addresses the following components:

- Determining the ambient noise levels,
- Determining the expected pile driving sound pressure levels,
- Calculating the underwater sound attenuation,
- Interim injury thresholds,
- Behavioral thresholds,
- Determining the impact zones, and
- Assessing the potential impacts on fish from pile driving noise.

4.6.1 Determining the Ambient Noise Levels

The general level of ambient underwater noise in the project area must be determined and considered when analyzing the effects of pile driving noise on fish. Commercial vessels and recreational boats produce high levels of underwater noise (Scholik and Yan 2001). Commercial shipping in the Northern Hemisphere has been implicated in increasing oceanic noise levels by 10–100 fold (Tyak 2000 cited in Scholik and Yan 2001). Large tankers and naval vessels produce up to 198 dB, depth sounders can produce up to 180 dB (Heathershaw et al. 2001 cited in WSDOT 2006), and commercial sonar operates in a range of 150 to 215 dB (Stocker 2002 cited in WSDOT 2006). Even small boats with large outboard motors can produce sound pressure levels in excess of 175 dB (Heathershaw et al. 2001 cited in WSDOT 2006). Ambient noise also is produced by natural sources, such as snapping shrimp, lightning strikes, snowfall (Crum et al. 1999), and breaking waves (Wilson et al. 1997). In the absence of real ambient noise level data for a particular site, Table 4-3 provides ambient noise level data for various environmental settings that may be used when analyzing impacts on fish from pile driving noise. It is difficult to specify ambient underwater noise levels in stream environments because the effects of depth and velocity compounded by the type of substrate and presence of rock or woody debris can result in generation of underwater noise as the water flows over or through these features.

Table 4-3. Reported Ambient Underwater Noise Levels (dB re: 1 μPa) Recorded at Various Open Water Locations in the Western United States

Environment	Location	Ambient Noise Levels	Source
Large marine bay, heavy industrial use, and boat traffic	San Francisco Bay – Oakland outer harbor	120 – 155 dB_{PEAK}, 133 dB_{RMS}	Strategic Environmental Consulting, Inc. 2004
Large marine bay and heavy commercial boat traffic	Elliot Bay – Puget Sound, Washington	147 – 156 dB_{PEAK}, 132 – 143_{RMS}	Laughlin 2006
Large marine inlet and some recreational boat traffic	Hood Canal, Washington	115 – 135 dB_{RMS}	Carlson et al. 2005
Open ocean	Central California coast	74 – 100 dB_{PEAK}	Heathershaw et al. 2001 cited in WSDOT 2006
Large marine bay, nearshore, heavy commercial, and recreational boat traffic	Monterey Bay, California	113 dB_{PEAK}	O'Neil 1998
Large marine bay, offshore, heavy commercial, and recreational boat traffic	Monterey Bay, California	116 dB_{PEAK}	O'Neil 1998
Marine surf	Fort Ord beach, California	138 dB_{PEAK}	Wilson et al. 1997

4.6.2 Determining the Expected Pile Driving Sound Pressure Levels

The following items should be considered when assembling information and framing an analysis for impacts on fish from pile driving noise:

- Type of pile driver,
- Type and size of piling, and
- Type of attenuation (if used).

The compendium attached as *Appendix I* includes the studies cited in this chapter and additional information, such as sound measurements at a variety of distances and water depths and sound measurements of pile driving with noise attenuation measures. Detailed data of sound pressure levels produced by different pile types at different depths with and without attenuation measures also may be found in Illingworth & Rodkin (2001). Hammer and pile type descriptions are discussed in detail at http://www.dot.ca.gov/hq/esc/construction/Manuals/OSCCompleteManuals/Foundation.pdf.

4.6.2.1 Type of Pile Driver

Generally, three types of pile drivers may be used: vibratory, push, and impact hammer pile drivers. The type and size of pile driving equipment can affect the underwater noise generated during pile driving events. Impact pile driving is the most commonly used pile driving method. Impact pile drivers are piston-type drivers that use various means to lift a piston (ignition, hydraulics, or steam) to a desired height and drop the piston (via gravity) against the head of the pile in order to drive it into the substrate. The size and type of impact driver used depend on the energy needed to drive a certain type of pile in various substrates to the necessary depth. The magnitude and characteristics of underwater noise generated by a pile strike depend on the energy of the strike, and the pile size and composition (see Table 2-1 and *Appendix I*).

In some instances, a vibratory hammer may be used to drive piles. Vibratory hammers use oscillatory hammers that vibrate the pile, causing the sediment surrounding the pile to liquefy and allow pile penetration. Peak sound pressure levels for vibratory hammers can exceed 180 dB; however, the sound from these hammers rises relatively slowly. The vibratory hammer produces sound energy that is spread out over time and is generally 10 to 20 dB lower than impact pile driving.

Although this method results in lower levels of noise generated during the “driving” of a pile, it cannot be used in all situations (e.g., because of certain sediment conditions or load-bearing requirements). Further, load-bearing piles typically need to be driven with impact hammers, at a minimum to determine their load- bearing strength (proofing).

The push pile hammer is a newer technology that potentially can be used under some circumstances. With this system, hydraulic rams are used to push piles into the ground using static force. As with piles driven with vibratory hammers, this technology cannot be used in many situations and proofing of piles with an impact hammer may be required.

4.6.2.2 Type and Size of Piles

Piles are generally fabricated out of wood, concrete, or steel. The material a pile is fabricated out of is an important consideration due to the differences in sound pressure levels generated by driving piles constructed of different materials. Different types and diameters of piles produce different levels of underwater noise when they are driven. The peak sound pressure levels from driving piles of different sizes and compositions have been measured; they generally range from 177 dB (for a 12- to 14-inch wood pile) to 220 dB (for a 96-inch steel pile), as measured 10 meters from the pile. Table 2-1and *Appendix I* identify the anticipated sound pressure levels produced by different pile types and sizes, with and without noise attenuation measures.

4.6.2.3 Type of Attenuation

Several types of noise attenuation methods can be used to increase noise attenuation and thus decrease the distance that pile driving noise would be detectable. Several methods, including air bubble curtains, cofferdams, isolation casings, and cushion blocks, are described in Section 4.4.2 (Best Management Practices).

4.6.3 Calculating the Underwater Sound Attenuation

An analysis of hydroacoustic effects on fish is complicated by a number of factors that include the type of water body (open water versus a river or stream, deep versus shallow water), uncertainties associated with predicting ambient and pile driving sound pressure levels, and uncertainties associated with determining the mobility of the fish being evaluated. Considerations for piles driven in open water and rivers and streams, and piles driven near surface waters are addressed. Models often are used to predict sound levels at various distances from the pile and the distance at which pile driving sound attenuates to a specific criterion level.

The practical spreading loss model is typically used to estimate the attenuation of underwater sound over distance. NOAA Fisheries and USFWS have accepted the use of the practical spreading loss model to estimate transmission loss of sound through water. The point where project noise attenuates to the baseline/ambient noise level underwater[1] provides the maximum distance from the source where sound will be detectable. This distance is considered when determining the extent of the project action area for projects producing underwater noise. The practical spreading loss model is provided below (Equation 4-1).

Equation 4-1

$$\text{Transmission loss (dB)} = F * \log(D_1/D_2)$$

Where:

D_1 = The distance at which the targeted transmission loss occurs;

D_2 = The distance from which transmission loss is calculated (usually 10 meters);

F = A site-specific attenuation factor based on several conditions, including water depth, pile type, pile length, substrate type, and other factors; and

Transmission loss (TL) = The initial sound pressure level (dB) produced by a sound source (i.e., pile driving) *minus* the ambient sound pressure level or a target sound pressure level (e.g., the injury threshold for salmon). TL also can be thought of as the change in sound pressure level between D_1 and D_2.

Measurements conducted by the Department and its consultants indicate that the attenuation constant (F in Equation 4-1) can be in the range of 5 to 30. The discussion below provides a summary of F values measured under various conditions. It is common to express the rate of attenuation as the dB of attenuation per doubling of distance. This can be determined by inserting D_1/D_2 as 0.5 in the equation below. For example, when F = 5, the attenuation is 1.5 dB per doubling of distance. When F = 30, the attenuation is 9 dB per doubling of distance.

[1]The practical spreading loss model assumes that sound energy decreases at a rate of 4.5 dB per doubling of distance.

To solve for the distance at which the ambient noise level or threshold sound pressure level will be reached, solve for D_2 as shown in Equation 4-2.

Equation 4-2

$$D_2 = D_1/(10^{TL/F})$$

4.6.3.1 Empirical Sound Attenuation Data

When conducting an underwater noise assessment, the attenuation of sound over distance should be estimated based on measured data from projects with conditions similar to the project being evaluated. The following discussion provides a summary of sound attenuation measured in various conditions.

With the exception of the relatively few larger bridges (e.g., in San Francisco Bay, Humboldt Bay, and San Diego), pile driving is usually conducted in shallow water where depths are 15 meters or less. Much of the pile driving measured in California has been conducted in very shallow water where depths are less than 10 meters. Measured transmission loss rates in shallow water typical at pile driving sites have been found to vary considerably from site to site. The rates also vary somewhat between the different measurement metrics: peak SPL, RMS, and SEL. A logarithmic rate has provided the best fit to the data since sound pressure waves spread out in a spherical pattern. The rate that sound attenuates with distance underwater is complicated by the air/water boundary and the bottom boundary conditions and substrate type. Over long distances (greater than 500 meters), linear correction factors accounting for excess attenuation have improved the prediction. Because hearing is frequency dependent and the transmission loss also is frequency dependent, predicting audibility (or detectability) with any certainty at distances beyond 500 to 1,000 meters is not possible.

Empirical data provide examples of sound attenuation with distance. Projects involving pile driving that were studied indicate that a base 10 logarithmic rate of attenuation is most appropriate. Examples of these projects are described below.

At the San Francisco-Oakland Bay Bridge Project, the transmission loss rates for unattenuated piles varied as a function of pile location and the direction of the measurement from the pile. Attenuation rates were in the range of 4.5 to almost 9 dB per doubling of distance (F values in the range of 15 to 30). When an air bubble curtain was in operation, the attenuation rate was somewhat higher. Measurements between 100 and 1,000 meters indicated F values of 19 and 18, respectively, for peak and RMS sound pressure levels. For distances between 10 and 100 meters from the source, F was found to be 20. When pile driving was conducted within a dewatered cofferdam, F was found to be 15.

Under each of these conditions, sound pressure levels measured at the same distance varied by at least 5 dB, even at positions close to the pile. As the measurement position was moved further away from the pile, the variation in sound pressure levels measured increased to 10 dB. For dewatered cofferdams, sound pressure levels either did not drop off or actually increased within 100 to 150 meters of the pile. Sound pressure levels then decreased, but at different rates for different directions. In some cases, the measured peak SPL at 500 meters in one direction was similar to the measured peak SPL close to the pile (within 100 meters).

At the Benicia-Martinez Bridge, numerous measurements were taken to document the variation in sound pressure level as a function of distance from an unattenuated pile. F values for distances between 100 and 500 meters from unattenuated piles were found to be 15, 16, and 17, respectively, for peak SPL, RMS, and SEL.

Greeneridge Sciences measured transmission loss at Port MacKenzie during the driving of 36-inch-diameter pipe piles. At distances between 60 and 1,000 meters from an unattenuated pile, F values were found to be in the following ranges:

- F_{peak} = 18 to 21
- F_{RMS} = 18 to 23
- F_{SEL} = 16 to 22

The range in F values was dependent on the depth of the water column, with lowest values at the deepest depths.

Measurements taken for pile driving at the Russian River near Geyserville reflect how the transmission loss varies with the depth of the pile. Because this project was in shallow water, the transmission loss through the saturated ground substrate was substantial. During the initial stages of driving the pile, sound pressure levels were greatest near the pile. As the pile was driven deeper, sound pressure levels near the pile (10 to 20 meters) decreased, but levels increased slightly at positions 50 meters farther away. However, sound pressure levels at 70 meters were much lower than 50 meters and did not show much of a change through the entire driving period.

For pile driving sounds that are predominately high frequency (e.g., small-diameter steel pipe or steel H-type piles), the transmission loss can be higher than losses associated with piles that predominantly produce lower frequencies (e.g., larger diameter piles). Small-diameter steel H-type piles have been found to have high F values in the range of 20 to 30 near the pile (i.e., between 10 and 20 meters). Small unattenuated steel pipe piles show F values in the range of 15 to 25. Most measurements for concrete piles have been made only close to the pile at distances of about 10 meters. Some projects included limited measurements at 10 and 20 meter positions, and one project included measurements at 100 meters. The F value for concrete piles, based on these data, is about 15.

The use of attenuation systems such as air bubble curtains complicates the drop off rate. These systems can be very effective at reducing underwater sounds where the primary source of sound is the pile in the water column. As one moves farther away from the pile, ground-borne sound generated from vibration at the tip of the pile may become the primary source of sound. Therefore, the attenuation rate may flatten out, or in some cases become positive (i.e., the sound pressure level may increase with increasing distance) for a short distance.

As these data indicate, the attenuation of sound over distance is highly complex. Determination of appropriate attenuation rates requires careful consideration of site-specific conditions and empirical sound attenuation data from pile driving in conditions similar to the project under consideration.

4.6.4 Interim Injury Thresholds

4.6.4.1 Background

Beginning in 2004, the Department has been at the forefront of efforts to develop interim sound pressure level criteria for injury to fish from pile driving. In coordination with the Federal Highway Administration (FHWA) and the departments of transportation in Oregon and Washington, the Department established a Fisheries Hydroacoustic Working Group (FHWG) to improve and coordinate information on fishery impacts due to underwater sound pressure caused by in-water pile driving. In addition to the above transportation agencies, the FHWG is composed of representatives from NOAA Fisheries (Southwest), NOAA Fisheries (Northwest), USFWS, DFG, and the Corps. The FHWG is supported by a panel of hydroacoustic and fisheries experts who have been recommended by the FHWG members. A Steering Committee oversees the FHWG and is composed of managers with decision-making authority from each of the member organizations.

This effort has resulted in preparation of the following key reports and documents:

- *The Effects of Sound on Fish* (Hastings and Popper 2005).
- *Interim Criteria for Injury to Fish Exposed to Pile Driving Operations: A White Paper* (Popper et al. 2006).
- *Update on Recommendations for Revised Interim Criteria for Pile Driving* (Carlson et al. 2007).
- *Application of Interim Pile Driving Impact Criteria* (Buehler et al. 2007).
- Agreement in Principal for Interim Criteria for Injury to Fish from Pile Driving Activities (FHWG 2008).

These and other related documents are available on the Department website at: http://www.dot.ca.gov/hq/env/bio/fisheries_bioacoustics.htm.

Buehler et al. 2007 provides guidance in the application of the updated revised interim criteria recommended in Carlson et al. 2007. A meeting of the FHWG in June 2008 resulted in the Agreement in Principal for Interim Criteria for Injury to Fish from Pile Driving Activities (FHWG 2008). Because of the ongoing research efforts related to these criteria, they likely will evolve as new information is developed.

4.6.4.2 Update on Recommendations for Revised Interim Criteria for Pile Driving (Carlson et al. 2007)

The updated revised interim criteria recommended in Carlson et al. 2007 are expressed in terms of peak and accumulated SEL, and address the three major effects associated with pile driving:

- Non-auditory tissue damage,
- Auditory tissue damage (hair cell damage), and
- Temporary threshold shift (TTS).

The criteria are further classified by fish type (hearing specialist or hearing generalist) and fish weight (mass in grams [g]). In California, virtually all fish of concern are hearing generalists; therefore, the criteria for hearing generalists typically are used. These criteria are further described below.

Juvenile fish most commonly evaluated in California (e.g., listed species such as salmon, steelhead, and green sturgeon) during in-water work windows have a mass in the range of 2 to 8 g. Migrating smolts typically would have a mass in the range of 8 to 12 g. The weight of sturgeon can vary widely, depending on project location and timing. Accordingly, this discussion assumes that the mass of most juvenile fish is in the range of 2 to 12 g. For most Department pile driving projects, a 2-g fish is the smallest fish likely to be encountered.

The most stringent peak SPL criterion for all hearing generalist fish, for all types of effects, is 206 dB_{PEAK}.

The updated revised interim $SEL_{ACCUMULATED}$ criteria for hearing generalists recommended in Carlson et al. 2007 are as follows:

- Non-auditory tissue damage: 183 to 213 dB-$SEL_{ACCUMULATED}$ sliding scale corresponding to fish mass between 0.5 and 200 g,
- Auditory tissue damage: 189 to 213 dB-$SEL_{ACCUMULATED}$, and
- Temporary threshold shift: 185 dB-$SEL_{ACCUMULATED}$.

(**Note:** The Department does not consider TTS to be "injury" because a fish recovers from this effect. Although this likely will be a point of discussion with the resource agencies, the impact analysis should focus only on the thresholds related to auditory and non-auditory tissue damage, as described below.)

The non-auditory tissue damage threshold for a fish with a mass of 1.7 g recommended in Carlson et al. 2007 is 189 dB-SEL. As noted above, the smallest fish likely to be encountered in California is 2 g; therefore, the 189 dB-SEL threshold for auditory tissue is the lowest threshold that typically would be used based on these recommendations. In summary, for a project in California, the updated revised interim thresholds for injury (injury thresholds) recommended in Carlson et al. 2007 simplify to the following two levels:

- 206 dB_{PEAK}, and
- 189 dB-$SEL_{ACCUMULATED}$.

Subsequent to preparation of Carlson et al. 2007, a meeting of the FHWG was held to discuss injury thresholds. During this meeting, an agreement in principal between the participating agencies was reached regarding thresholds. This agreement is discussed below.

4.6.4.3 Agreement in Principal for Interim Criteria for Injury to Fish from Pile Driving Activities

The FHWG met in June 2008 to further discuss injury thresholds. The result of this meeting was the Agreement in Principal for Interim Criteria for Injury to Fish from Pile Driving Activities (AIP). A copy of the agreement is provided in *Appendix IV*. The agreed upon criteria identify sound pressure levels of 206 dB-peak and 187 dB accumulated SEL for all listed fish except those that are less than 2 g. In that case, the criterion for the accumulated SEL is 183 dB.

These criteria should be used for Department underwater pile driving noise impact studies that involve impact pile driving. They should not be used to assess noise from vibratory pile driving because the thresholds for impact driving are likely to be much lower than the thresholds for non-impulsive, continuous sounds produced by vibratory drivers (Stadler pers. comm.).

4.6.4.4 Criteria for Injury to Fish from Vibratory Pile Driving

As of this writing, there has been no formal agreement on criteria that should be applied to vibratory pile driving. However, previous research (presented in Popper et al. 2006) based on research using a continuous wave sound on gouramis and goldfish showed adverse effects (i.e., stunning, unconsciousness, and mortality) when the accumulated SEL approached 220 and 250 dB, respectively. From this research, a recommendation was made in January 2007 by Dr. Popper to apply an interim threshold of 220 dB for the accumulated SEL from impact pile driving. Ultimately, this recommendation was not accepted by the FHWG for use in evaluating impact pile driving because it was based on continuous sound. However, because vibratory pile driving produces continuous sound, the 220-dB threshold for accumulated SEL is a reasonable starting point for identifying a threshold for vibratory driving. The ultimate threshold will likely be somewhere between 187 and 220 dB.

4.6.5 Behavioral Thresholds

The ESA defines "harm" to include actions that would kill or injure fish or wildlife by significantly impairing essential behavioral patterns, including breeding, spawning, rearing, migrating, feeding, and sheltering. "Harass" is defined as any act that creates the likelihood of injury to a species to such an extent as to significantly disrupt normal behavior patterns such as feeding, breeding, or sheltering.

Little is known regarding the thresholds of behavioral effects of pile driving noise on fish. When is a behavioral modification considered harm or harassment? It is clear that fish can react to sudden loud noise with a startle or avoidance response, but they also may quickly habituate to the noise. Hastings and Popper (2005) and Popper et al. (2006) indicate that no scientifically supported threshold for the onset of behavioral effects from underwater noise generated from pile driving can currently be established. The AIP specifically states that behavioral impacts to fish are not addressed in the agreement. Accordingly, at the time of this writing, there is no agreement on impact thresholds for behavior.

As a conservative measure, NOAA Fisheries and USFWS generally have used 150 dB_{RMS} as the threshold for behavioral effects to ESA-listed fish species (salmon and bull trout) for most biological opinions evaluating pile driving, citing that sound pressure levels in excess of 150 dB_{RMS} can cause temporary behavioral changes (startle and stress) that could decrease a fish's ability to avoid predators. As of this writing, neither NOAA Fisheries nor USFWS has provided any research data or related citations to support this threshold. Nonetheless, until further research is conducted, it should be anticipated that NOAA Fisheries and USFWS will expect to see a discussion of the effects of pile driving on fish behavior (with reference to the 150 dB_{RMS} threshold) in biological assessments. NOAA Fisheries staff informally indicated at the June FHWG meeting that they do not expect exceedance of the 150 dB_{RMS} behavior threshold to trigger any mitigation.

4.6.6 Determining the Impact Zones

The project action area is defined as all areas that are predicted to be affected directly and indirectly by the federal action, not merely the immediate area involved in the action. NOAA Fisheries and USFWS require identification of a project action area for Section 7 consultation under the federal ESA. With regard to underwater noise from pile driving, the Services consider the project action area to be the underwater area where peak pile driving noise is predicted to exceed the ambient noise level. The project action area is therefore defined by the distance needed for the peak sound pressure level generated by pile driving activities to attenuate to a level that is equal to the ambient noise level. The determination of this distance is at best a rough approximation due to the uncertainties associated with determining the ambient noise level and the attenuation of sound over distance.

A similar process is used to estimate the acoustic impact area, which is based on the distance at which pile driving sound attenuates to a level that equals an injury threshold. In general, if the injury thresholds are not predicted to be exceeded beyond 10 meters from the pile, no further analysis is necessary and no injury to fish is indicated. If the thresholds are predicted to be exceeded beyond 10 meters from the pile, the acoustic impact area needs to be determined.

The following discussion describes the process used to determine the project action area and the acoustic impact area.

4.6.6.1 Underwater Noise Prediction Methods and Tools

As discussed above, NOAA Fisheries has developed a spreadsheet that estimates the distance at which pile driving sound attenuates to threshold levels. This spreadsheet and reference data from *Appendix I* are the primary tools for estimating underwater sound levels from pile driving.

Project Action Area

The process of determining the project action area for in-water pile driving typically focuses on peak sound pressure levels anticipated to be produced by the pile driving activity. The first step in the process is to estimate the typical peak ambient noise level using measured data from a similar environment (refer to Table 4-3 for typical ambient sound pressure level data). In some cases, such as in the case of a highly controversial project, it may be appropriate to actually measure the ambient sound level in the water at the project site. The next step is to identify a sound attenuation factor (F) appropriate for the environment that is based on measured data from a similar environment. The predicted peak pile driving sound pressure level, the attenuation factor, and the ambient sound pressure level are then used in Equation 4-2 to determine the distance at which the pile driving sound pressure level attenuates to a level that is equal to the ambient noise level. Examples below demonstrate how this calculation is typically done.

In some cases, only RMS ambient noise level data are available. The relationship between the peak ambient noise-level and the RMS ambient noise level can be highly variable, depending on the nature of the underwater noise sources in the area. Accordingly, there is no fixed relationship between peak and RMS ambient sound pressure levels. For the purposes of determining the project action area, the peak pile driving sound pressure level can be compared to the RMS ambient sound pressure level. Using this approach will overestimate the peak ambient noise level. In many environments, peak ambient noise levels exceed the RMS ambient noise level by 5 to 10 dB. Accordingly, it may be appropriate in many situations to add 5–10 dB to the RMS ambient noise level in order to estimate the peak ambient noise level.

For the reasons discussed above, predicting audibility (or detectability) with any certainty at distances beyond 500 to 1,000 meters is not possible. Consequently, the project action area based on pile driving noise should never be considered to extend more than 1,000 meters from the pile driving activity.

In open water conditions such as San Francisco Bay, the project action area typically will be defined by the distance at which the pile driving noise attenuates to a level that is equal to the ambient noise level in all directions (Figure 4-1). In rivers and streams, the project action area can extend bank to bank across the river and the distance upstream and downstream at which the pile driving noise attenuates to the ambient noise level (Figure 4-2).

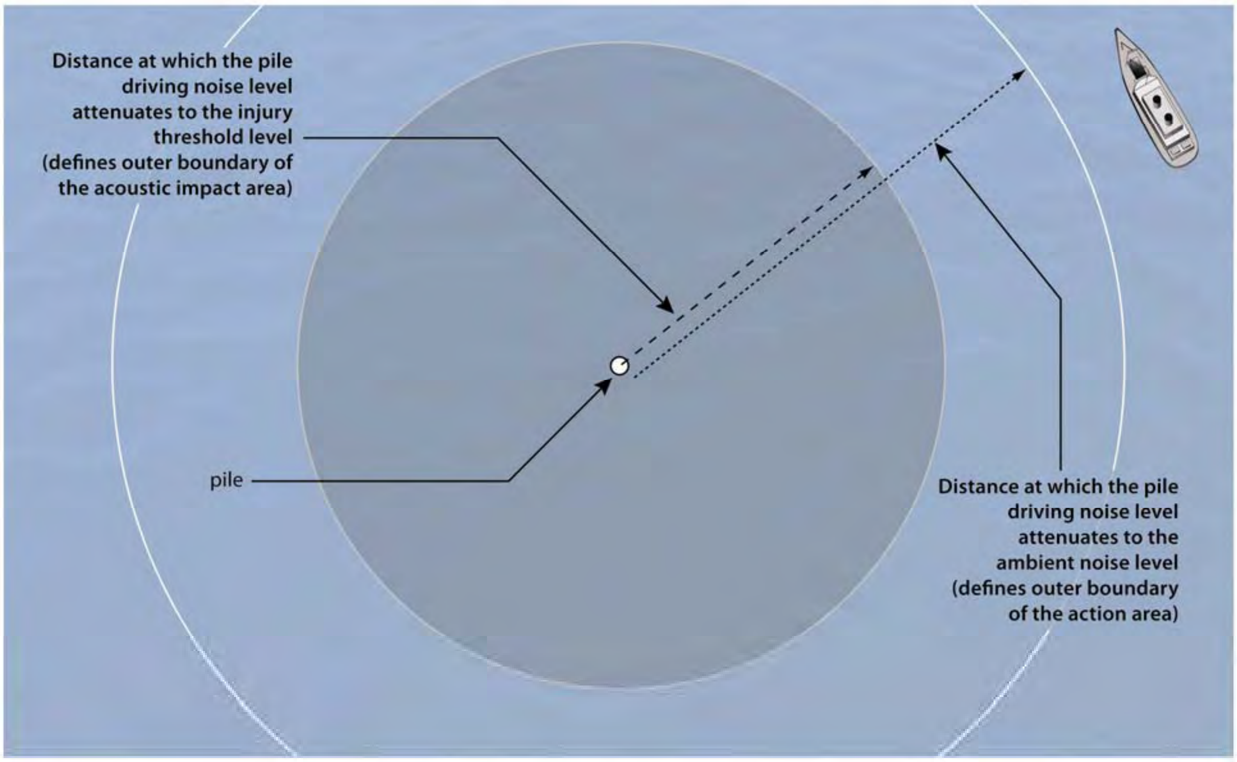

Figure 4-1. Action Area and Acoustic Impact Area in Open Water

4.6.6.2 Acoustic Impact Area for In-Water Pile Driving

Before describing the use of the NOAA Fisheries spreadsheet, the following describes the methods that are used by the model to determine the acoustic impact area of underwater pile driving noise. The process for determining the acoustic impact area for in-water pile driving is similar to the process described above for the project action area in that an area is defined by a distance within which a criterion sound pressure level is exceeded. The process for determining acoustic impact area is substantially more complicated because two thresholds (peak and accumulated SEL) are involved. The distance calculation relative to the peak sound pressure level is straightforward because it simply involves the use of Equation 4-2 and the difference between the peak pile driving sound pressure level and the 206-dB_{PEAK} threshold. The distance calculation for accumulated SEL is also straightforward if it is assumed that the fish are stationary for the entire duration of exposure to the pile driving sound. In this case, the single-strike SEL value is constant over the entire exposure period, and the accumulated SEL can be calculated from the single-strike SEL and the estimated number of pile strikes. The distance within which the

187 dB-SEL criterion (or the 183 dB-SEL criterion in cases where fish less than 2 g are present) is exceeded then can be calculated using Equation 4-2.

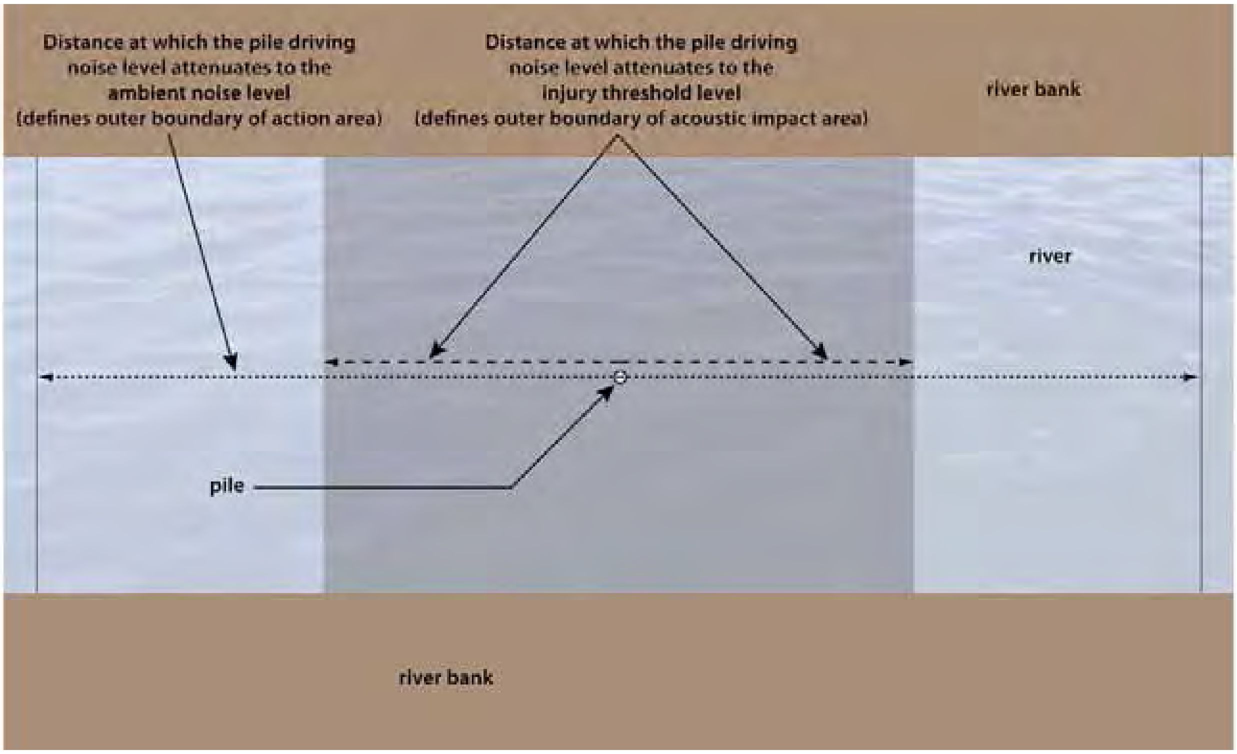

Figure 4-2. Action Area and Acoustic Impact Area in River

The accumulated SEL calculation becomes substantially more complicated in the situation where fish are traveling through the pile driving area. In this case, the single-strike SEL will vary over the duration of exposure. The accumulated SEL value must be calculated from the single-strike SEL values, which increase and then decrease as the fish approaches and then departs from the pile. The NOAA Fisheries spreadsheet described in Section 4.6.6.1 includes a module for calculating accumulated SEL values under these conditions.

In open water conditions such as San Francisco Bay, the acoustic impact area typically will be defined by the distance at which the pile driving noise level attenuates to the injury threshold level (Figure 4-1). In rivers and streams where this distance is greater than half the width of the channel, the acoustic impact area will be equal to twice the calculated distance multiplied by the width of the river (Figure 4-2).

4.6.6.3 Acoustic Impact Area for Near-Water Pile Driving

The process for determining the acoustic impact area for piles driven near but not in water would be essentially the same as that described for in-water pile driving; however, data measured for similarly driven piles (piles driven near the water's edge) should be used for the source sound pressure levels.

4.6.6.4 Example Calculations

The following simple examples show the general process used to determine the project action area and the acoustic impact area.

Example 1

For example 1, the following conditions are assumed:

- Site conditions: Large marine bay, nearshore, with heavy commercial and recreational boat traffic
- Pile type: 96-inch-diameter CISS pile
- Driver: Impact hammer
- Attenuation device: None
- Piles driven per day: One
- Injury criteria: 206 dB_{PEAK} and 187 $dB\text{-}SEL_{ACCUMULATED}$

The first step in the process is to estimate the sound pressure level produced by the pile driving. Data for a similarly sized pile and site conditions should be used for this purpose. *Appendix I* provides a detailed summary of source levels for various types of piles and conditions. The data in Table I.2-3 in *Appendix I* for 96-inch-diameter CISS piles driven in San Francisco Bay indicate that piles of this size driven with an impact hammer in this environment will produce single-strike sound pressure levels of 220 dB_{PEAK} and 194 dB-SEL at 10 meters. Attenuation data collected for this same project indicate an F value of 16 for use in the practical spreading model (Equation 4-1).

To determine the project action area, the ambient sound pressure level must be estimated. Data in Table 4-3 indicate that 155 dB_{PEAK} is a reasonable estimate for the ambient sound pressure level in this environment. This information, in combination with the source sound pressure level and attenuation assumptions, then is used with Equation 4-2 to estimate the project action area. In this case, TL is the difference between the source pressure level at 10 meters and the ambient sound pressure level (220 – 155 = 65 dB).

Equation 4-2 is used as follows:

$$D_2 = D_1/(10^{TL/F})$$

$$D_2 = 10/(10^{-65/16})$$

$$D_2 = 115{,}000 \text{ meters}$$

Because this value is greater than 1,000 meters, the project action area should be assumed to be within 1,000 meters of the pile driving activity.

Equation 4-2 also is used to determine the acoustic impact area based on the peak sound pressure level. In the case of the peak sound pressure level, the change in the sound pressure level needed to attenuate noise to 206 dB is 14 dB. Equation 4-2 then is used to determine the distance needed to attenuate to this level, as follows:

$$D_2 = D_1/(10^{TL/F})$$

$$D_2 = 10/(10^{-14/16})$$

$$D_2 = 75 \text{ meters}$$

To calculate the acoustic impact area based on accumulated SEL, the accumulated SEL first must be calculated. This requires an estimate of the number of pile strikes per day. Ideally, this number should be determined through consultation with the project engineer. In the absence of project-specific data, the number of pile strikes can be estimated using data from Table 2-3. Driving of similar-sized piles required 7,000 strikes per day. To simplify the calculation, it is assumed that fish are resident in the area and would be exposed to a constant single-strike SEL value throughout the entire exposure period.

Equation 2-1 then is used, as follows:

$$SEL_{ACCUMULATED} = SEL_{SINGLE\ STRIKE} + 10 \log (\#\text{ of pile strikes})$$

$$SEL_{ACCUMULATED} = 194_{SINGLE\ STRIKE} + 10 \log (7{,}000)$$

$$SEL_{ACCUMULATED} = 194_{SINGLE\ STRIKE} + 38$$

$$SEL_{ACCUMULATED} = 232 \text{ dB at 10 meters}$$

Equation 4-2 then is used to determine the distance needed for sound to attenuate to 187 dB, as follows:

$$D_2 = D_1/(10^{TL/F})$$

$$D_2 = 10/(10^{-45/16})$$

$$D_2 = 6{,}500 \text{ meters}$$

Because this value is greater than 1,000 meters, the area of criterion exeedance should be assumed to be within 1,000 meters of the pile driving activity.

Example 2

For Example 2, the following conditions are assumed:

- Site conditions: Inland river with recreational boat traffic
- Pile type: 24-inch-diameter octagonal concrete pile
- Driver: Impact hammer
- Attenuation device: None
- Piles driven per day: Five
- Injury criteria: 206 dB_{PEAK} and 187 dB-$SEL_{ACCUMULATED}$

Table I.2-3 in *Appendix I* has data for several conditions involving 24-inch-diameter octagonal concrete piles. None are in a river environment. However, conditions at the Port of Oakland in the Oakland estuary are most similar to conditions in a river environment. The data from the Port of Oakland indicate that piles of this size driven with an impact hammer in this environment will produce single-strike sound pressure levels of 188 dB_{PEAK} and 166 dB-SEL at 10 meters. Attenuation data collected for this same project indicate an F value of 13 for use in the practical spreading model (Equation 4-1).

To determine the project action area, the ambient sound pressure level must be estimated. Data in Table 4-3 indicate that 135 dB_{PEAK} is a reasonable estimate for the ambient sound pressure level in this environment (a marine inlet with recreational boat traffic). This information, in combination with the source sound pressure level and attenuation assumptions, then are used with Equation 4-2 to estimate the project action area. In this case, TL is the difference between the source level at 10 meters and the ambient sound pressure level (188 – 135 = 53 dB).

Equation 4-2 is used as follows:

$$D_2 = D_1/(10^{TL/F})$$

$$D_2 = 10/(10^{-53/13})$$

$$D_2 = 119{,}000 \text{ meters}$$

Because this value is greater than 1,000 meters, the project action area should be assumed to be within 1,000 meters of the pile driving activity.

Because the peak sound pressure level at 10 meters of 188 dB is less than the 206-dB_{PEAK} injury threshold, it is not necessary to calculate the distance to 206 dB. It clearly does not extend beyond 10 meters from the pile.

To calculate the distance within which the accumulated SEL criterion would be exceeded, the accumulated SEL must first be calculated. Using data from Table 2-3 for 24-inch-diameter concrete piles, the total number of strikes in a single day is estimated to be 2,900 (five times 580).

Equation 2-1 then is used, as follows:

$$SEL_{ACCUMULATED} = SEL_{SINGLE\ STRIKE} + 10 \log (\text{\# of pile strikes})$$

$$SEL_{ACCUMULATED} = 166_{SINGLE\ STRIKE} + 10 \log (2{,}900)$$

$$SEL_{ACCUMULATED} = 166_{SINGLE\ STRIKE} + 35$$

$$SEL_{ACCUMULATED} = 201 \text{ dB at 10 meters}$$

Equation 4-2 then is used to determine the distance needed for sound to attenuate to 187 dB, as follows:

$$D_2 = D_1/(10^{TL/F})$$

$$D_2 = 10/(10^{-11/13})$$

$$D_2 = 70 \text{ meters}$$

This indicates that the 187 dB-$SEL_{ACCUMULATED}$ threshold would be exceeded within 70 meters of the pile.

Example 3

Example 3 is the same as Example 1, except that an air bubble curtain attenuation device is applied. Based on the information provided in Section 4.4.2.1, it is assumed that the air bubble curtain would reduce the source level by 20 dB. With 20 dB of attenuation, the source levels would be reduced from 220 dB_{PEAK} and 194 dB-SEL to 200 dB_{PEAK} and 174 dB-SEL. The project action area then is calculated as follows:

$$D_2 = {}_{D1}/(10^{TL/F})$$

$$D_2 = 10/(10^{-45/16})$$

$$D_2 = 6{,}493 \text{ meters}$$

Because this value is greater than 1,000 meters, the project action area should be assumed to be within 1,000 meters of the pile driving activity.

Because the peak sound pressure level would be reduced to less than 206 dB_{PEAK}, there is no acoustic impact area based on the peak threshold. As in Example 1, Equation 2-1 is used, as follows:

$$SEL_{ACCUMULATED} = SEL_{SINGLE\ STRIKE} + 10 \log (\#\text{ of pile strikes})$$

$$SEL_{ACCUMULATED} = 174_{SINGLE\ STRIKE} + 10 \log (7{,}000)$$

$$SEL_{ACCUMULATED} = 174_{SINGLE\ STRIKE} + 38$$

$$SEL_{ACCUMULATED} = 212 \text{ dB at 10 m}$$

Equation 4-2 then is used to determine the distance needed for sound to attenuate the accumulated SEL value of 212 dB to 187 dB, as follows:

$$D_2 = D_1/(10^{TL/F})$$

$$D_2 = 10/(10^{-25/16})$$

$$D_2 = 365 \text{ meters}$$

The use of the air bubble curtain would reduce the accumulated SEL impact distance from greater than 1,000 to 365 meters, a substantial reduction.

4.6.6.5 Application of the Practical Spreading Model and NOAA Fisheries Calculation Spreadsheet

NOAA Fisheries staff from the Northwest Region (John Stadler, (360) 753-9576, John.Stadler@noaa.gov) and Southwest Region (David Woodbury, (707) 575-6088, David.P.Woodbury@noaa.gov) offices have developed a spreadsheet that implements the practical spreading loss model. The spreadsheet is available for downloading at the following website: http://www.wsdot.wa.gov/Environment/Biology/BA/default.htm.

The spreadsheet implements Equations 4-1 and 4-2 to develop distances within which specific thresholds are exceeded. The spreadsheet addresses a condition where fish are assumed to be stationary relative to the pile driving and a condition where fish are assumed to be traveling past the pile driving at a fixed speed and fixed distance from the pile. For the stationary fish condition, the spreadsheet allows input of single-strike peak, SEL, and RMS values; the number of pile strikes; and the attenuation constant (F). For the condition with moving fish, additional assumptions are required that include the pile strike interval, speed of the fish, and the closest distance that the fish are expected to be to the pile.

As a simple example for stationary fish, assume that pile driving produces a sound of 208 dB-peak at a distance of 10 meters. To estimate the sound level at 100 meters, Equation 4-1 is used. With an attenuation constant of 15, the sound level at 100 meters is predicted as follows:

Transmission loss = 15 log (10/100) = -15 dB

Peak sound level at 100 meters = 85 dB (100 dB – 15 dB)

To determine the distance at which the peak sound level attenuates to a specific criterion level (for example, 206 dB) Equation 4-2 is used. The difference between 206 dB and 208 dB is -2 dB (transmission loss is always a negative as applied here). Therefore, -2 dB is the transmission loss needed to attenuate the sound to 206 dB. The distance to 206 dB is predicted as follows:

$D_2 = 10 / (10^{-2//15}) = 13.6 \sim 14$ meters

These same equations can be used with SEL values and the number of pile strikes to evaluate the accumulated energy associated with pile driving. As an example, assuming that the single-strike SEL is 180 dB at 10 meters and the pile will be driving with 1,000 pile strikes, the accumulated SEL is 210 dB using Equation 2-1. To determine the distance to a specific criterion level (for example, 187 dB accumulated SEL) Equation 4-2 is once again used. The difference between 187 dB and 210 dB is -23 dB. The distance to 187 dB is predicted as follows:

$D_2 = 10 / (10^{23/15}) = 341$ meters

The NOAA Fisheries spreadsheet introduces the concept of “effective quiet.” This concept assumes that energy from pile strikes that is less than 150 dB-SEL does not accumulate to cause injury. For any given condition, at some distance, sound attenuates to the level of effective quiet (i.e., 150 dB-SEL). Under the concept of effective quiet, this spreadsheet assumes that the distance to the accumulated criterion level cannot extend beyond the distance to effective quiet. Using the example above of a single-strike SEL value of 180 dB, the distance to the effective quiet level of 150 dB is 1,000 meters using Equation 4-2 and a transmission loss value of -30 dB. Therefore, the spreadsheet limits the distance to the accumulated SEL criterion to 1,000 meters for these specific conditions. This corresponds to about 5,000 pile strikes; if the number of pile strikes is greater than 5,000, the distance to the 187 dB accumulated SEL does not increase. For conditions where fish are moving through a channel, the “moving fish” section of the spreadsheet can be used. The calculations for moving fish are substantially more complex and cannot be represented here by simple equations. Nevertheless, the following is an example of typical input assumptions and the resulting calculation output.

<u>Input Assumptions</u>

Strike interval: 1.5 seconds

Fish speed (meters/second): 0.1 meter/second

Number of strikes: 2,000

Closest distance fish passes pile (meters): 5 meters

Estimated single-strike peak SPL (dB re 1μPa): 200 dB

Threshold for peak pressure: 206 dB

Estimated single-strike SEL (dB re 1μPa2s): 174 dB

Threshold for accumulated SEL: 187 dB

Estimated single-strike RMS SPL (dB re 1μPa): 185 dB

Behavioral threshold for RMS (dB): 150 dB

Distance (meters) from which pile measurements were taken: 10 meters

Transmission loss constant (F): 15

Calculation Output

Peak SPL at closest distance to pile: 205 dB

Distance (meters) to 206 dB peak isobar: 4 meters

Accumulated SEL for given number of strikes: 200 dB

RMS at closest distance to pile: 190 dB

Distance (meters) to 150 dB RMS isobar: 2,154 meters

By modifying the closest distance that a fish passes, the distance at which the accumulated SEL value drops to 187 dB can be determined. For conditions described above, this distance is 200 meters.

4.6.7 Assessing Potential Impacts on Fish from Pile Driving Noise

The foregoing discussion describes the analytical methods to determine the acoustic footprint of underwater sound produced by pile driving, and the interim thresholds to evaluate the area of water where a fish could be exposed to sound loud enough or long enough to produce injury (based on the interim criteria). The following section describes how one would approach estimating the number of fish potentially exposed to underwater sound that exceeds the interim criteria. Two scenarios are described. The first describes a conceptual approach to estimating the number or percent of a cohort of migratory fish (the focus is generally on juvenile salmon and steelhead migrating to the ocean) that might be exposed to pile driving sound above the interim criteria. The second describes how to estimate the number of non-migrating fish (e.g., summer rearing salmonids) that might be exposed to peak or accumulated sound levels.

4.6.7.1 Impact Assessment When Construction Occurs during Migration Periods

Although in most cases in-water pile driving would be limited to the in-water work windows when migrating fish presence would be minimal, in some cases (e.g., large projects such as the Bay bridges retrofits projects), pile driving may be required during migration periods. In the case of evaluating pile driving projects in waters with migratory fishes and constrained channels, fish movement through the impact areas must be understood to estimate the impact. Many factors influence fish migration, both temporally and spatially. Temporally, salmon and steelhead have two migration periods each year: when young salmon and steelhead smolts migrate downstream to the ocean and when adult salmon and steelhead migrate upstream to their natal spawning grounds. Smolts typically migrate in spring, and most adults migrate upstream in late summer to winter (consult with fisheries agencies to determine the migration timing for the evolutionarily significant units [ESUs] of salmon and steelhead that potentially occur in the watershed where the project is to occur). On a shorter time scale, these migrations also can be affected by river conditions such as water flow and water temperature. For instance, returning adult salmon may return to their natal river and hold in the lower river until they mature to the appropriate spawning condition, or until river flow or temperature conditions are appropriate.

Spatially, migrating fish may occur within a particular portion of a river where conditions are more favorable to their migration. For instance, in the lower reaches of rivers in and near estuaries, fish may "prefer" migration in the deeper, swifter water within the thalweg (the deepest part of the channel) to accelerate their entry to the sea. This was evident in recent acoustic tracking studies of Chinook salmon near the Richmond-San Rafael Bridge (Corps 2007).

To effectively assess migrant transit (or entry) into acoustic impact zones, a probabilistic model would need to be developed. Probabilistic models involve statistical analysis that estimates, on the basis of past (historical) data, the probability of an event occurring again. This type of model would allow a realistic evaluation (with ranges of input parameters and resultant ranges in potential impacts) based on a variety of conditions and development of reasonable worst-case conditions. To date, no probabilistic model has been prepared.

A simplistic model can be used to conceptually discuss the factors required for analysis. However, this conceptual approach is subject to large variances in results, depending on the assumptions made. The concept model described here illustrates the basic concepts in evaluating pile driving noise impacts on annual cohorts (brood years) of migrating fishes (the effects on cohorts of specific species are particularly important when evaluating impacts for projects with multi-year pile driving).

A pile driving event can be conceptually modeled to estimate the proportion of migrating fish that might transit acoustic impact areas, as follows (Equation 4-3).

Equation 4-3

$$PESUI_n = PESU * PAI_n * t_n$$

Where:

$PESUI_n$ = The percent of annual juvenile salmon migrant population affected per pile driving event (*n*);

$PESU$ = The percent of annual migrating juvenile salmon passing a pile being driven *each minute* based on the monthly percentage of emigration *divided by* [number of days in that month *times* 24 hours/day *times* 60 minutes/hour];

PAI_n = The proportional area affected for each event (the area in meters^2 within which single-strike sound pressure levels meet or exceed either of the interim criteria for the pile being evaluated *divided by* the total estuary area in meters^2 (for non-migratory species or lifestages);

Or alternatively,

The diameter or length of the impact zone for each event within which single-strike sound pressure levels meet or exceed either of the interim criteria for the pile being evaluated *divided by* the total estuary or channel width at that location (for migratory species or lifestages); and

t_n = The amount of time (minutes) per pile driving event that single-strike sound pressure levels exceed either of the interim criteria.

The calculation estimates the relative proportion of fish that might pass through the acoustic impact area during a day of pile driving compared to the daily population of juvenile salmon migrating downstream. The daily population (fish that move past a given point in the river in a day), would be estimated by the timing of the downstream migration. For simplicity, a symmetric (normally distributed) bell-shaped distribution can be used to estimate the proportion of each ESU that might pass the project site each month (i.e., to determine the percentage of each emigrant ESU that would move through the project action area each month). If reasonably accurate monthly downstream migration proportions are documented, use of that data would be more appropriate.

In theory, all events then would be summed for each ESU to determine the overall percent of the annual migrating population of juvenile salmon potentially exposed to peak or accumulated SELs that were equal to or exceeded the interim criteria.

The difficulty arises when one tries to apply assumptions concerning the spatial and temporal distribution of the fish in relation to the pile at the time a strike occurs. The concept above assumes a homogeneous temporal and spatial distribution of the fish—that is, it assumes a constant density through the river and through time. Thus, if fish migrate at night when pile driving does not typically occur, or if fish use a preferred area of the river (such as the thalweg) when pile driving in shallow waters, this approach could result in significant error.

Impact analyses for migrating fishes such as salmon are further complicated when evaluating the effects of accumulated exposure. The fish's transit speed through the project area and its location in the channel in relation to the pile being driven will substantially affect accumulated sound exposure. The speed at which a fish transits the acoustic impact zone would affect how many pile strikes the fish would be exposed to while transiting. The location in the channel would determine the distance between the fish and the actively driven pile; thus, its received sound (the attenuation distance) would vary.

The NOAA spreadsheet model can be used to calculate exposure for a specific pile driving event with a set of assumptions regarding the number of fish transiting the site during an exposure period (the period during which piles are driven, not the daily rates), the fish transit speed, and the location of the fish within the channel in relation to the pile being driven. In theory, the results from each event could be summed to estimate the number of fish that might be exposed to sound above the thresholds during a project. Extreme care should be taken when developing and an approach and reporting results. All assumptions need to be well documented.

In addition to the spatial and temporal issues associated with estimating fish exposure, accurately portraying pile driving operations is problematic. The actual drive times typically are less than the total operational time because of other activities that occur between the time a pile is put into position and the time the operation is completed. Other activities could include dead blows (ineffective hammer strikes), equipment breakdown, welding sections of piles, environmental delays (wind and tidal velocity), realigning piles, removing or relocating driving templates, installing pile driving followers, and adjusting hammer leads. Because of these other activities, using the total operation time to drive a pile would overestimate the exposure of fish to pile driving noise.

Until an accepted probabilistic model is developed that includes a realistic estimate for drive time, the assessment of pile driving on migrating fish will be a significant point of discussion with the resource agencies. Agreement on assumptions and methods has taken from 6 to 8 months in the case of some of the large bridge projects. Projects that could occur in waters with migrating fish should allow sufficient time in their permitting schedules for model development and negotiation, and consultation with the agencies should be initiated early in the process (see Section 4.7).

4.6.7.2 Impact Assessment When Construction Occurs during Non-Migration Periods

Depending on the time of year and the location of the project, pile driving can occur in areas supporting summer-rearing salmonids (e.g., coho salmon and steelhead) or other summer-rearing fish, rather than migrating salmon. In this case, an estimate of the density of fish within the area exposed to sound pressure levels above the interim peak criteria or fish that would be exposed to accumulated sound pressure levels above the $SEL_{ACCUMULATED}$ criteria would need to be made. This analysis would need to be conducted for all permanent and temporary piles driven in water and piles driven close to water where sound might propagate into the surface water from the pile driving activity. The information needs and an example analysis for a hypothetical bridge replacement project involving in-water pile driving are presented below. To perform the analysis (exposure to stationary fish), you can use the NOAA Fisheries model or create a relatively simple spreadsheet based on the equations presented in Section 4.6.3.1 and illustrated in Table 4-4.

As a simple example, assume that a new bridge project requires two piers to be constructed immediately adjacent (e.g., within 10 meters of the wetted channel) to a salmon-bearing river that supports summer rearing. Each pier consists of two 2.2-meter- (7-foot-) diameter piles. Because of their length, each pile consists of four welded sections. For each pier, one section of each pile can be driven in 1 day (i.e., two sections driven in 1 day) and then from 3 to 5 days are required to weld on the subsequent section and inspect the piles before pile driving can continue. This process is repeated until all four sections are welded and driven for each pile. The example assumes that each pier will be contained within a cofferdam that will be dewatered or contain an air bubble curtain to provide some attenuation. Assuming four sections per pile, the number of pile driving days for one pier (two piles) would be 4 (8 days total for the two piers).

This example project assumes that the abutments are more than 25 meters from the wetted channel and that the piles are small enough (e.g., 0.3-meter [12-inch] H-type piles) that driving these piles would not propagate pile driving noise to the water.

For simplicity, the example assumes that no temporary piles or trestles will be required for construction. If they were required, assessments would be needed for each.

An example analysis similar to this sample bridge project analysis is presented in Table 4-4. The values for the source sound pressure levels were determined by the acoustic engineer based on data collected from numerous hydroacoustic monitoring studies summarized in the Compendium (*Appendix I*).

Based on data from similar projects, the acoustic engineer estimated that the peak sound pressure level from driving 2.2-meter- (7-foot-) diameter piles would be from 190 to 205 dB (depending on which pile section is being driven [the first sections driven are quieter than the top sections]), which is lower than the interim peak criteria of 206 dB_{PEAK}. Attenuation would lower the received sound at 20 meters from the pile to 200 dB or less (Table 4-4). Based on this analysis, fish would not be exposed to peak sound pressure levels above the interim criteria at distances greater than 10 meters from the pile during the driving of the 2.2-meter- (7-foot-) diameter piles.

The example assumes that, based on previously recorded pile driving events with similar conditions, the acoustic engineer estimated that 900 pile strikes over 15 minutes would be required to drive each 2.2-

Table 4-4. Example of Prediction of Daily Underwater Sound Levels for 7-Foot-Diameter Piles with Two Sections Driven per Day

Activity Description	Drive Time per Pile (min) [a]	Piles per Day	Drive Time (min) [a]	Events [b]		Maximum Peak at 10 m	Maximum Peak at 20 m	Maximum Peak at 45 m	Maximum Peak at 75 m	Estimated SEL per Strike [c] at 10 m	Estimated SEL per Strike [c] at 20 m	Estimated SEL per Strike [c] at 45 m	Estimated SEL per Strike [c] at 75 m	Accumulated SEL [d] at 10 m	Accumulated SEL [d] at 20 m	Accumulated SEL [d] at 45 m	Accumulated SEL [d] at 75 m	Estimated Distance to 187 dB Accumulated SEL (m)
Year 1 - Southbound Bridge Piers and Abutments																		
Pier 1																		
Impact Drive 2 bottom sections	15	2	30	900	strike	190	185	180	177	165	160	155	152	195	190	185	181	32
Impact Drive 2 pile sections	30	2	60	1,800	strike	200	195	190	187	170	165	160	157	203	198	193	189	109
Impact Drive 2 pile sections	30	2	60	1,800	strike	205	200	195	192	170	165	160	157	203	198	193	189	109
Impact Drive 2 pile sections	30	2	60	1,800	strike	205	200	195	192	170	165	160	157	203	198	193	189	109
Pier 2																		
Impact Drive 2 bottom sections	15	2	30	900	strike	190	185	180	177	165	160	155	152	195	190	185	181	32
Impact Drive 2 pile sections	30	2	60	1,800	strike	200	195	190	187	170	165	160	157	203	198	193	189	109
Impact Drive 2 pile sections	30	2	60	1,800	strike	205	200	195	192	170	165	160	157	203	198	193	189	109
Impact Drive 2 pile sections	30	2	60	1,800	strike	205	200	195	192	170	165	160	157	203	198	193	189	109

Pile driving time with impact hammer: 420 min

[a] Based on best estimate of drive times from previous studies. Drive times may vary substantially.

[b] Assumes large hydraulic hammer for cast-in-shell-steel piles, striking about once every 2 seconds, except for initial quieter blows.

[c] Based on average sound exposure level (SEL) per strike for impact driving from past measurement data for similar projects.

[d] SEL per event + 10* Log_{10}(no. of events).

meter- (7-foot-) diameter pile section. Under this scenario, 1,800 strikes would occur during each pile driving day, with 30 minutes of actual pile driving per day.

Also based on previously recorded data for asimilar site conditions and pile drives, the acoustic engineer estimated that the source sound pressure levels (at 10 meters from the pile) generated by a pile strike of a 2.2-meter- (7-foot-) diameter pile driven near shore and attenuated by a dewatered cofferdam or air bubble curtain range from 165 to 170 dB-$SEL_{SINGLE\ STRIKE}$, depending on which pile section is being driven (the first sections driven are quieter than the top sections). The accumulated SEL from a day of pile driving was estimated to be from 195 to 203 dB-$SEL_{ACCUMULATED}$ at 10 meters, which exceeds the interim criteria of 187 dB-$SEL_{ACCUMULATED}$. To determine the area where stationary fish would be exposed to a sound level of 187 dB over a day of pile driving, the transmission loss through water is applied to determine where the accumulated SEL would attenuate to 187 dB-$SEL_{ACCUMULATED}$ (as shown in the example calculations in Section 4.6.6.5). For this example, the area exposed to an accumulated SEL above 187 dB-$SEL_{ACCUMULATED}$ would extend up to 109 meters (358 feet) from the pile driving site (see Table 4-4). Thus, if a fish had remained within 109 meters of the pile driving activity for a day, it would have been exposed to accumulated SEL exceeding the criteria.

For this example project, the river being crossed is 20 meters wide and 1 to 2 meters deep. Based on the estimated distance to attenuate to the $SEL_{ACCUMULATED}$ criteria at 109 meters, it is estimated that an area of 2,180 square meters would be subject to accumulated sound pressure levels above the $SEL_{ACCUMULATED}$ criteria during each pile driving day.

Depending on the waterbody, data to estimate summer salmonid rearing densities may, or may not be available. It is best to first consult the local area fisheries biologists with DFG and the NOAA Fisheries biologists. In some cases, river conditions are appropriate for conducting reconnaissance-level or more intensive snorkel surveys to gather reach specific data. Snorkel surveys are generally not required but can be very effective in verifying the species and densities that might be affected.

The example used here assumes that no scour holes or other habitat features would concentrate fish and that no other characteristics of the river would affect a uniform density. Based on data for this particular reach of river (or data from a similar river situation), the example assumes (again for simplicity) a density of the fish rearing in this reach of the river of one fish per 10 square meters. Assuming this density, approximately 218 fish could be exposed to $SEL_{ACCUMULATED}$ above the interim criteria on each pile driving day (given that two pile sections are driven in a day).

4.7 Lessons Learned

4.7.1 Initiating Discussions with Resource Agencies Early

The permitting processes for projects involving pile driving in fish-bearing waters can take considerable time. To minimize the potential for project delays related to permitting, Department staff should initiate discussions with resource agency staff as early as possible in the process. Understanding the agencies' concerns early in the process can facilitate more timely permit processing by ensuring that the concerns are addressed in the permitting documentation.

4.7.2 Understanding the Issues

The evaluation of bioacoustic impacts to fish from pile driving activities requires a clear understanding of construction methods, fish biology, and underwater acoustics. It is also important to recognize that the analysis of pile driving noise on fish is not an exact science; it requires best professional judgment based on scientific research and experience. Further, the knowledge regarding bioacoustic assessments is evolving and it is important to keep current. It is likely that the interim criteria will change as the research efforts continue.

In some cases, the staff from the regulating agency will not be completely familiar with this type of analysis and what can and cannot be done to minimize impacts. It is important that the assumptions, analysis, and conclusions are clear and understandable in the documentation to the reviewing agency.

4.7.3 Portraying Reasonable Worst-Case Conditions

For some projects, complete details are not available at the time of the analysis. Where specific information is not available, it is appropriate to develop reasonable worst-case estimates. For instance, if the exact number or size of temporary piles for a construction trestle is not known, a reasonable range should be developed by the project engineer and included in the project description. As a reasonable worst-case scenario, the higher end of the range should be used for the analysis. In providing a worst-case estimate, the likelihood of needing to reinitiate consultation or modify permits is reduced because modifications to the project presumably would reduce the estimated adverse effects included in the worst-case documentation. However, if the reasonable worst-case conditions would result in significant impacts to species, or could result in a jeopardy determination (a determination under ESA that an action would be reasonably expected—directly or indirectly—to reduce appreciably the likelihood of both the survival and recovery of a listed species in the wild by reducing the reproduction, numbers, or distribution of that species), Department staff should work with the design staff to provide measures to avoid and minimize take such that the action would not result in a jeopardy determination—even under the worst-case scenario.

4.7.4 Understanding the Ramifications of Permit Conditions

Regulatory agencies can require that numerous conditions be met as a condition to issuing permits. Permit conditions related to pile driving can be included in the Biological Opinion (terms and conditions), the 1602 Streambed Alteration Agreement, CESA consistency determination, the Coastal Development Permit, and others. Permit conditions related to pile driving can include a wide variety of requirements, as applicable, such as daily and seasonal timing restrictions, peak and cumulative noise limitations, requirements for underwater noise attenuation systems, fish salvage and/or exclusion, hydroacoustic monitoring, fish monitoring, special studies, and mitigation plans for the take of state-listed species.

It is important that Department staff understand the implications of permit conditions. It is always prudent to ask to review a draft of permit conditions from the permitting agency. Conditions that are not feasible, significantly affect schedule, or are cost prohibitive should be resolved with the permitting agency.

4.7.5 Developing Mitigation under CESA

If the project results in the take of state-listed fish species, mitigation will be required. The CESA consistency determination must evaluate the effect of the project on listed species and the effect of the mitigation in offsetting that take, based on information from the federal consultation. It is therefore important to determine mitigation options while preparing the Biological Assessment (BA) and to include an analysis of the mitigation as part of the BA. The BA also must provide statements committing Department funding to the mitigation plan.

4.8 Conclusion

The evaluation of potential effects of pile driving noise on fish is one of the most significant tasks associated with permitting many of the bridge projects carried out by the Department and is probably the least understood. This guidance manual was developed to provide Department staff with up-to-date information regarding recent developments in the evaluation of pile driving noise and its potential effects on fish. Developing an understanding of this issue requires knowledge of the underlying acoustic principals related to sound generation and transmission of sound through water, the biology and behavior of fishes, the physical effects of sound on fish (both temporary and permanent), the regulatory framework in which the effects are evaluated, and the information/evaluation gaps. By providing this information to Department staff who are involved in permitting, it is hoped that Department staff become better informed regarding pile driving and its potential effects and thus can be better prepared to address resource agency requests and concerns during the permitting process.

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Appendix I Compendium of Pile Driving Sound Data

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List of Acronyms

CISS	cast-in-steel shell
RMS	root mean square
SEL	sound exposure level
dB	decibels
msec	millisecond(s)
Hz	hertz
ft-lbs	foot-pounds
SFOBB	San Francisco-Oakland Bay Bridge
PIDP	Pile Installation Demonstration Project
MMSZ	marine mammal safety zone
GS	Greeneridge Sciences, Inc.
I&R	Illingworth & Rodkin, Inc.
Caltrans	California Department of Transportation
RSRB	Richmond-San Rafael Bridge
CIDH	cast-in-drilled hole

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 6.5 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 chapters that 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 chapters:

- Summary (I.2) – provides an overview of data contained within the compendium.
- Steel Pipe or CISS Piles (I.3) – provides 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 (I.4) – provides limited available data on the installation of steel H-type piles.
- Concrete Piles (I.5) – provides data on the installation of concrete piles typically used for wharf construction such as berth construction at ports.
- Steel Sheet Piles (I.6) – provides some information on steel sheet piles used to construct walls and cofferdams in marine environments.
- Timber Piles (I.7) – provides very limited data on timber piles; these piles are not commonly used in Northern California.
- New Benicia-Martinez Bridge Project (I.8) – 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 (I.9) – 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 (I.10) – provides data on a wide variety of steel pile sizes ranging from 12 to 150 inches in diameter, using several different types and methods of pile driving hammers.
- Humboldt Bay Bridges Project (I.11) – 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 on the size of the pile and the size of the hammer. Other factors, however, 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 I.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 use of a drop hammer. Results from these projects were highly variable and cannot be summarized into one level for a certain type of pile. 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, root mean square (RMS) , and sound exposure level (SEL) where available; an approximation of the attenuation rate; and 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 I.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 pile	<5 meters	210	195	185
2.4-meter (96-inch) steel CISS pile	~10 meters	220	205	195

CISS = Cast-in-steel shell

Table I.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)
** Sound exposure level (SEL) for 1 second of continuous driving

Table I.2-3 Summary of Unattenuated Sound Measurements for Marine Pile Driving (Page 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 from 5 to 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 installed 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		Temporary trestle piles driven in relatively shallow waters along the western 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 2 meters at the deepest channel of the river, which was only 15 meters wide. Levels varied considerably during 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	

Table I.2-3 Summary of Unattenuated Sound Measurements for Marine Pile Driving (Page 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	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.
				(Delmag D100-13)		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	4m	4m	219	202	NA		CIDH piles driven through temporary trestle constructed using 30-inch piles. Piles driven in fairly shallow water along the western portion of the Richmond-San Rafael Bridge.
				(Delmag D62 or D100)		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		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.
				(Menck MHU500T)		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	~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 fourth or last portion of pile driving was conducted.
				(Menck MHU1700T)		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	~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 2 years.
				(Menck MHU1700T)		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	Dewatered Cofferdam	50m	185-190	165-180	NA		Production piles driven in a dewatered cofferdam, where surrounding waters were from 5 to 8 meters deep. Sound levels varied considerably with direction and distance. These measurements represent the loudest portion of the pile driving, when the last portion of the pile was driven.
				(Menck MHU1700T)	~5-8m	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	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 considerably with direction and distance. These measurements represent the loudest portion of the pile driving, when the last portion of the pile was driven.
				(Menck MHU1700T)		50m	213	200	187		
						100m	197-204	186-192	174-180	>12 dB at 50 - 100m	
						400m	186	175	165	or ~*20 Log(Dist)*	

Table I.2-3 Summary of Unattenuated Sound Measurements for Marine Pile Driving (Page 3 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	126-inch	Richmond-San Rafael Bridge, CALTRANS	San Rafael, CA - San Francisco Bay	Hydraulic Impact Submersible IHC	>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.
						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 2-meter-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	--		

Table I.2-3 Summary of Unattenuated Sound Measurements for Marine Pile Driving (Page 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 (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)*	
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. Piles 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. Sound levels of some driving events exceeded 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 from 5 to 15 feet.
						20m	170	160	NA	>5dB at 20m	

[1] Attenuation rates applies to the range of measurements

Source: Illingworth & Rodkin, Inc. (Ver. 2/6/2009)

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 (CISS) piles. Most of these projects were small, and some involved only 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 Shell 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 meter (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 from 190 to 192 decibels (dB) peak, and the RMS-impulse sound pressure levels were typically from 175 to 177 dB RMS. The East Pile, which was driven in very shallow water, resulted in peak sound pressures of about 185 to 188 dB and RMS sound pressure levels of 170 to 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 with 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 Driving 12-Inch-Diameter Steel Shell Piles – El Cerrito, CA

		Sound Pressure Levels in dB Measured at 10 Meters		
Pile	**Conditions**	**Peak**	**RMS**	**SEL**
Center	Unattenuated – diesel impact hammer	192	177	--
East	Unattenuated – diesel impact hammer	188	172	--

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

I.3.2 60-Inch-Diameter CISS Piles for 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, California[2]. Temporary H-type piles were also driven for this project, but they are discussed in a different section. 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 to 150 meters from the piles.

Figure I.3-1 CISS Piles Driven for the Noyo River Bridge Replacement Project

Results of the measurements 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 greater 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 conducted only to identify the extent of the marine mammal safety zone, which was based on RMS sound pressure level measurements, detailed analyses of acoustic signals were not performed. Therefore, SELs are not available.

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

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	**RMS**	**SEL**
Cofferdam – in water	Unattenuated – impact hammer at 10 meters	207	192	--
	Unattenuated – impact hammer at 50 meters	190	175	--
	Unattenuated – impact hammer at 80 meters	187	171	--
	Unattenuated – impact hammer at 125 meters	175	160	--

I.3.3 12-Inch-Diameter Steel Shell Piles in Shallow Water Using Drop Hammer at Galilee Marina – Sausalito, CA

Two small-diameter steel pipe piles were driven in March 2003 in Sausalito, California3. 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. Because the water depth was about 2 meters, the hydrophones were positioned at 1-meter water depth. Measured sound pressure data are summarized in Table I.3-3. At 10 meters, the average peak pressure was 175 dB, and most strikes were 178 dB or lower. The 20-meter 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 [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 Driving 12-Inch-Diameter Steel Shell Piles – Galilee Marina, Sausalito, CA

		Sound Pressure Levels in dB Measured at 10 Meters		
	Conditions	Peak	RMS	SEL
1 and 2	Unattenuated – drop impact hammer	175	165	152

The representative signal analyses (see Figure I.3-2) describe 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 msec into the 75-msec event. As a result, the rate sound energy accumulated was relatively slow. The SEL for these typical strikes was 152 dB.

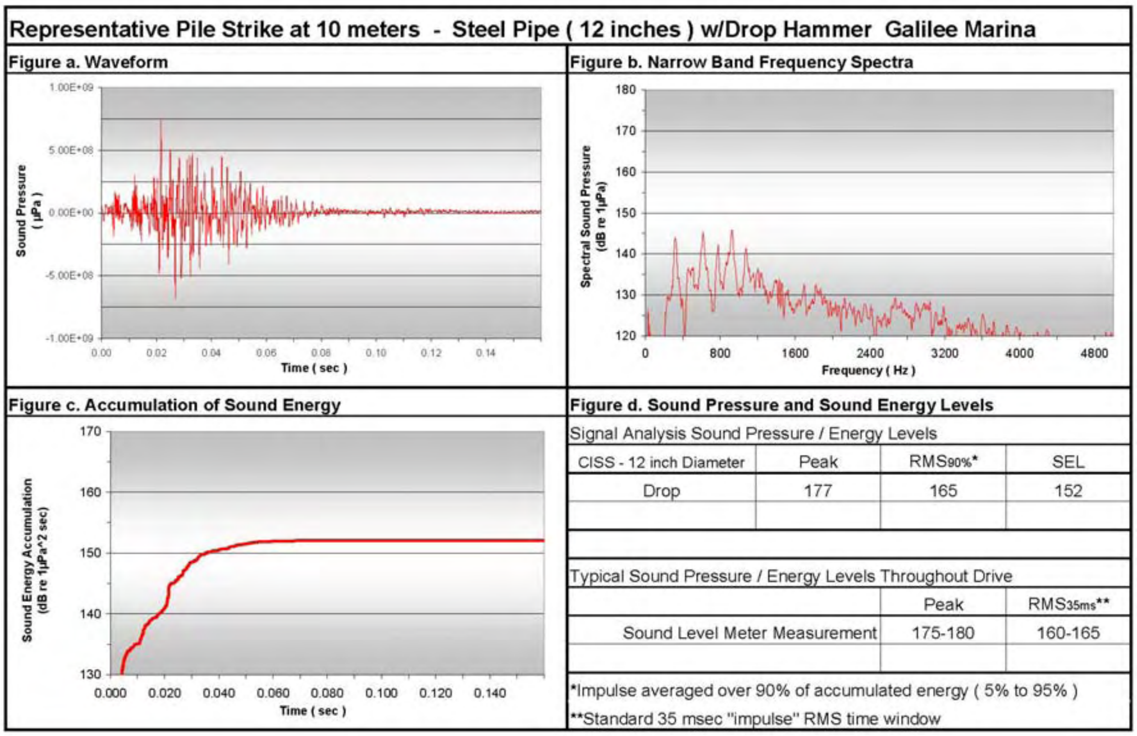


Figure I.3-2 Representative Signal Analyses for 12-Inch-Diameter Steel Shell Piles at Galilee Marina

I.3.4 13-Inch-Diameter Steel Shell Piles for Mad River Slough Pipeline Construction – Arcata, CA

Three steel pipe piles were driven in July 2003 at the Mad River Slough near Arcata, California[4]. The purpose of the project was to retrofit a water pipeline. Steel pipe piles with a diameter of 0.3 meter (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 10 and 20 meters for the second pair. Measured sound pressure levels are summarized in Table I.3-4. Signal analyses of individual pile strikes were not performed; therefore, SEL data for this installation are not available.

Figure I.3-3 Installation of 13-Inch-Diameter Steel Pipe Piles 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 20 meters, 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.

I.3.5 Vibratory Installation of 72-Inch-Diameter Steel Pile 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, California5. 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 2 days of pile installation involved the use of an 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.

Table I.3-4 Summary of Sound Pressures Measured for Driving 13-Inch-Diameter Steel Shell Piles – Mad River Slough, Arcata, CA

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

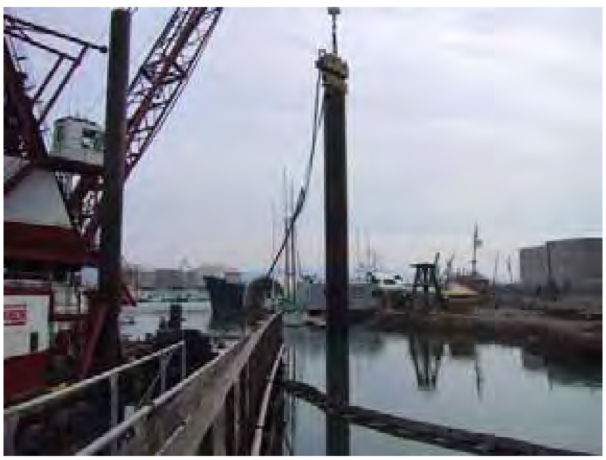


Figure I.3-4a Pile Installation Using the APE Model "King Kong" Vibratory Driver/Extractor

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 been associated 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; it produced consistent peak sound pressures of about 180 to 182 dB, with an absolute maximum peak pressure of 184 dB. Measurements were also made at 20 meters and 30 meters, 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 because the sounds are nearly continuous. Keeping in mind that the SEL is an event descriptor, the selection of a 1-second period is somewhat arbitrary.

Table I.3-5 Summary of Sound Pressures Measured for Vibratory Installation of 72-Inch-Diameter Steel Shell Piles – Richmond Inner Harbor, Richmond, CA

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL (1sec)
Day 1	Vibratory hammer at 10 meters	183	170	170
Day 1	Vibratory hammer at 20 meters	176	164	164
Day 1	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
Day 3	Vibratory hammer at 20 meters	174	163	163

Signal analyses 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-msec rise time). Analyses 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.

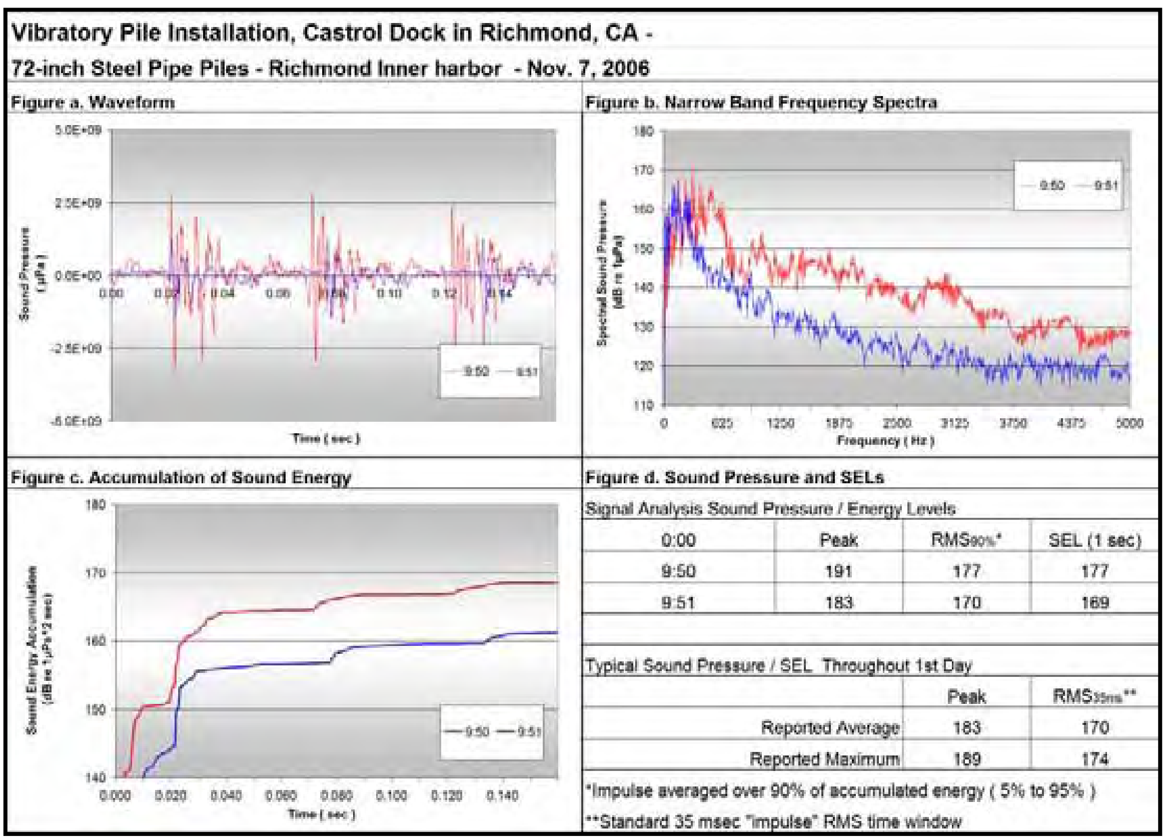


Figure I.3-5 Representative Signal Analyses for Vibratory Installation of 72-Inch-Diameter Steel Shell Piles at Richmond Inner Harbor

Furthermore, the pulse from vibratory pile installation has not been defined. If the imbedded pulse (25 msec long) were used, 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 [in the following section]). 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 1 second because the sounds are continuous and accumulate over the entire second when the event is occurring.

I.3.6 24-Inch-Diameter Steel Piles Installed at Conoco/Phillips 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 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 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 from 202 to 203 dB. The RMS sound pressure levels were from 188 to 189 dB. At 50 meters, 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.

Table I.3-6 Summary of Sound Pressures Measured for Driving 24-Inch-Diameter Steel Pipe Piles – Conoco/Phillips Dock, Rodeo, CA

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

Analyses of pulses recorded at 10 and 50 meters are shown in Figure I.3-6. 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 10 meters and 167 dB at 50 meters.

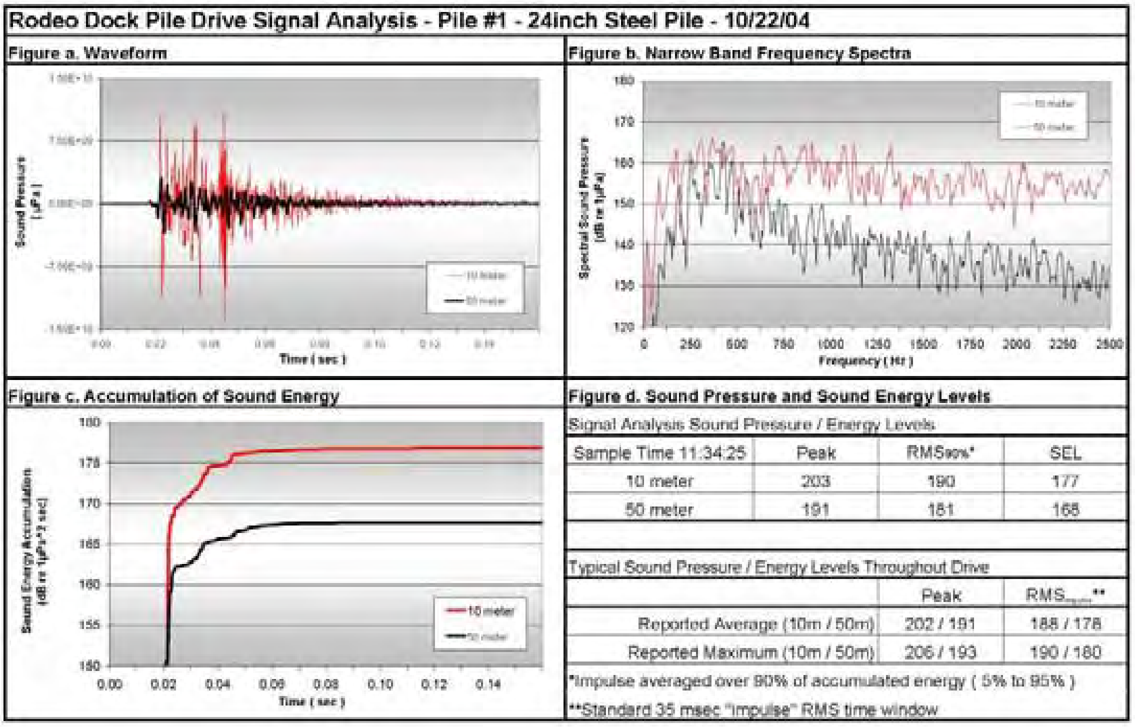


Figure I.3-6 Representative Signal Analyses for 24-Inch-Diameter Steel Pipe Piles at Conoco/Phillips Dock near San Pablo

I.3.7 20- and 36-Inch-Diameter Steel Piles for 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, California[7]. The purpose of the project was to construct a pipeline utility crossing over 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 the 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 2 feet from the bottom of the casing. Measurements were made at both 10 and 20 meters from the piles and at 1 meter from the bottom of the channel because the depth of the channel was less than 4 meters.

 **Figure I.3-7a Driving 20-Inch-Diameter Piles near Shore**	 **Figure I.3-7b Driving 36-Inch-Diameter Pile with Attenuation**

Figure I.3-8 Casing for the Confined Air Bubble Curtain System

20-Inch-Diameter Trestle Piles Driven in Water

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

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 typical differences between RMS and

SEL levels of about 10 dB occurred. SELs 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 20-Inch-Diameter Trestle Piles in Water, Unattenuated – Stockton Wastewater Treatment Plant, Stockton, CA

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

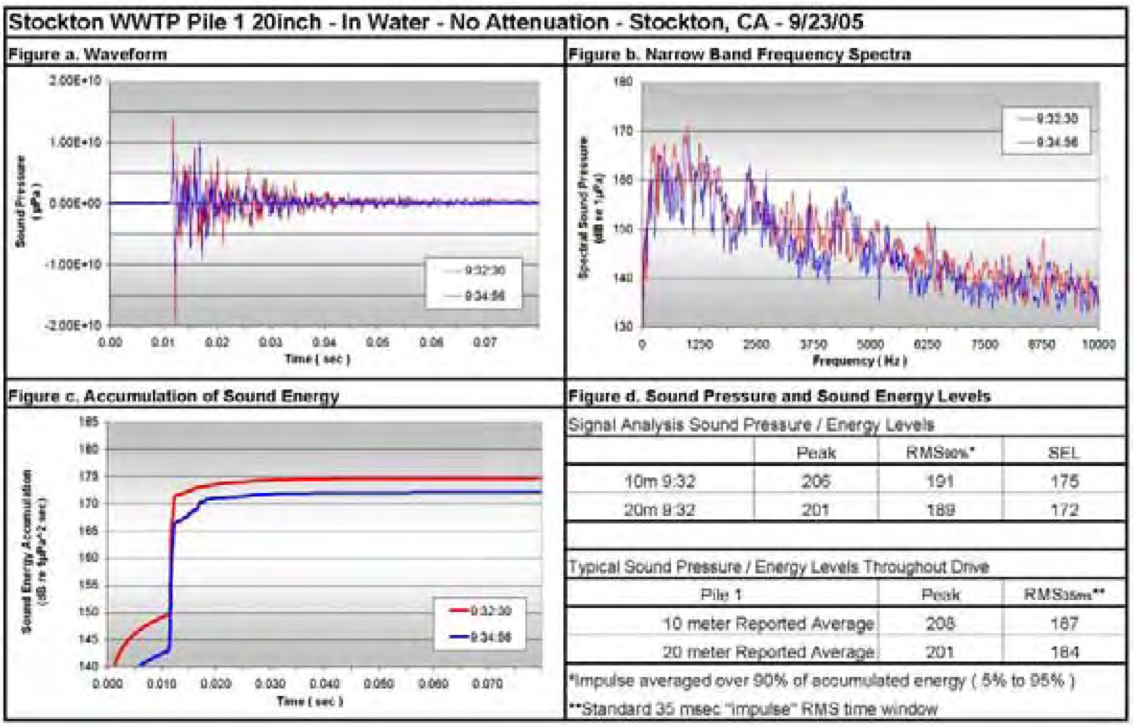


Figure I.3-9 Representative Signal Analyses for 20-Inch-Diameter Piles Unattenuated in Water at Stockton Wastewater Treatment Plant

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

Results are summarized in Table I.3-8. The levels of the first three piles were very consistent 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 20-Inch-Diameter Trestle Piles on Land next to Water – Stockton Wastewater Treatment Plant, Stockton, CA

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

The signal analyses 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 1,500 Hz. The received pulses were highly attenuated because they propagated through the bottom sediments. These levels are probably the maximum attenuation that could be achieved from these piles driven in this environment. Additional 20-inch-diameter piles were driven in the water with attenuation systems; these are discussed in the next section.

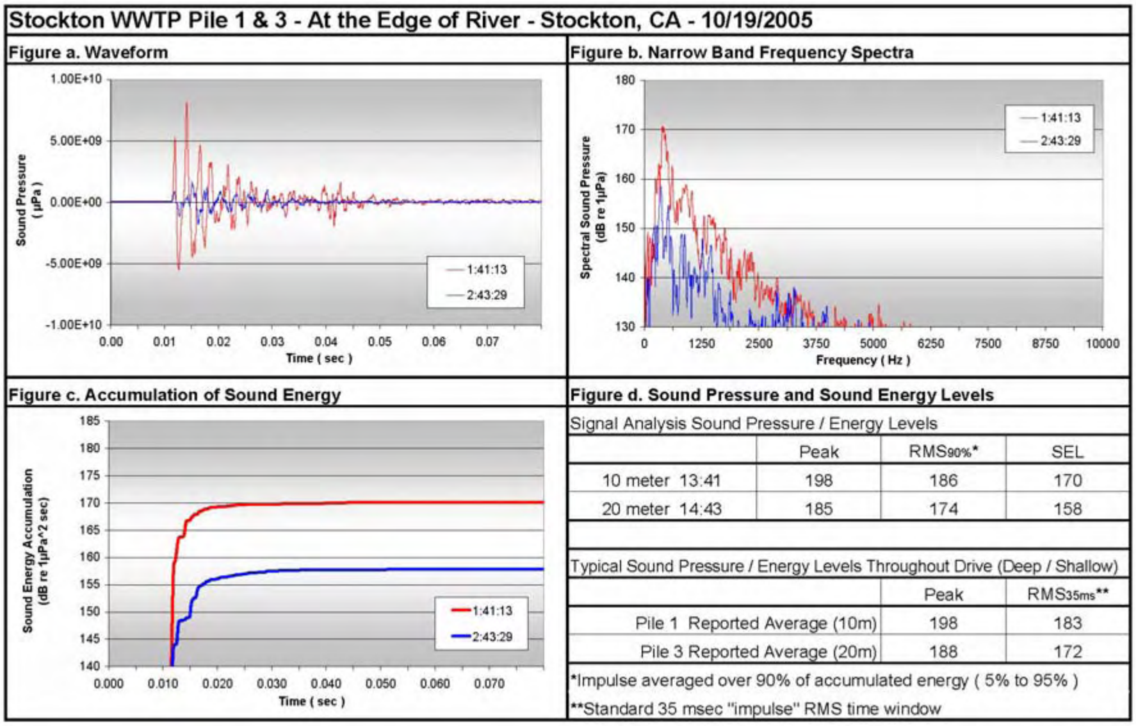


Figure I.3-10 Representative Signal Analyses for 20-Inch-Diameter Piles on Land at Stockton Wastewater Treatment Plant

20-Inch-Diameter 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 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 was less than 5 dB.

Table I.3-9 Summary of Sound Pressures Measured for 20-Inch-Diameter Trestle Piles in Water with Attenuation – Stockton Wastewater Treatment Plant, Stockton, CA

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

The signal analyses for Piles 1 and 3 are shown in Figure I.3-11. Comparison to Figure I.3-9 (unattenuated 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 levels and SELs were dominated by the low-frequency sound content of these pulses.

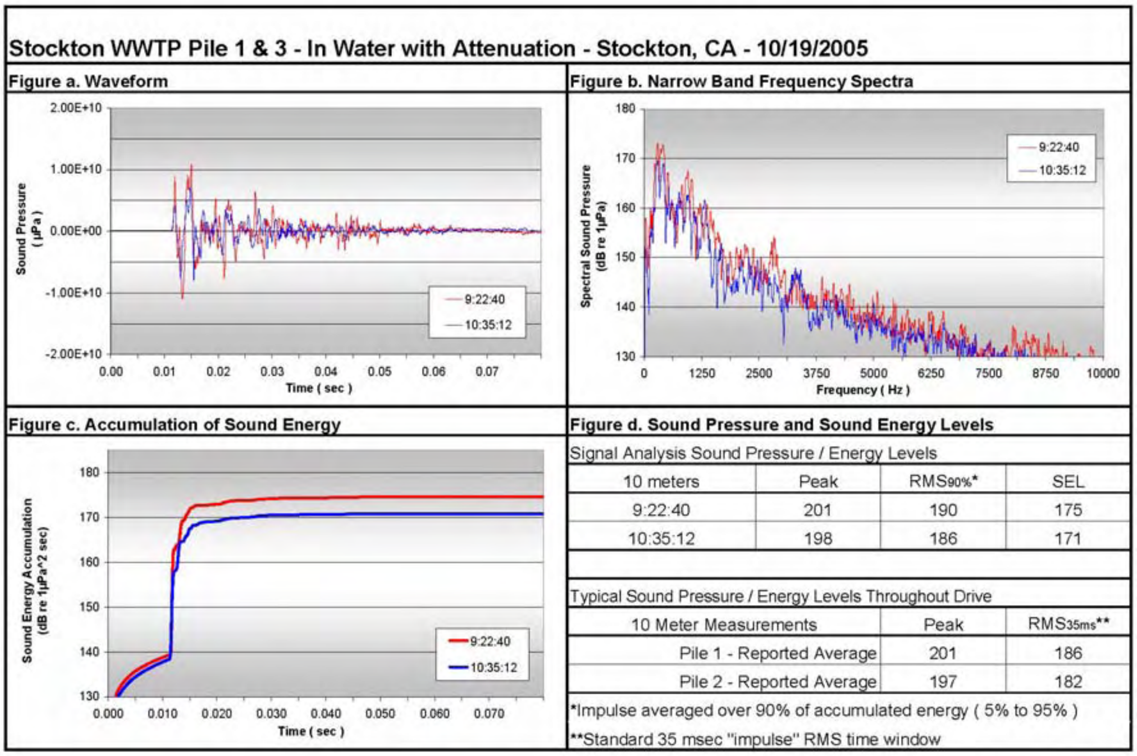


Figure I.3-11 Representative Signal Analyses for 20-Inch-Diameter Piles Attenuated in Water at Stockton Wastewater Treatment Plant

36-Inch-Diameter 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; therefore, corresponding SEL data are available only 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 to, 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.3-10 Summary of Sound Pressures Measured for 36-Inch-Diameter Bent 4 Piles on Land – Stockton Wastewater Treatment Plant, Stockton, CA

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
1	Vibratory installation – impact hammer at 10 meters	164	155	--
1	Vibratory installation – impact hammer at 20 meters	158	150	--
1	Land driven – impact hammer at 10 meters	201	186	173
1	Land driven – impact hammer at 20 meters	198	183	170
2	Vibratory installation – impact hammer at 10 meters	165	157	--
2	Vibratory installation – impact hammer at 20 meters	158	149	--
2	Land driven – impact hammer at 10 meters	199	184	174
2	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 1,000 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.

36-Inch-Diameter 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.3-11. 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.

At Pile 4, the closest pile to the trestle, the isolation casing/air bubble curtain was lowered into the river channel—settling into the mud so that the bubble ring was near the mud line as designed. During the placement of the casing for Pile 3, the isolation casing rested on an obstruction at the bottom and did not settle into the mud. Consequently, the bubble ring was 1 to 2 feet above the channel bed, and sound levels with this pile were not effectively attenuated.

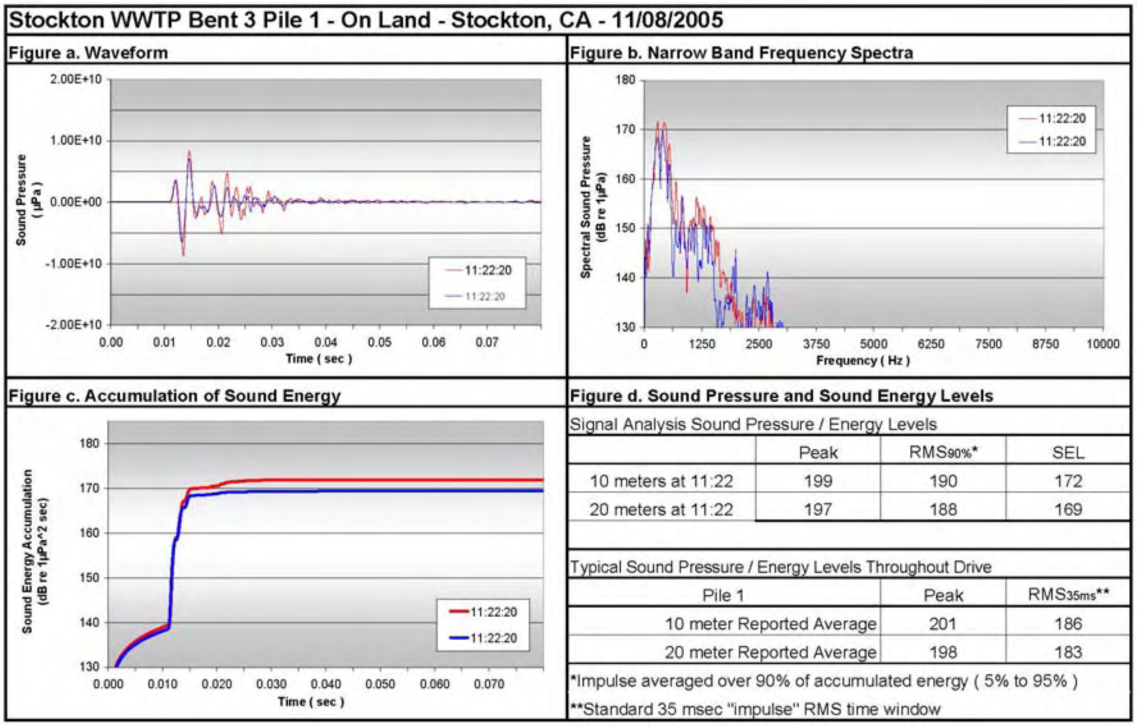


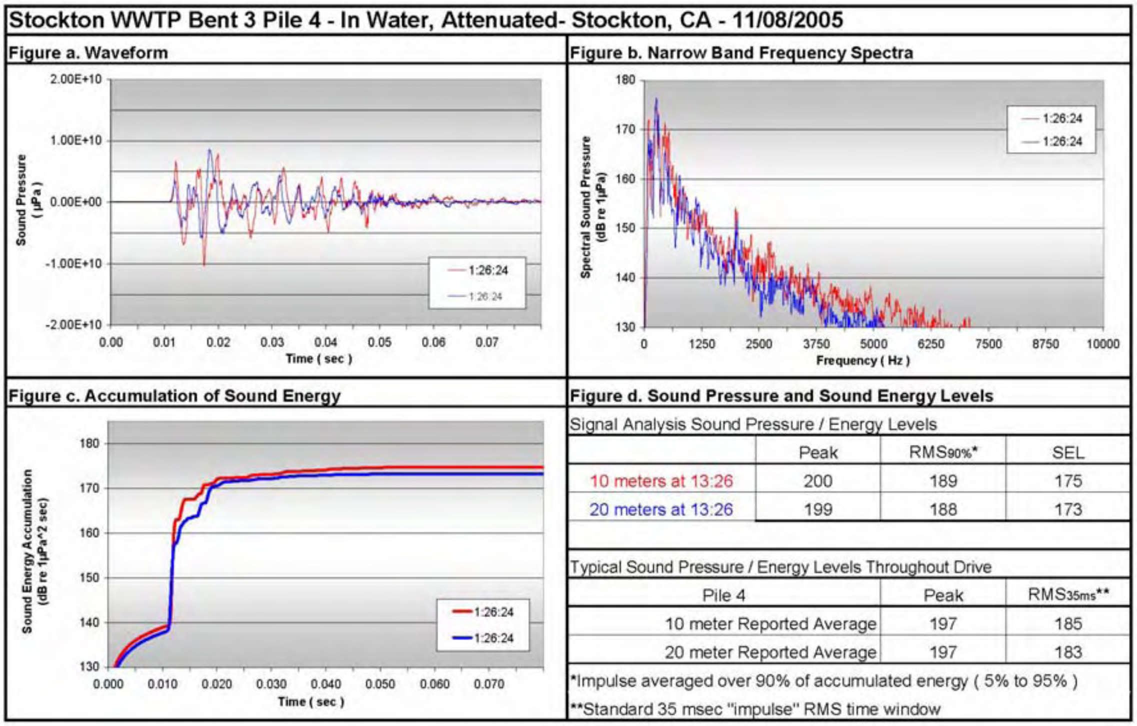
Figure I.3-12 Representative Signal Analyses for 36-Inch Bent 4 Piles on Land at Stockton Wastewater Treatment Plant

Table I.3-11 Summary of Sound Pressures Measured for 36-Inch-Diameter Bent 3 Piles in Water with Attenuation – Stockton Wastewater Treatment Plant, Stockton, CA

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

* The sound from pile driving was only partially attenuated due to problems setting the isolation casing/air bubble curtain.

Signal analyses of vibratory pile installation sounds were not performed; therefore, corresponding SEL data are available only 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 pressure levels measured at 20 meters.



Signal Analysis Sound Pressure / Energy Levels

	Peak	RMS90%*	SEL
10 meters at 13:26	200	189	175
20 meters at 13:26	199	188	173

Typical Sound Pressure / Energy Levels Throughout Drive

Pile 4	Peak	RMS35ms**
10 meter Reported Average	197	185
20 meter Reported Average	197	183

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

**Standard 35 msec "impulse" RMS time window

Figure I.3-13 Representative Signal Analyses for 36-Inch-Diameter Bent 3 Piles Attenuated in Water at Stockton Wastewater Treatment Plant

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

Pile driving was conducted to upgrade dock facilities at Tesoro's Amorco Wharf near Martinez, California, 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 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 six battered piles and six plumb or vertical piles.

Each pile was about 100 feet long. The driving durations were between about 10 and over 30 minutes. A diesel impact hammer was used to drive the piles; however, the type and size were 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.3-12 Summary of Sound Pressures Measured for Driving 24-Inch-Diameter Steel Pipe Piles – Amorco Wharf Construction, Martinez, CA

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

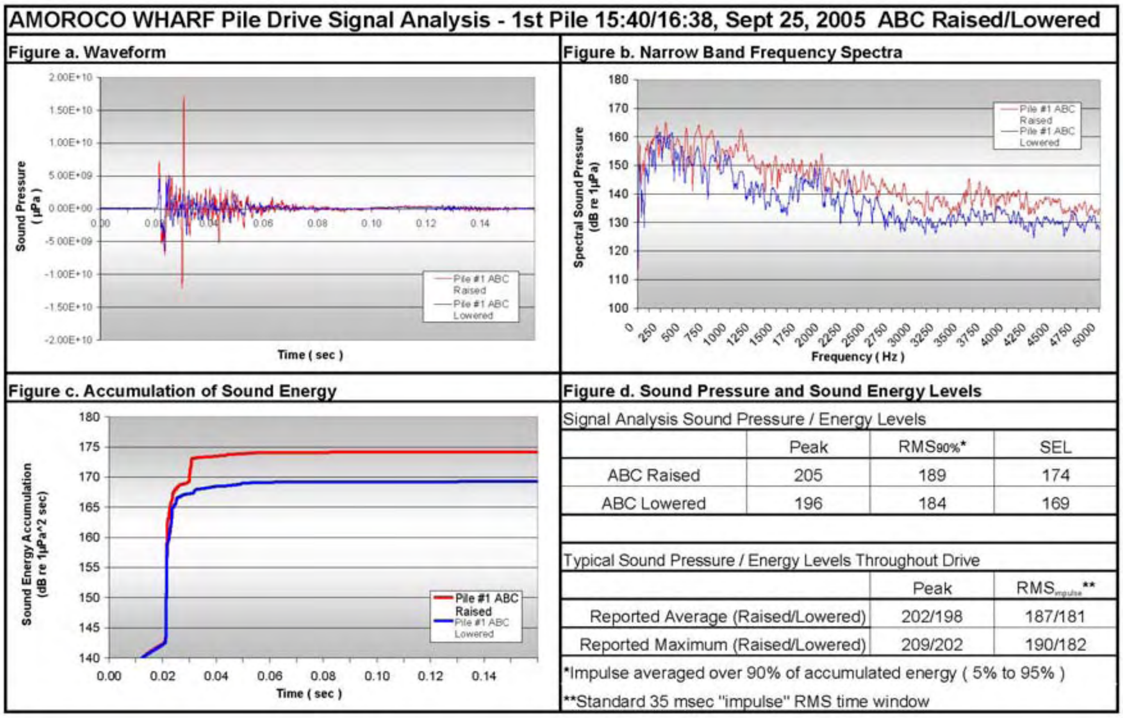
Pile Group 1 – East Breasting Dolphin

The first group of piles was 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 1 hour for some of the battered piles. Peak sound pressures at 10 meters ranged from less than 195 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 from 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 analyses shown in Figure I.3-14 indicate 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.

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, respectively. Typical SELs were 175 dB. There were some directionality differences. At 10 meters to the west, average and maximum sound levels were 190 and 192 dB peak and 176 and 178 dB RMS, respectively. At 10 meters to the east, average and maximum sound levels were 189 and 190 dB peak and 177 and 179 dB RMS, respectively. For the vertical piles, average and maximum sound pressure levels were 200 and 205 dB peak and 185 and 190 dB RMS, respectively. Typical SEL was 173 dB. At the two alternate locations, 10 meters to the north and east, average and maximum sound levels were 200 and 203 dB peak and 185 and 190 dB RMS, respectively. Spot measurements at 10 meters show that 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.



Signal Analysis Sound Pressure / Energy Levels

	Peak	RMS90%*	SEL
ABC Raised	205	189	174
ABC Lowered	196	184	169

Typical Sound Pressure / Energy Levels Throughout Drive

	Peak	$RMS_{impulse}$**
Reported Average (Raised/Lowered)	202/198	187/181
Reported Maximum (Raised/Lowered)	209/202	190/182

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

**Standard 35 msec "impulse" RMS time window

Figure I.3-14 Representative Signal Analyses for 24-Inch-Diameter Piles with and without Effective Air Bubble Curtain System at Amorco Wharf

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. The 10- to 15-dB difference in sound pressure levels indicates substantial variation in air bubble curtain performance. Not only were the sound pressures lower to the west, but also sound energy accumulated at a slower rate.

Pile Group 3

The third group of piles was driven on October 29 and 30. Drive times were less than the first two groups, from 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. 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.

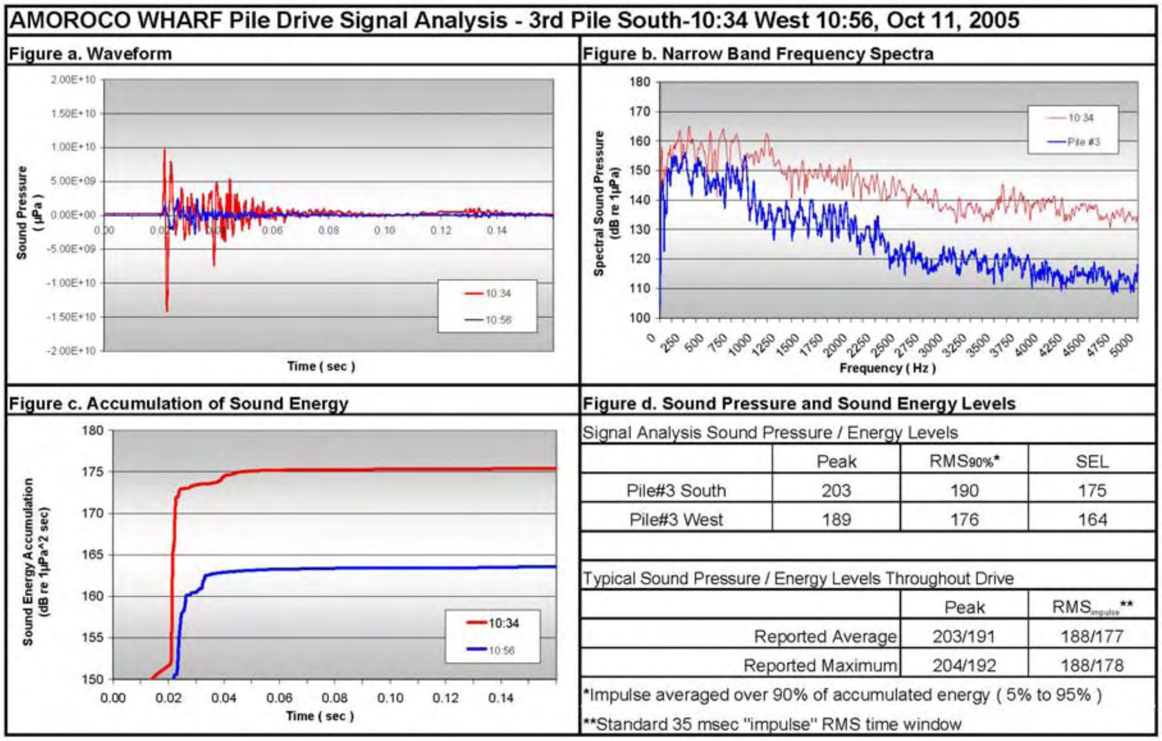


Figure I.3-15 Representative Signal Analyses for 24-Inch-Diameter Piles Directional Measurements with Air Bubble Curtain System at Amorco Wharf

Air Bubble Curtain System Performance

The existing wharf piers and strong currents compromised the air bubble curtain system performance at times. A large range of sound pressures was 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 sixth and seventh 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. These were indicative of poor air bubble curtain performance in some directions. This may have been caused by the positioning of the system, complicated by the existing piers or the current. In any event, this air bubble curtain system was capable of providing up to 15 dB of attenuation but lower reductions were typical.

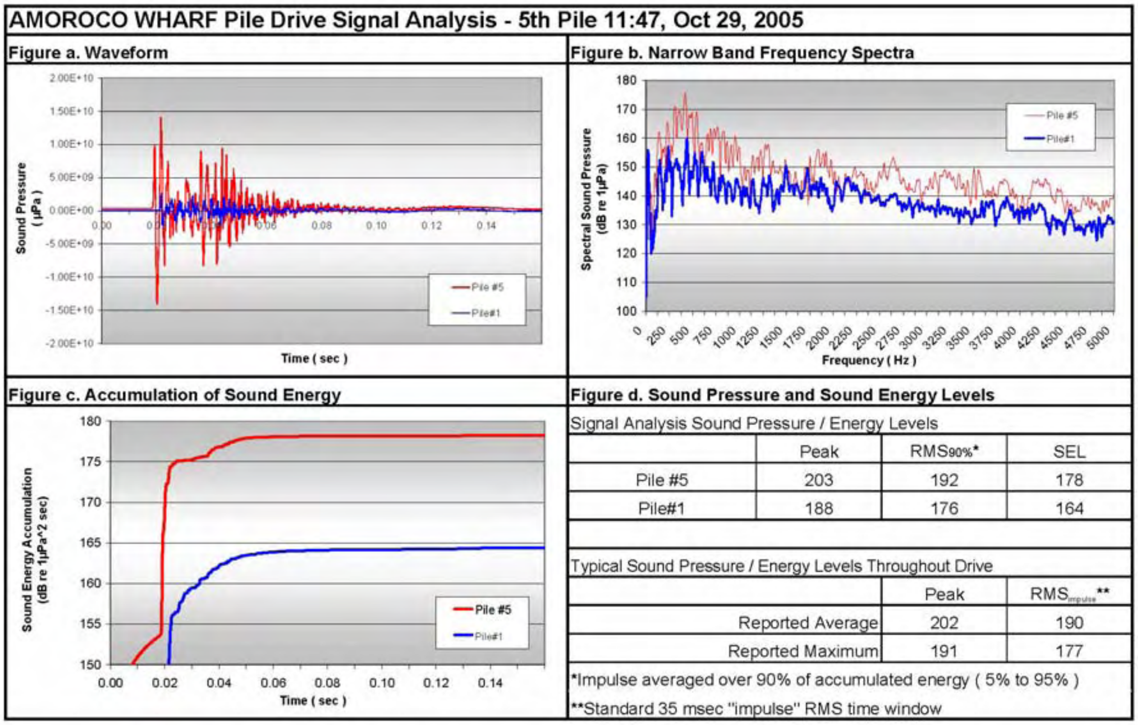


Figure I.3-16 Representative Signal Analyses for 24-Inch-Diameter Piles Showing Pulse for Two Different Battered Piles with Air Bubble Curtain System at Amorco Wharf

I.3.9 24- and 48-Inch-Diameter Piles to Construct New Bridge across the Russian River – Geyserville, CA

Emergency bridge replacement work was conducted in 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 an 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-Diameter Trestle Piles

The 24-inch-diameter trestle piles were driven both on land and in water during spring 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 an IHC SC75 hydraulic hammer was used. This technique did not work efficiently; 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 taken during only one productive driving event on April 10, 2006. Because of 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 to 195 dB throughout much of the drive. Maximum peak pressures near the end of the drive were 198 dB (two strikes). RMS sound pressure levels were from 177 to 182 dB. Signal analyses could not be performed; therefore, SEL levels were not measured.

Table I.3-13 Summary of Sound Pressures Measured for Driving 24-Inch-Diameter Steel Pipe Piles – West Side of 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.

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. Levels at 30 to 35 meters from the pile in the deep-water channel (10 meters from shore) averaged 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.

Table I.3-14 Summary of Sound Pressures Measured for Driving 24-Inch-Diameter Steel Pipe Piles – East Side of 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
Piles 1–8, 4/5/2006	Land – impact hammer at 30–35 meters	186	172	~162
Piles 1–8, 4/5/2006	Land – impact hammer at 90–95 meters	178	164	NA
Piles 1–4, 4/10/2006	Land – impact hammer at 15 meters	197	185	173
Piles 1–4, 4/10/2006	Land – impact hammer at 35 meters	186	174	163
Piles 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
Piles 1–3, 4/26/2006	Attenuated – impact hammer at 18 meters	182	167	160
Piles 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.

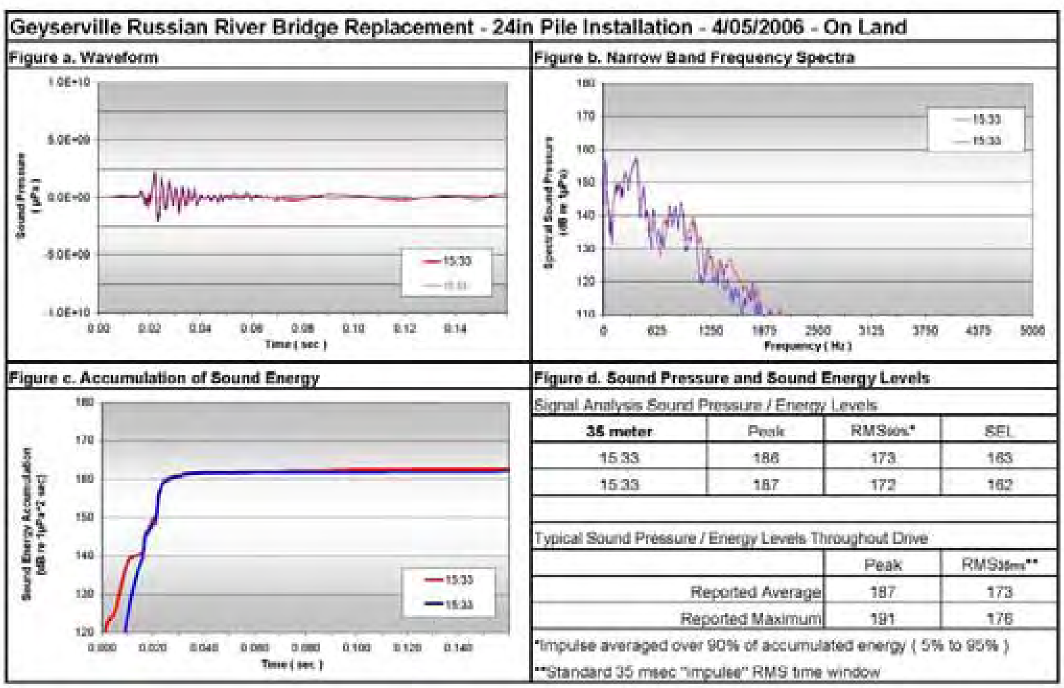


Figure I.3-19 Representative Signal Analyses for Temporary 24-Inch-Diameter Piles Driven 35 Meters away on Land (at Shore) at the Russian River

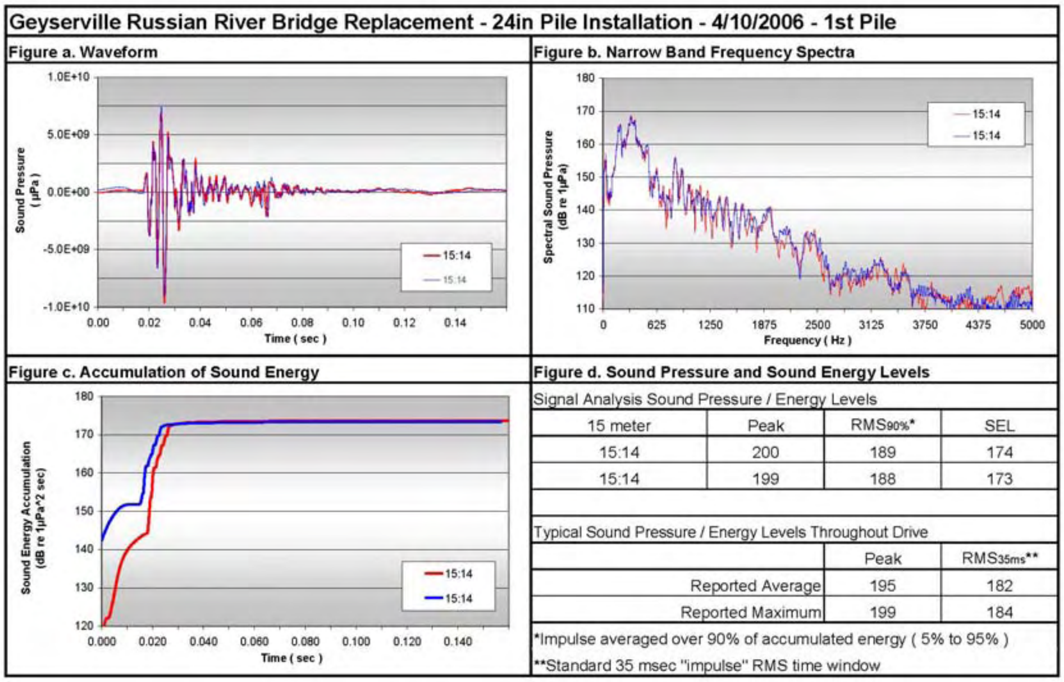


Figure I.3-20 Representative Signal Analyses for Temporary 24-Inch Piles Driven 15 Meters away on Land (at Shore) at the Russian River (1st Pile)

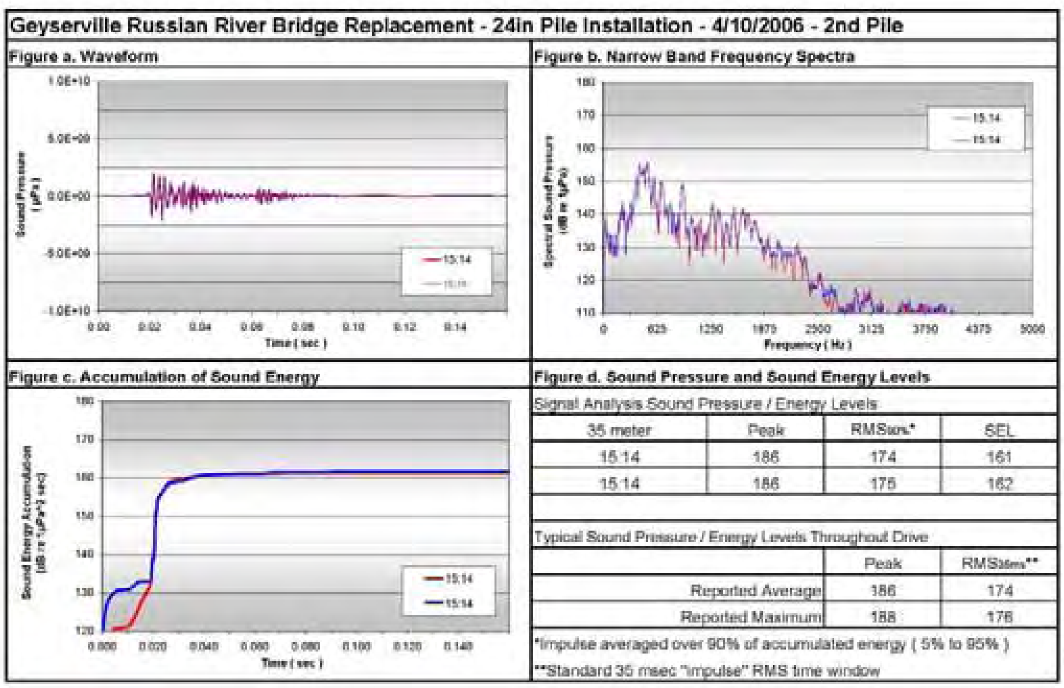


Figure I.3-21 Representative Signal Analyses for Temporary 24-Inch-Diameter Piles Driven 15 Meters away on Land (at Shore) at the Russian River (2nd Pile)

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 illustrate the somewhat higher frequency content of these sounds, when compared to those from driving on April 5.

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 likely was 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 analyses only indicated pulses with relatively low frequency content and peak sound pressures below 190 dB.

48-Inch-Diameter 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 (248,000 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 five bents, each of which 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 also were 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 onto 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.3-15 Summary of Sound Pressures Measured for Driving 48-Inch-Diameter CISS Piles on Land – 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 sound pressures for the last 1 minute of driving were almost 10 dB higher than for 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 from 70 to 180 dB. At 60 meters, highest peak sound pressures were less than 170 dB. 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 also were 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 (with a maximum of 171 dB). Signal analyses 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 1.5-hour 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 50-meter 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 1.5-hour period. 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.

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, more dampening occurred, 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 is 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 at 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.

Table I.3-16 Summary of Sound Pressures Measured for Driving 48-Inch-Diameter CISS Piles in Water (Bent 5) – 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

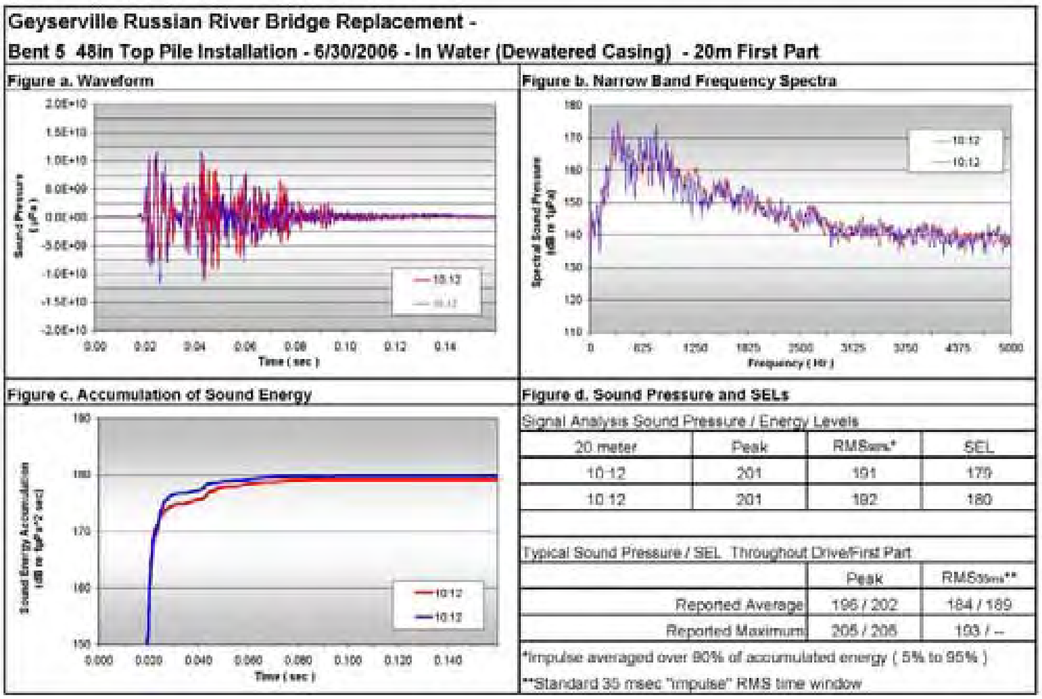


Figure I.3-23 Representative Signal Analyses for 48-Inch-Diameter Piles Driven 20 Meters away through Dewatered Casing in 2 Meters of Water – Beginning Portion of Drive at Geyserville Bridge, Russian River

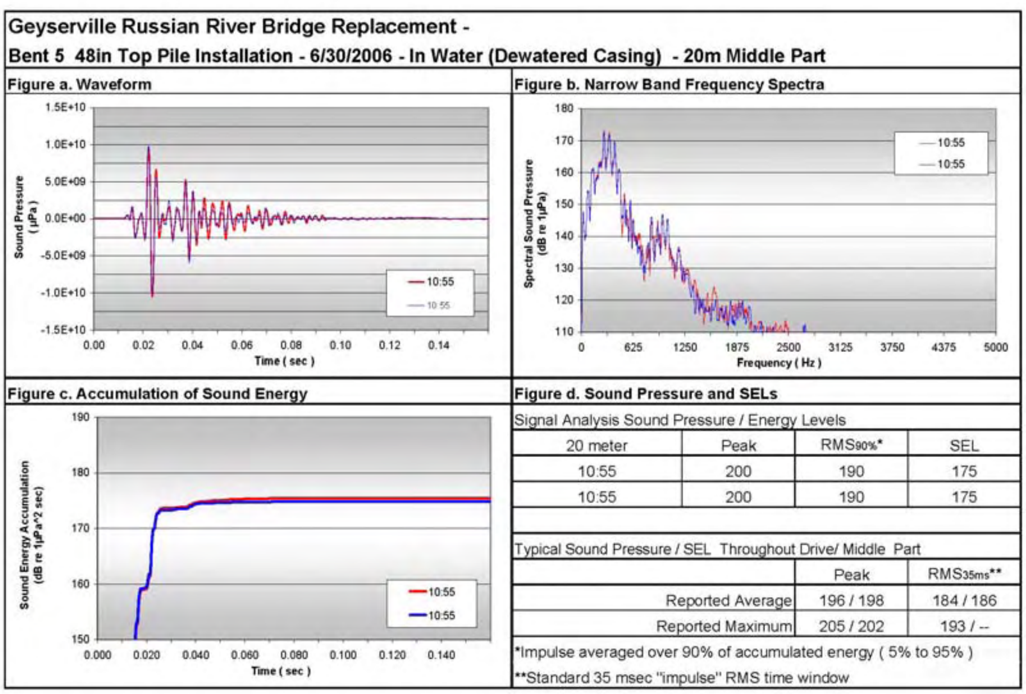


Figure I.3-24 Same as Previous, Except Middle Portion of 48-Inch-Diameter Pile Drive at Geyserville Bridge, Russian River

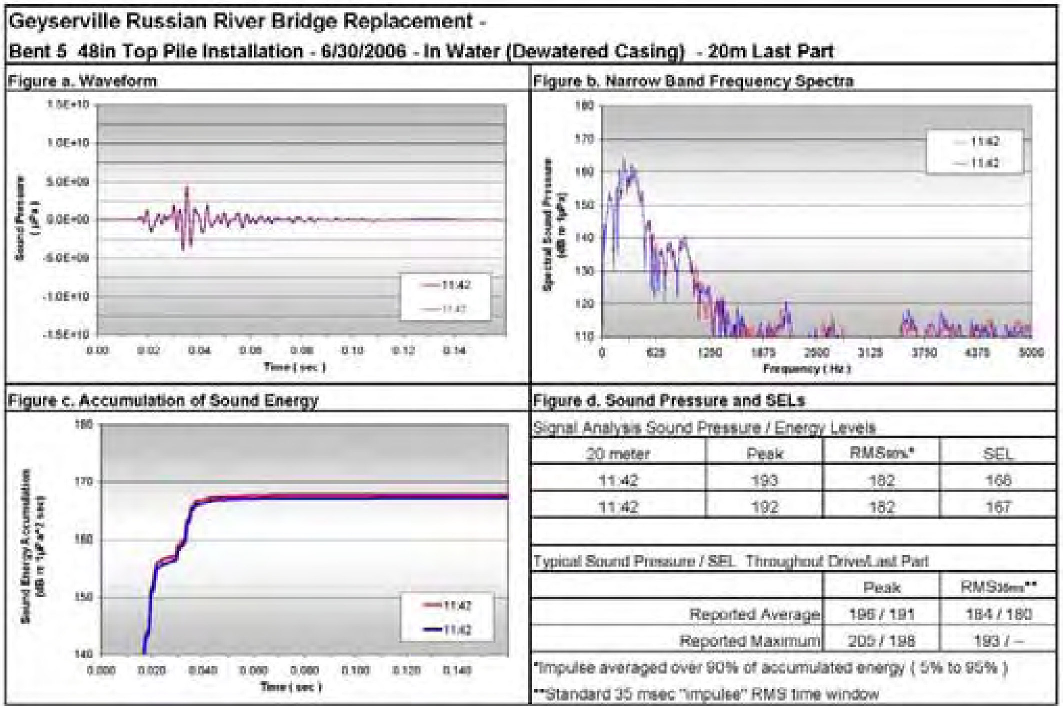


Figure I.3-25 Same as Previous, Except Last Portion of 48-Inch-Diameter Pile Drive at Geyserville Bridge, Russian River

I.3.10 40-Inch-Diameter Steel Piles at Bay Ship and Yacht Dock – Alameda, CA

Measurements were made for about twenty 1-meter- (40-inch-) diameter steel shell piles driven at the Bay Ship and 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 piles 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 kilojoules (221,269 ft-lbs). Figures I.3-26a and I.3-26b show the pile driving operation and air bubble curtain system used to attenuate underwater sound.

Table I.3-17 summarizes the sound levels measured for the 20 different 40-inch piles. Two 30-inch piles also were 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).

Figure I.3-26a Driving 40-Inch-Diameter 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 Summary of Sound Pressures Measured for Driving 40-Inch-Diameter Steel Piles in Water – Bay Ship and Yacht Dock, Alameda, CA

Pile No. and Date	Conditions*	Sound Pressure Levels in dB		
		Peak	RMS	SEL
Piles 1–4, 6/19/2006	Water – impact driver at 10 meters typical maximum levels	201 205	186 188	175 NA
Pile 5, 6/19/2006	Water – impact driver at 10 meters attenuated (air bubble curtain) unattenuated	 194 208	 180 195	 170 180
Pile 6, 6/20/2006	Water – impact driver at 10 meters typical maximum levels	193 200	178 182	NA NA
Piles 7 and 8,** 6/20/2006	Water – impact driver at 10 meters typical maximum levels	198 202	185 187	175 NA
Piles 9–12, 6/21/2006	Water – impact driver at 10 meters typical maximum levels	195 205	182 188	NA NA
Piles 13, 15, and 16, 6/22/2006	Water – impact driver at 10 meters typical maximum levels	200 207	185 190	NA NA
Pile 14, 6/19/2006	Water – impact driver at 10 meters air bubble curtain lowered air bubble curtain raised	 198 208	 187 195	 170 180
Pile 17 + re-strikes, 6/28/2006	Water – impact driver at 10 meters typical maximum levels	199 204	184 189	NA NA
Piles 18–22, 6/29/2006	Water – impact driver at 10 meters typical maximum levels	200 207	187 190	NA 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 (for Pile 13).

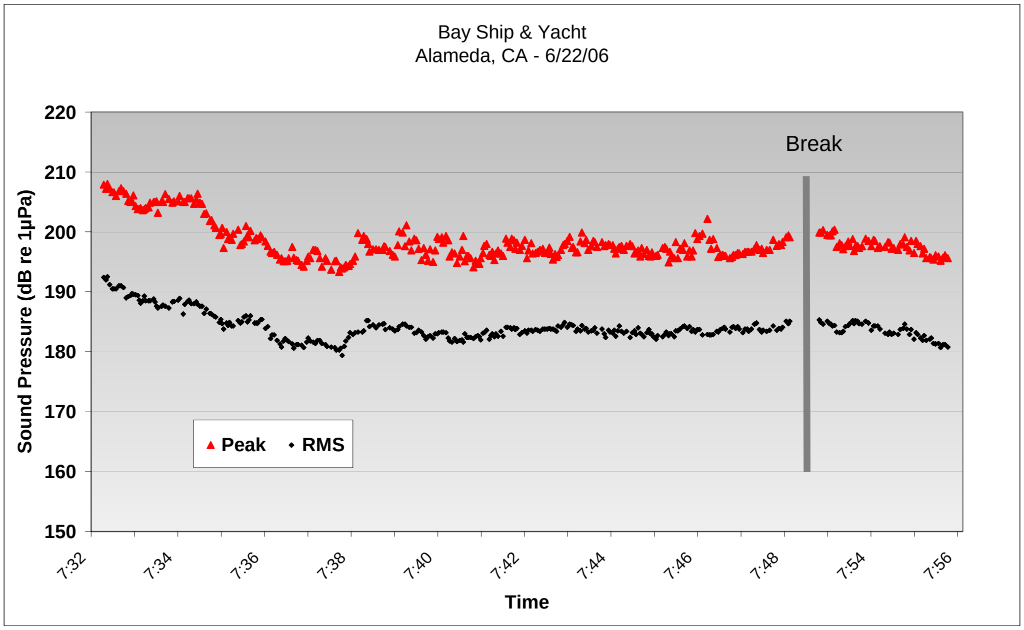


Figure I.3-27 Time History of Pile Driving Event for Pile 13 Where Levels Are Highest When Air Bubble Curtain System Is Raised Slightly above the Bottom – Alameda, CA

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

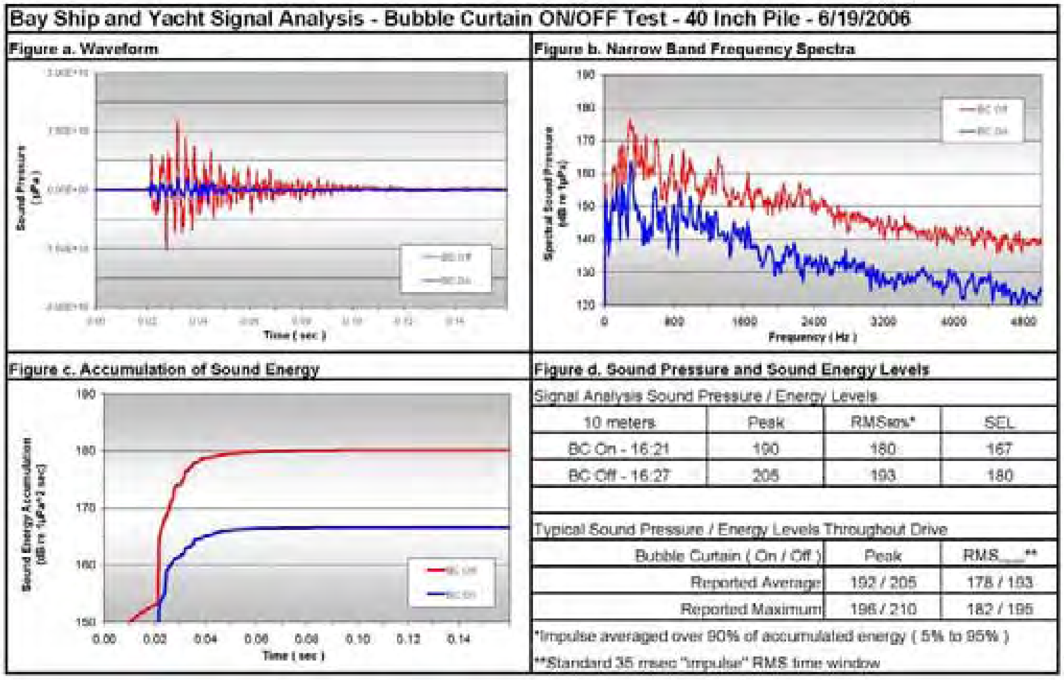


Figure I.3-28 Representative Signal Analyses for 40-Inch-Diameter Piles during Test of Air Bubble Curtain System (On and Off) at Bay Ship and Yacht – Alameda, CA

I.3.11 References

1. Illingworth & Rodkin, Inc. 2002. Point Isabel Foundation Repair El Cerrito, California – Report of Underwater Sound Level Measurements Resulting from Pile Driving. October 24.

2. 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.

3. Illingworth & Rodkin, Inc. 2003. *Letter to Les Shorter reporting Underwater Sound Measurement Results for Sausalito Dock Construction Pile Driving*. Revised April 30, 2003.

4. Illingworth & Rodkin, Inc. 2003. *Letter to Gary Lester (Winzler & Kelly Consulting Engineers) reporting Underwater Sound Measurement Results (7/21/2003) for Mad River Slough Construction Pile Driving*. August 25.

5. Illingworth & Rodkin, Inc. 2003. *Letter to Michael Cheney reporting results of underwater sound measurements – Castrol Pile Installation at Richmond Inner harbor*. November 9.

6. Illingworth & Rodkin, Inc. 2004. *Letter to Roy Neal of Conoco/Phillips from Clayton R. Anderson, reporting the results of underwater sound measurements*. November 9.

7. Illingworth & Rodkin, Inc. 2006. Results of Underwater Sound Measurements for the Construction of Utility Crossing at Stockton Regional Wastewater Control Facility. Report to CH2M Hill dated April 17.

8. Illingworth & Rodkin, Inc. 2005. *Letter to Sharon Lim (Tesoro) reporting results of underwater sound measurements – Amorco Wharf 24-Inch Steel Pipe Pile Installation*. December 21.

9. Illingworth & Rodkin, Inc. 2006. Russian River at Geyserville – Underwater Sound Measurements Data, Driving of Steel Pipe Piles for Construction of a Temporary Trestle. Report to Caltrans District 4 (Chuck Morton), dated June 7.

10. Illingworth & Rodkin, Inc. 2006. Russian River Replacement Bridge at Geyserville – Underwater Sound Measurements Data for Driving Permanent 48-Inch CISS Piles. Report to Caltrans District 4 (Chuck Morton), dated August 3.

11. Illingworth & Rodkin, Inc. 2006. *Letter to Bill Cooke (Manson Construction Co.) reporting results of underwater sound measurements – Impact Driving of 40- and 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, little information is known about the hammer or driving energies used to install these piles. Most of these projects were small, and some involved the measurements only 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-Diameter Steel H-Type Piles for Noyo River Bridge Replacement – Fort Bragg, CA

Temporary H-type 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, California[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 from 1 to 2 meters (3 to 6 feet) outside the channel and from 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 show typical H-type pile installation in water and on land during construction of the temporary trestle.

Figure I.4-1a Impact Driving of On-Shore H-Type Piles

Figure I.4-1b Impact Driving of In-Water H-Type Piles

Measurements were made across the main channel of the harbor at positions ranging from 23 to 85 meters 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. Consequently, 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 Driving Steel H-Type Piles – Noyo River Bridge Replacement, Fort Bragg, CA

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

Underwater levels varied with distance and direction. Sound levels were from 0 to 10 dB higher for piles driven in the water, compared to those driven on shore near the water. The acoustical signals were not analyzed as part of this project; therefore, SELs 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-Diameter H-Type Piles for Sea Wall Construction – San Rafael, CA

Six 10-inch- (0.3-meter-) wide H-type 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-type 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 that 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 Driving 10-Inch-Diameter H-Type Piles – Seawall Construction, San Rafael, CA

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
1	Unattenuated – impact hammer at 10 meters	190	175	
	Unattenuated – impact hammer at 20 meters	170	160	
2–6	Unattenuated – vibratory hammer at 10 meters	161	147	--
	Unattenuated – vibratory hammer at 20 meters	152	137	--

I.4.3 15-Inch-Diameter Steel H-Type Piles in Breakwater Construction at Ballena Isle Marina – Alameda, CA

Several steel H-type piles were driven in open water at the Ballena Isle Marina in Alameda, California[4]. Eight field trips were made from February through early April 2005 to measure the underwater sound from these piles. Extensive measurements were conducted because 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-type piles that were battered and ~15-inch thick-walled H-type piles that were driven vertically. Water depth was about 2 to 3 meters. Measurements were made at 10 meters and 1 meter 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-Type Pile with Attenuation System, with Vertical Thin-Walled H-Type Piles in Foreground

Figure I.4-2b Close-View of Confined Air Bubble Attenuation System next to Vertical H-Type 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 period by turning the air delivery off during the driving of a vertical pile. Supplemental measurements for short 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 Driving 15-Inch-Diameter Steel H-Type Piles – Ballena Isle Marina, Alameda, CA

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
Battered – air bubble curtain OFF	Unattenuated – impact hammer at 10 meters	187	164	154
Battered – air bubble curtain ON	Attenuated – 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-Walled H-Type Piles

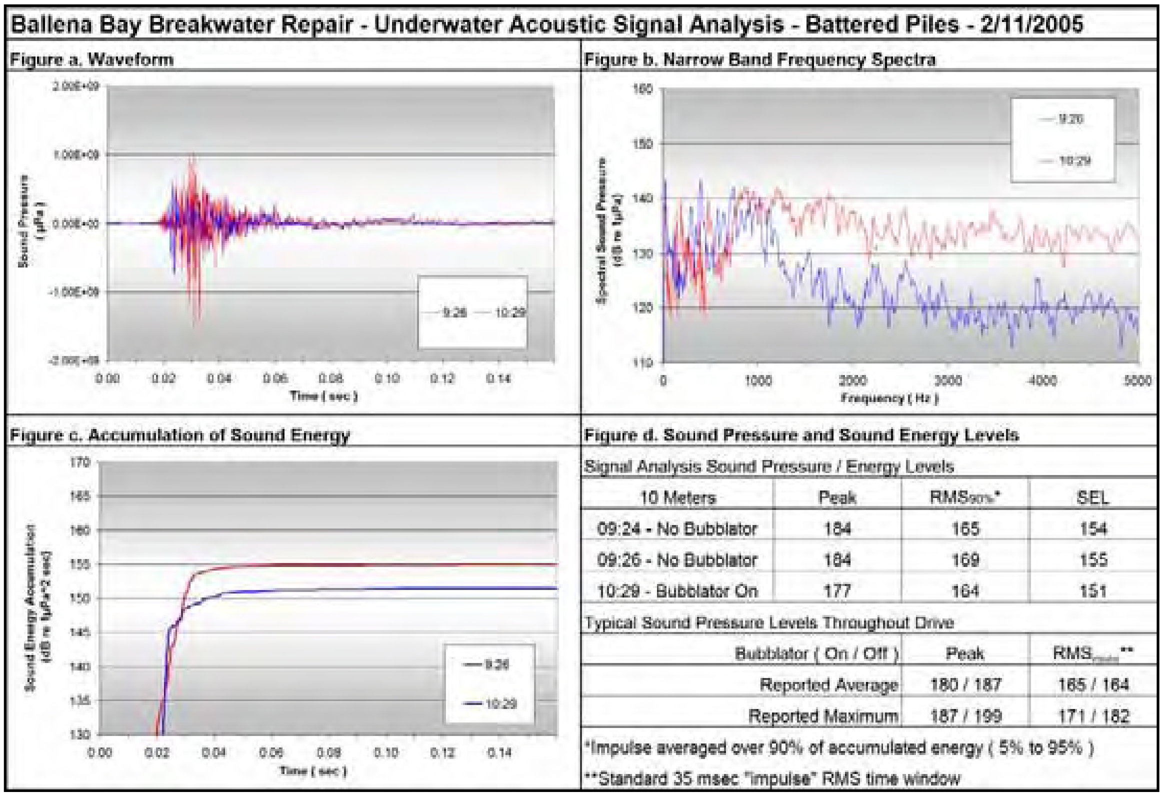
At 10 meters, and with no attenuation system, average peak sound pressures were 187 dB, with a maximum peak of 199 dB. Average RMS sound pressures were 164 dB, with a maximum of 182 dB. The typical SEL was 154 dB. The attenuation system was tested on the first day for a short period. The system appeared 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-walled H-type piles were measured with the attenuation system working. The levels reported in Table I.4-4 are the typical highest levels measured. 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 to 20 minutes. The piles were driven with a diesel impact hammer that struck the piles about once every 1.5 seconds.

Vertical Thick-Walled H-Type Piles

At 10 meters, typical peak sound pressures were 195 dB for the thick-walled vertical H-type 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 was 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 in Figure I.4-4 for a vertical thick-walled pile. Note that H-type 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 effect 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.



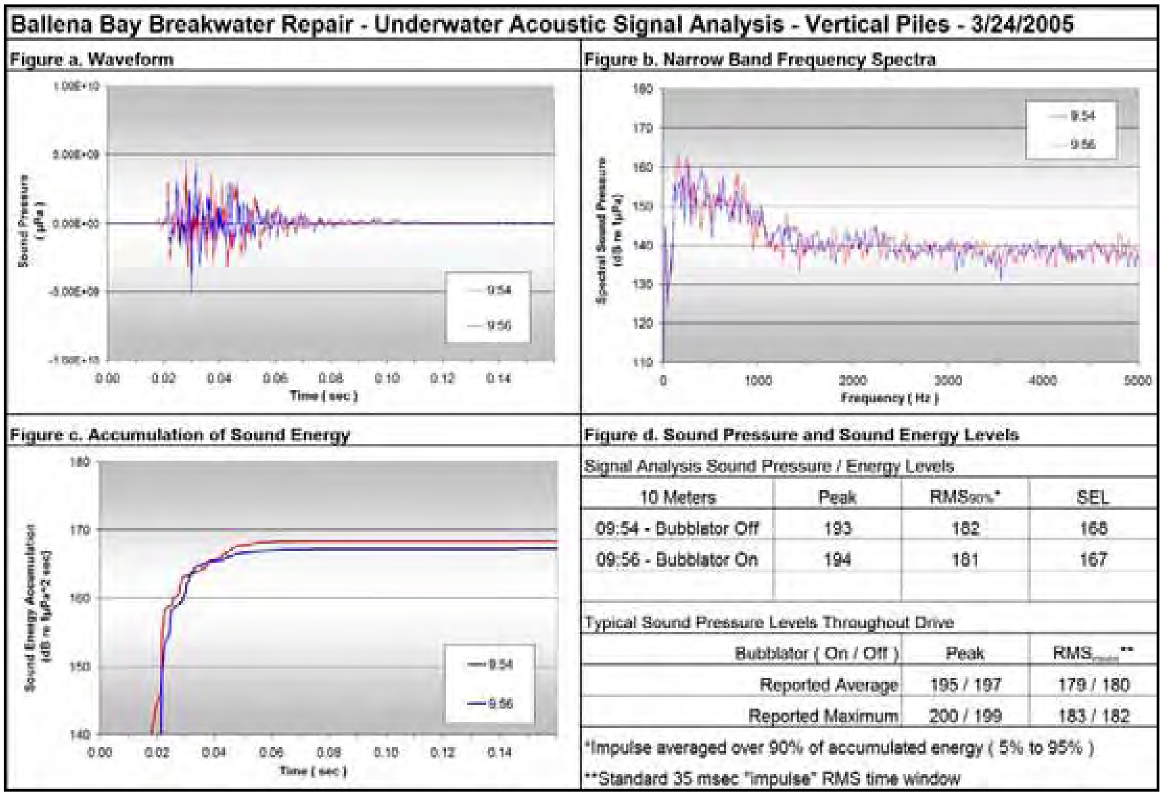
Signal Analysis Sound Pressure / Energy Levels			
10 Meters	Peak	RMS90%*	SEL
09:24 - No Bubblator	184	165	154
09:26 - No Bubblator	184	169	155
10:29 - Bubblator On	177	164	151

Typical Sound Pressure Levels Throughout Drive		
Bubblator (On / Off)	Peak	RMS**
Reported Average	180 / 187	165 / 164
Reported Maximum	187 / 199	171 / 182

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

**Standard 35 msec "impulse" RMS time window

Figure I.4-3 Representative Signal Analyses for Battered H-Type Piles with and without Air Bubble Curtain Attenuation System at Ballena Bay in Alameda, CA



Signal Analysis Sound Pressure / Energy Levels

10 Meters	Peak	RMS90%*	SEL
09:54 - Bubblator Off	193	182	168
09:56 - Bubblator On	194	181	167

Typical Sound Pressure Levels Throughout Drive

Bubblator (On / Off)	Peak	RMSimpulse**
Reported Average	195 / 197	179 / 180
Reported Maximum	200 / 199	183 / 182

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

**Standard 35 msec "impulse" RMS time window

Figure I.4-4 Representative Signal Analyses for Vertical H-Type Piles with and without the Air Bubble Curtain Attenuation System at Ballena Bay in Alameda, CA

I.4.4 Thick-Walled Steel H-Type Piles for Interstate 80 Platte River Bridge Pile Driving – Platte River, NB

The driving of three permanent steel thick-walled H-type 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 show the cofferdam and pile driving operation.

 **Figure I.4-5a H-Type Pile Driving at the Platte River in Nebraska**	 **Figure I.4-5b Dewatered Cofferdam Excavated below Water Level**

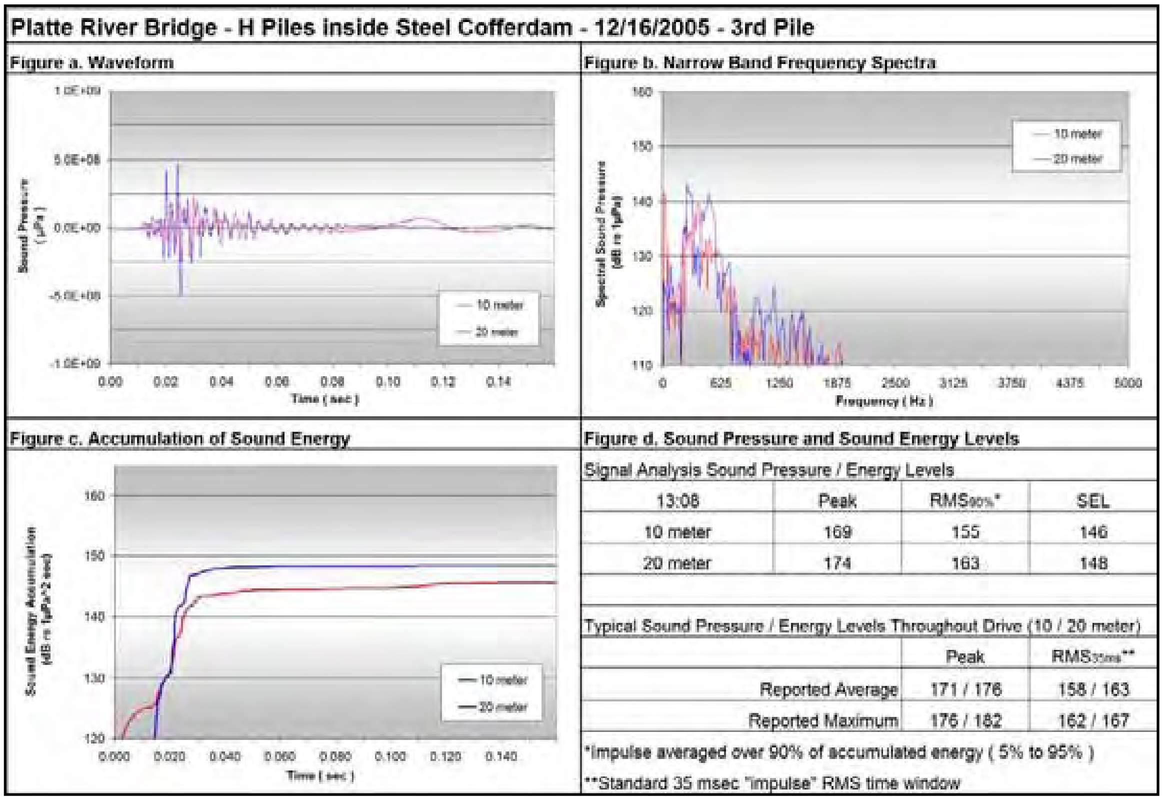
Underwater sound measurements were made at 10 and 20 meters during driving of the three different piles (see Table I.4-4). The average peak pressure at 10 meters was 172 dB, and the highest was 180 dB. Average and maximum RMS levels were 160 and 168 dB, respectively. The representative SEL was 147 dB. Higher sound pressures were measured farther 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 from 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 Driving Steel H-Type Piles – Platte River Bridge, Platte River, NB

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
1–3	Dewatered cofferdam – impact hammer at 10 meters	172	160	147
2 and 3	Dewatered cofferdam – impact hammer at 25 meters	177	164	148

The probable cause for measured levels to be higher at 25 meters from the pile than at 10 meters is shielding from the excavated cofferdam. The 10-meter position was much closer to the excavated cofferdam than the 25-meter 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) indicate 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.



Signal Analysis Sound Pressure / Energy Levels

13:08	Peak	RMS90%*	SEL
10 meter	169	155	146
20 meter	174	163	148

Typical Sound Pressure / Energy Levels Throughout Drive (10 / 20 meter)

	Peak	RMS35ms**
Reported Average	171 / 176	158 / 163
Reported Maximum	176 / 182	162 / 167

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

**Standard 35 msec "impulse" RMS time window

Figure I.4-6 Representative Signal Analyses for H-Type Piles Driven in the Platte River, Nebraska

I.4.5 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 meter (12 to 24 inches) 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 of the bottom of the pile to help penetrate dense sand layers. Sound pressures associated with concrete piles are much lower than comparably 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 at Concord Naval Weapons Station – Concord, CA

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 driving 16-inch square, 25-meter- (80-foot-) long concrete piles. A Vulcan 016 (65 kiloJoule [48,000 ft.-lb.]) steam-powered drop hammer was used to drive the first two piles (Piles 108 and 107). A Conmaco 200 (80 kiloJoule [60,000 ft.-lb.]) steam drop hammer was used to drive the last three piles (Piles 103, 105, and 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.

Figure I.5-1a Driving of 16-Inch-Square Piles

Figure I.5-1b Simple Air Bubble Curtain System Used to Attenuate Noise

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.

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

		Sound Pressure Levels Measured at 10 Meters		
Pile	**Conditions**	**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	--

Permit conditions for the project required 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 10:00 a.m. when the tide was slack and currents were light. Sound pressures varied considerably 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.

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 msec. 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.

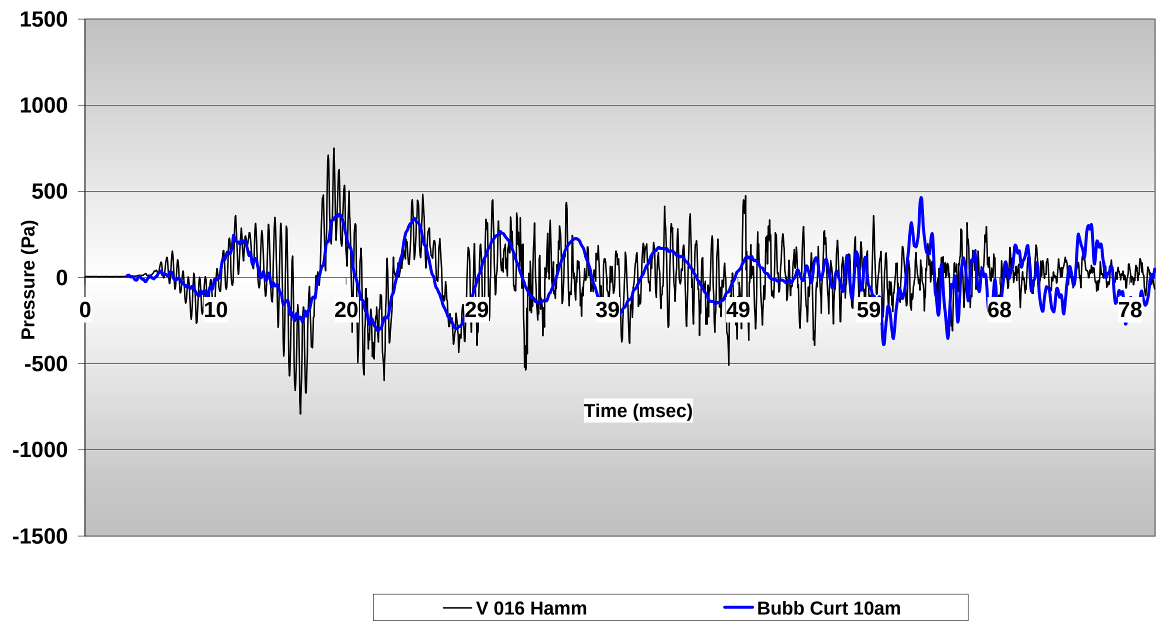


Figure I.5-2 Time History Analysis of Unattenuated and Attenuated Pile Strikes over an 8-Millisecond Period. Note initial low-frequency sounds followed by lower amplitude but higher frequency sounds. An air bubble curtain reduced the high-frequency content of these pulses.

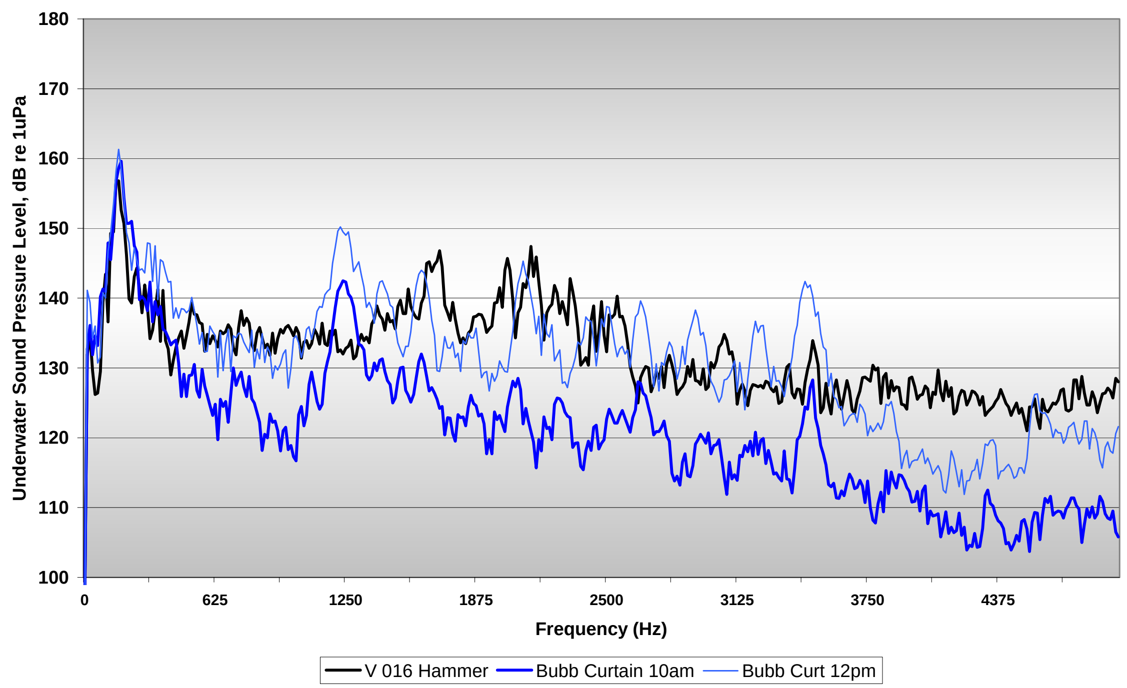


Figure I.5-3 Narrow Band Frequency Spectra for Pile Driving with Different Hammers and Bubble Curtain Conditions. Note that the bubble curtain at 10:00 a.m. was most effective when there was no effect from swift currents due to a slack tide condition.

I.5.2 24-Inch Octagonal Concrete Piles for Amports Pier 95 – Benicia, CA

Underwater sound levels were measured at Benicia, California on February 27, March 12, and March 19, 2003. The project involved driving 24-inch, octagonal, 125-foot-long concrete piles. The piles were driven vertically using a Del-Mag D66-22 diesel. Set on a maximum fuel setting, the hammer delivered a maximum impact energy of 220 kilojoules (165,000 ft-lbs). During the March 12 sound tests, the hammer was set on a lower fuel setting and delivered an impact energy of about 50 percent of maximum energy. The piles are located in rows parallel to the shore and are designated A–H. Monitoring was completed for piles in rows B and C. The piles located in row C were generally in shallower water than those in row B due to the slope of the bottom. Water depth at the piles was typically from 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, or "Bubbleator." The confined air bubble curtain 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 (Bubbleator) used for the project.

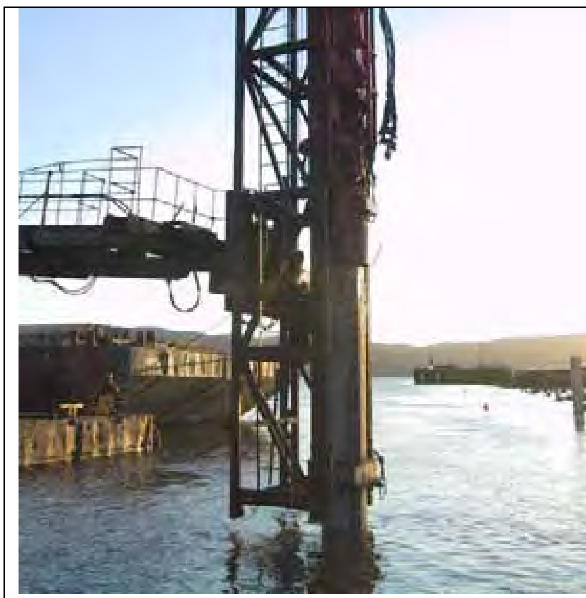


Figure I.5-4a 24-Inch Octagonal Piles Driven at Amports in Benicia, CA

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 from 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 Driving Octagonal Concrete Piles – Amports Pier, Benicia, CA

Date	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
Feb 27	Unattenuated – Row C no confined air bubble curtain – 10 meters	183 typ. 192 max	170 typ. 172 max	--
Feb 28	Attenuated – Row C with short confined air bubble curtain ON – 10 meters	165 typ. 175 max	152 typ. 162 max	--
Feb 28	Unattenuated – same as above, but confined air bubble curtain OFF	185	170	--
Mar 12	Attenuated – Row C with short confined air bubble curtain ON – 10 meters	~185	~172	--
Mar 12	Attenuated – Row C with short confined air bubble curtain ON – 20 meters	~179	~168	--
Mar 12	Unattenuated – Row C with short confined air bubble curtain ON – 10 meters	~192	~176	--
Mar 12	Unattenuated – Row C with short confined air bubble curtain ON – 20 meters	~186	~171	--
Mar 19	Attenuated – Row B with long confined air bubble curtain ON – 10 meters	172 typ. 181 max	157 typ. 167 max	--
Mar 19	Attenuated – Row B with long confined air bubble curtain ON – 20 meters	170 typ. 178 max	155 typ. 162 max	--
Mar 19	Attenuated – Row C with long confined air bubble curtain ON – 10 meters	162 typ. 167 max	145 typ. 150 max	--
Mar 19	Attenuated – Row C with long confined air bubble curtain 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 from 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 periods of subsequent drives where the attenuation system was turned on and off for testing. Measurements also were taken 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 taken 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 were 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 be reduced only by 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 ~24-Inch Diameter Concrete Piles at Pier 40 Marina Construction – San Francisco, CA

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

Figure I.5-5 24-Inch-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 meters from the pile in different directions were quite similar, indicating little variation in the radiation pattern near the pile. Sound pressures measured at 20 meters from the pile ranged from about 5 to over 10 dB lower than the 10-meter 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 Driving Square Concrete Piles – Pier 40, San Francisco, CA

Pile	Conditions	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 10 meters west	180	167	--
P-SS-29	Unattenuated – measured 10 meters 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	--
P-NS-25	Unattenuated – hammer on lowest fuel setting no jetting	186	173	--

I.5.4 24-Inch Octagonal Concrete Piles at Berth 22 – Port of Oakland, CA

Several 24-inch octagonal concrete piles were driven at the Port of Oakland in August 2004 and December 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, which 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]. Results of the measured sound levels are presented in Table I.5-4. 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 at a depth of 3 meters. 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 15 meters of water. Row A was in the deepest water, and Row E was at the shore. The typical duration of driving time per pile was about 15 to 30 minutes.

Figure I.5-6 Driving of 24-Inch 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 taken 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. Measurements are summarized in Table I.5-4.

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

Pile	Conditions	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

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 levels for Row A or B. In Row D, which was closest, the average and maximum sound levels were 191 and 193 dB peak and 179 and 181 dB RMS, respectively. In Row E, the average and maximum sound levels were 190 and 196 dB peak and 178 and 186 dB RMS, respectively.

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, respectively. In Row B, the average and maximum sound levels were 179 and 184 dB peak and 168 and 173 dB RMS, respectively. In Row C, the average and maximum sound levels were 181 and

185 dB peak and 169 and 171 dB RMS, respectively. In Row D, the average and maximum sound levels were 189 and 195 dB peak and 177 and 182 dB RMS, respectively. 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 exist.

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.

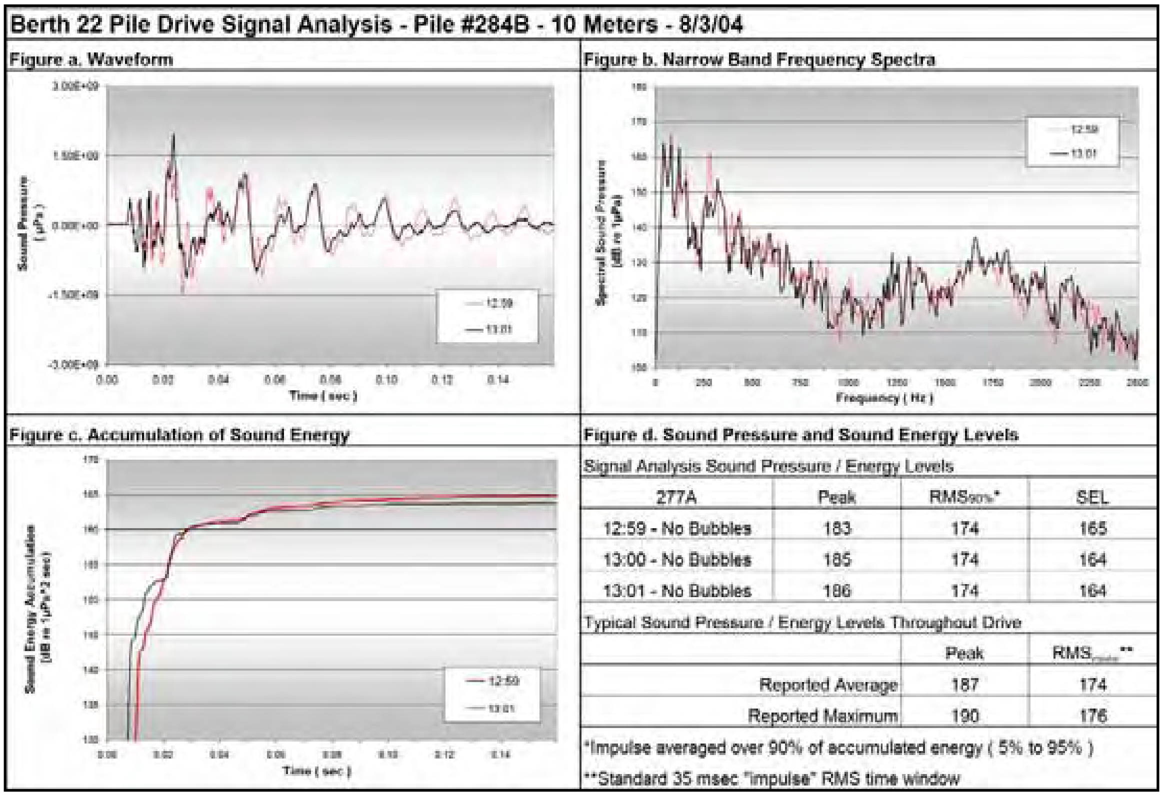


Figure I.5-7 Representative Signal Analyses for Two Pulses Associated with a 24-Inch Concrete Pile. Piles driven without attenuation system at Berth 22, Port of Oakland, CA during fish exposure study.

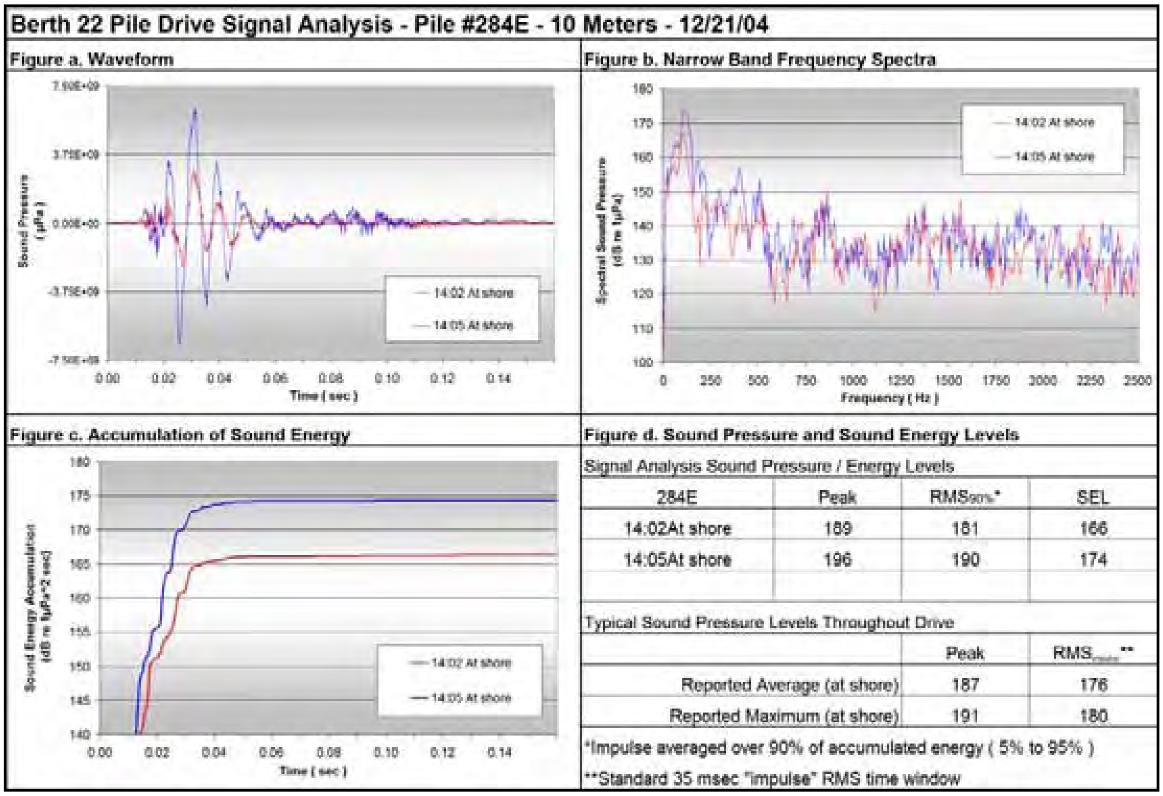
I.5.5 24-Inch Octagonal Concrete Piles Driven 0n Land Adjacent to Water at Berth 22 – Port of Oakland, CA

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, an engineered steep bank was 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. Measurements for Row E piles are summarized in Table I.5-5.

Table I.5-5 Summary of Sound Pressures Measured for Driving Octagonal Concrete Piles on Land Adjacent to Water – Berth 22, Port of Oakland, CA

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
Row E	First pile – 15 meters	190	180	NA
Row E	First pile – 25 meters	190	180	NA
Row E	First pile – 55 meters	176	165	NA
Row E	Second pile – 10 meters	192	180	170
Row E	Second pile – 25 meters	190	180	NA
Row E	Second pile – 35 meters	184	171	NA
Row E	Third pile – 10 meters	195	185	174
Row E	Third pile – 20 meters	189	178	NA
Row E	Third pile – 55 meters	180	170	NA
Row E	Fourth pile – 15 meters	188	178	NA
Row E	Fourth pile – 25 meters	187	175	NA
Row E	Fourth pile – 85 meters	175	164	NA

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.



284E	Peak	RMS90%*	SEL
14:02At shore	189	181	166
14:05At shore	196	190	174

Typical Sound Pressure Levels Throughout Drive

	Peak	RMS**
Reported Average (at shore)	187	176
Reported Maximum (at shore)	191	180

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

**Standard 35 msec "impulse" RMS time window

Figure I.5-8 Representative Signal Analyses 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 during Underwater Noise Monitoring for Fish Cage Study at Berth 22 – Port of Oakland, CA

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 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 Berth 22, Port of Oakland. Picture was 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.5-6. 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.5-6 Summary of Sound Pressures Measured for Driving Octagonal Concrete Piles – Berth 22, Port of Oakland, CA

Pile	Conditions	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 during Underwater Noise Monitoring at Berth 32 – Port of Oakland,CA

In September 2004, five 24-inch octagonal concrete piles were driven at Berth 32 at the Port of Oakland in 1 day. 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 kilojoules of energy on each blow. Attenuation systems were not used during these measurements.

Figure I.5-10 Driving of 24-Inch Octagonal Piles at Berth 32, Port of Oakland, CA

The piles were driven in water that was over 10 meters deep, and measurements were taken at a distance of 10 meters at 3 meters deep. The sound pressure data summarized in Table I.5-7 indicate generally consistent 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.5-7 Summary of Sound Pressures Measured for Driving Octagonal Concrete Piles – Berth 32, Port of Oakland, CA

Pile	Conditions	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 driving of 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.

Berth 32 Pile Drive Signal Analysis - 3rd Pile 14:26, Sept 27, 2004

Figure a. Waveform

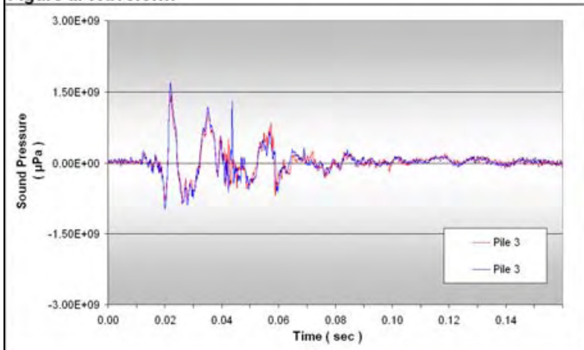


Figure b. Narrow Band Frequency Spectra

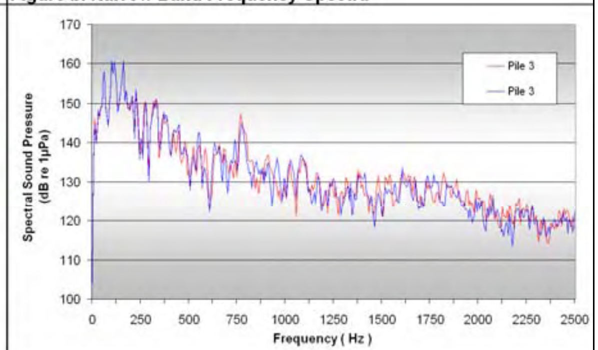


Figure c. Accumulation of Sound Energy

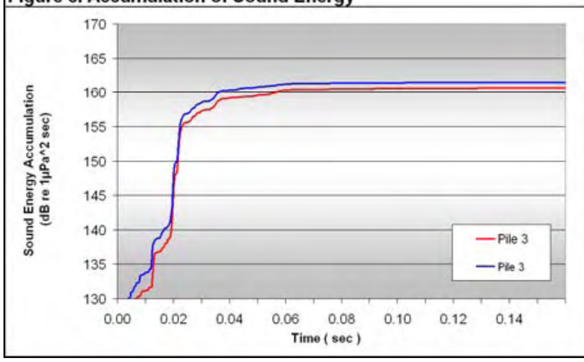


Figure d. Sound Pressure and Sound Energy Levels

Signal Analysis Sound Pressure / Energy Levels			
- 14:26:00	Peak	RMS90%*	SEL
Pulse #1	183	173	161
Pulse #2	185	175	161

Typical Sound Pressure / Energy Levels Throughout Drive		
	Peak	RMS impulse**
Reported Average	184	174
Reported Maximum	189	181

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

**Standard 35 msec "impulse" RMS time window

Figure I.5-11 Representative Signal Analyses 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 at Berth 32 – Port of Oakland, CA

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 also was used to drive these five piles. Measurements were made at 10 meters from the pile, 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.

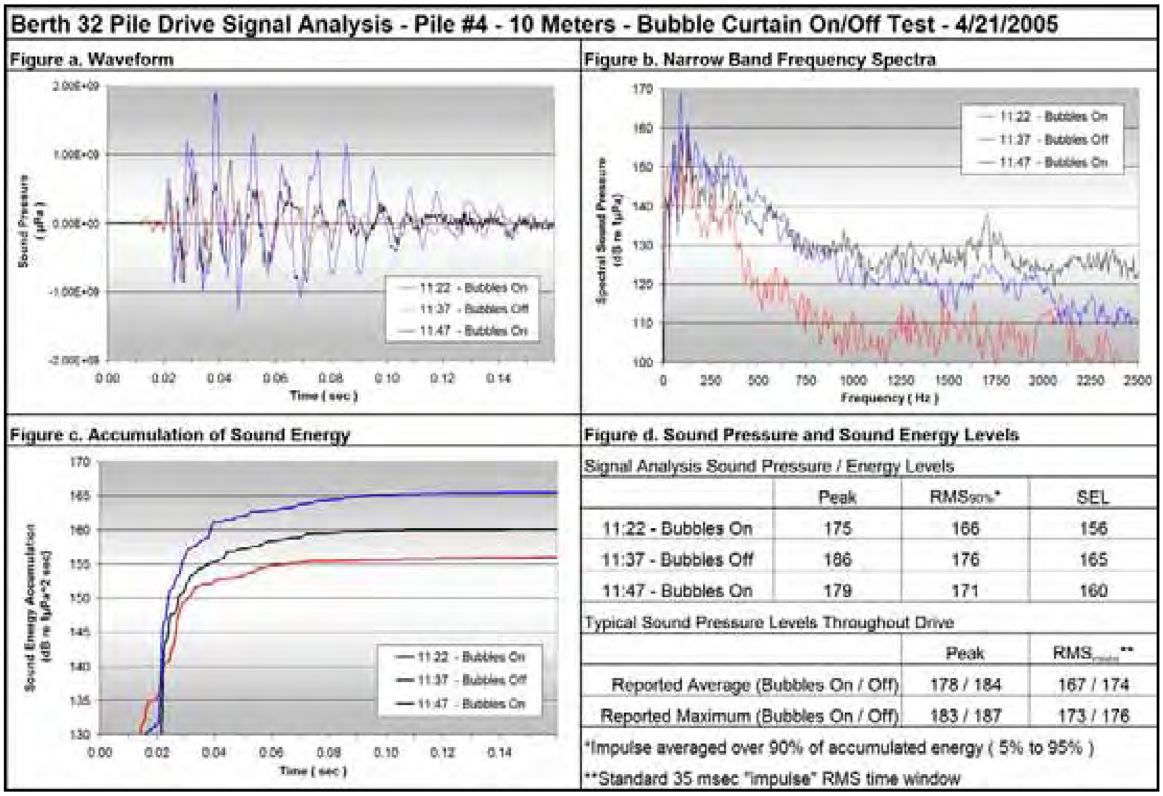
Figure I.5-12 Driving of 24-Inch Octagonal Piles at Berth 32, Port of Oakland with an Air Bubble Curtain System to Attenuate Sounds

Results from the driving of five piles are summarized in Table I.5-8. 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 Pile 5. Analysis of the data indicates that the variation may have been attributable to the air bubble curtain performance.

Table I.5-8 Summary of Sound Pressures Measured for Driving Octagonal Concrete Piles – Berth 32, Oakland, CA

		Sound Pressure Measured at 10 Meters		
Pile	**Conditions**	**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, about 10 dB of attenuation occurred 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.



Signal Analysis Sound Pressure / Energy Levels

	Peak	RMS90%*	SEL
11:22 - Bubbles On	175	166	156
11:37 - Bubbles Off	186	176	165
11:47 - Bubbles On	179	171	160

Typical Sound Pressure Levels Throughout Drive

	Peak	RMS**
Reported Average (Bubbles On / Off)	178 / 184	167 / 174
Reported Maximum (Bubbles On / Off)	183 / 187	173 / 176

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

**Standard 35 msec "impulse" RMS time window

Figure I.5-13 Representative Signal Analyses 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.

1.5.9 References

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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.

5. Illingworth & Rodkin, Inc. 2005. Port of Oakland Berth 22 Underwater Sound Measurement Data for the Driving of Octagonal Concrete Piles, August 2, 2004 – February 14, 2005. Report to Manson Construction dated April 4, 2005.

6. Strategic Environmental Consulting (SEC). 2005. Monitoring the Effects of Conventional Pile Driving on Three Species of Fish. April 8, 2005.

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 and 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 (0.6 meter) wide and range in length. They are commonly used to construct walls and cofferdams in marine environments. These piles usually are 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. Little information is 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 at Berth 23 – Port of Oakland, CA

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, California[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 then were 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 the underwater sound measurements made for driving five 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 5 to 40 meters but primarily at 10 meters. 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 10 meters 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 second pile, 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 10 meters and 166 dB at 20 meters. Measurements for the third, fourth, and fifth piles were made with the boat tied to the dockside in order to maintain a distance of 10 meters from the pile. In addition to the 10-meter position, a 20-meter position was added for driving of the fourth and fifth piles. These positions were along the sheet pile wall, not normal to the face of the pile as was done for the first and second pile driving events. A fairly steady peak pressure of 202 to 205 dB was measured at the 10-meter position. RMS levels were generally from 186 to 188 dB, and the SEL was about 175 dB. The fourth pile, driven from 14:20 to 14:33, was measured simultaneously from the dockside at positions of 10 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 to 210 dB. In terms of peak pressure, levels were highest for the fifth driving event, 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 Driving Steel Sheet Piles – Berth 23, Port of Oakland, CA

Pile	Conditions	Average Sound Pressure Measured in dB		
		Peak	**RMS**	**SEL**
1	10 meters normal to the sheet face	205	189	178
2	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	--	--
3	10 meters parallel to the sheet face	203	187	175
4	10 meters parallel to the sheet face	203	188	178
	20 meters parallel to the sheet face*	205	186	175
5	10 meters parallel to the sheet face	205	189	179
	20 meters parallel to the sheet face*	202	189	178

- Measurements made only 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 to 20 meters. The drop-off rate from 20 to 40 meters was over 10 dB. Measurements were made only at 10 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, compared to other impact pile driving pulses. The example shown in Figure I.6-2 is for pulses measured at 10 and 20 meters during the installation of the fourth sheet pile. The RMS impulse level (measured with the sound level meter) was similar or slightly lower than the calculated RMS (over 90 percent 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 percent). The majority of sound energy in the pulse was contained within the first 30 to 40 msec, but the pulse lasted over 100 msec. 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.

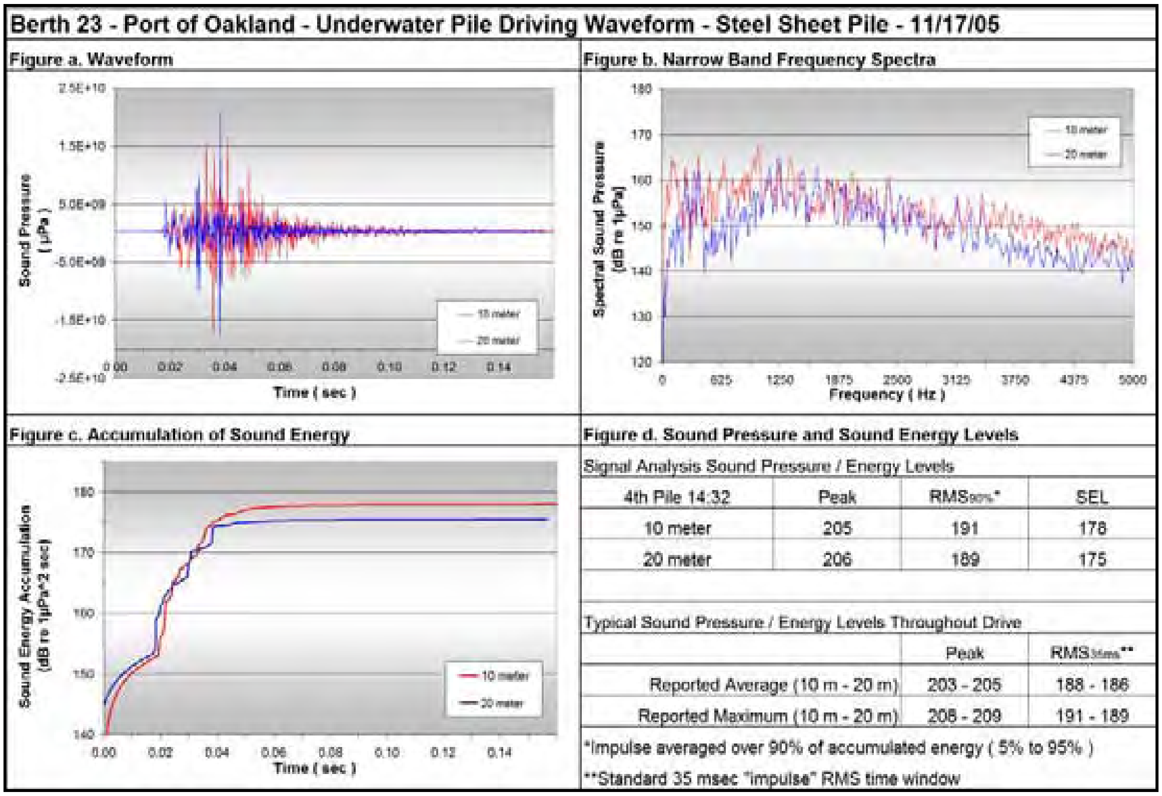


Figure I.6-2 Representative Signal Analyses for Sheet Piles Driven with Impact Hammer at Berth 23, Port of Oakland. Pulses received at 10 and 20 meters parallel to sheet wall.

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 period of 0.035 second 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 defined as either the entire duration of the sound or a fixed time. Using the duration of the event would not provide data that could be compared to other pile driving events. Therefore, we present the SEL as measured over 1 continuous second of vibratory pile installation.

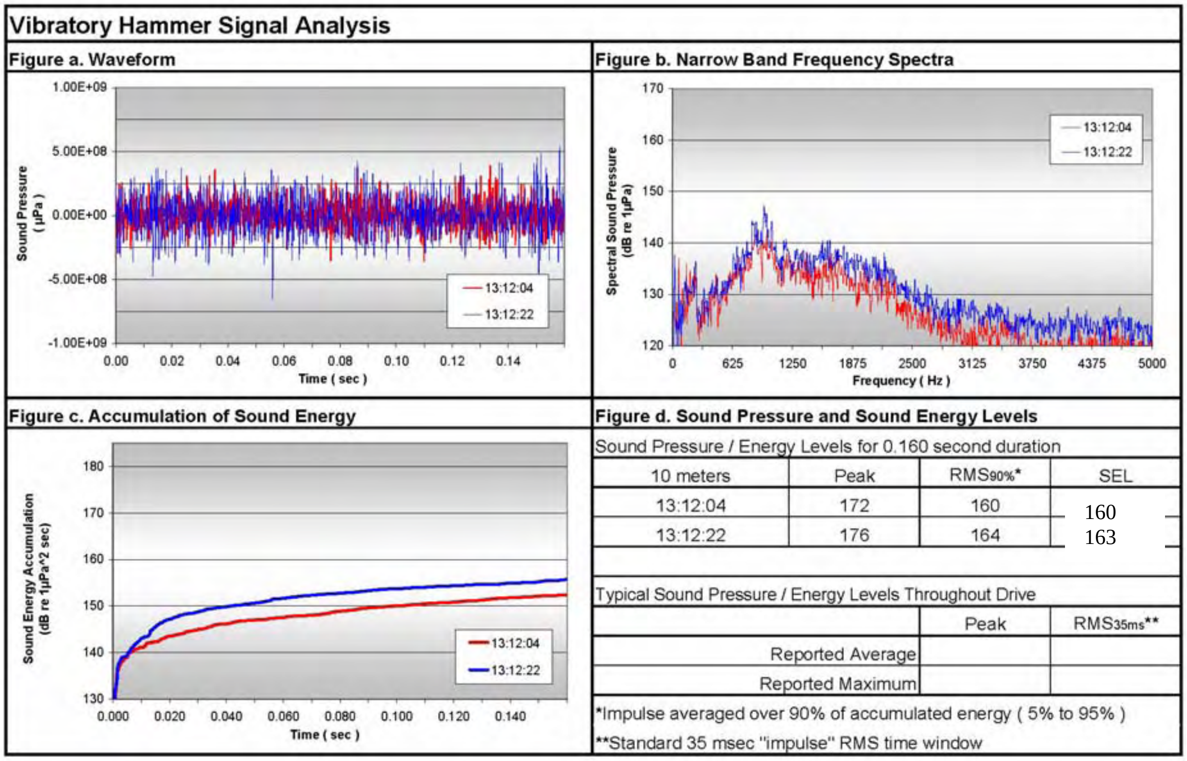


Figure I.6-3 Representative Signal Analyses for Sheet Piles Installed with Vibratory Driver/ Extractor at Berth 23, Port of Oakland. Pulses at 10 meters normal to sheet wall face.

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 at Berth 30 – Port of Oakland, CA

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 was tested involving a vibratory driver/extractor to avoid high-amplitude sounds. 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 driving of the piles below the water line. Pile lengths were about 15 meters, and water depth was about 12 meters.

Measured sound pressure data for the installation of five 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 with 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 sensors 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 Vibratory Driving of Steel Sheet Piles – Berth 30, Port of Oakland, CA

Pile	Conditions	Average Sound Pressure Measured at 10 meters in dB		
		Peak	RMS	SEL
1	10 meters from face, 3-meter depth	175 185 max	--*	160 165 max
2	10 meters from face, 3-meter depth	171	--*	159
	10 meters from face, 5-meter depth	172	--*	160
3	10 meters from face, 3-meter depth	166	--*	154
	10 meters from face, 5-meter depth	172	--*	160
4	10 meters from face, 3-meter depth	167	--*	155
	10 meters from face, 5-meter depth	174	--*	162
5	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 second, third, fourth, and fifth 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 (National Oceanic and Atmospheric Administration required position) were 165 to 175 dB. One second SELs were typically 12 dB lower than peak pressures and typically ranged from 155 to 162 dB, depending on the pile and sensor position. Pile installation ranged from 5 to 18 minutes. The first four piles took from 5 to 10 minutes to install, while the fifth 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 signals 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.

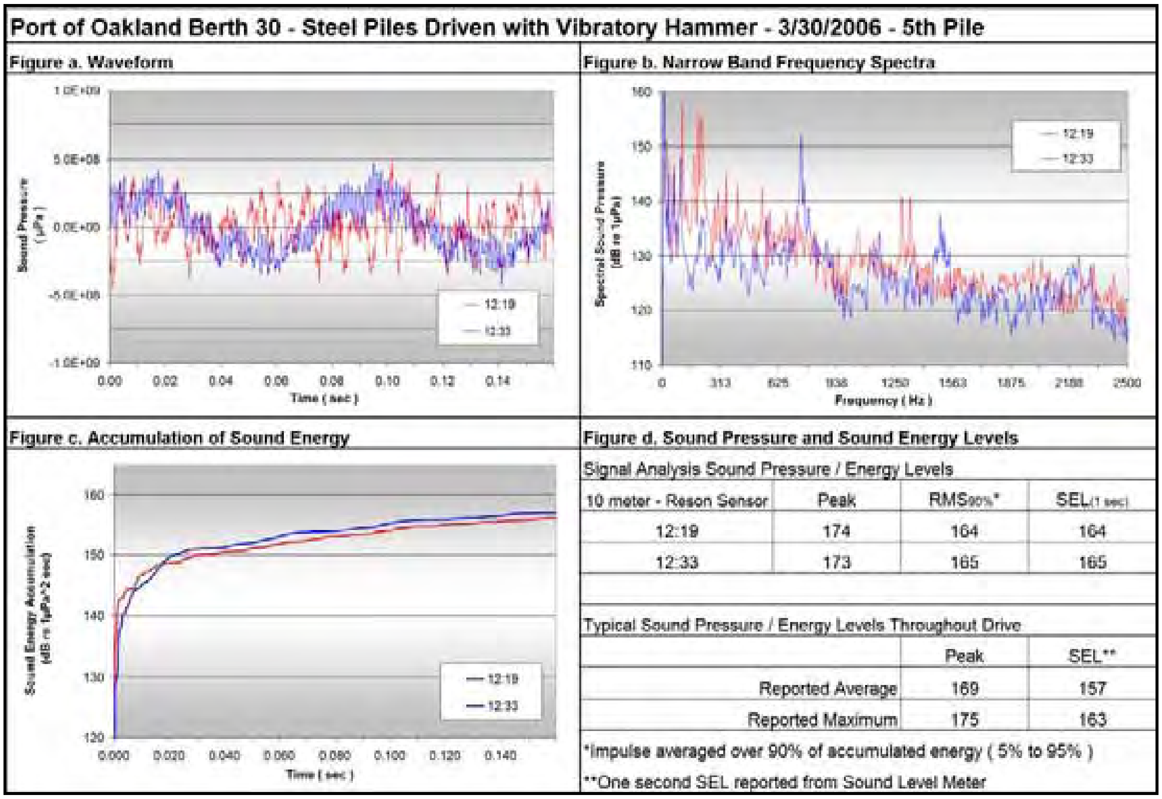


Figure I.6-4 Representative Signal Analyses for Sheet Piles Installed with Vibratory Driver/Extractor at Berth 30, Port of Oakland. Pulses at 10 meters normal to sheet wall face. Note low-frequency signal (blue) measured late in driving event.

I.6.3 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 and 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.

3. Illingworth & Rodkin, Inc. 2006. Port of Oakland Berth 30 – Underwater Sound Measurements for the Installation of Steel Sheet Piles with a Hydraulic Vibratory Hammer. Report to the Port of Oakland, dated May 8, 2006.

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 Construction at Ballena Bay Marina – Alameda, CA

Underwater sound pressure levels were measured for driving 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.

Table I.7-1 summarizes results of the underwater sound measurements made for driving the four 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 ranges of sound levels were reported, since these typically varied by 10 dB or more.

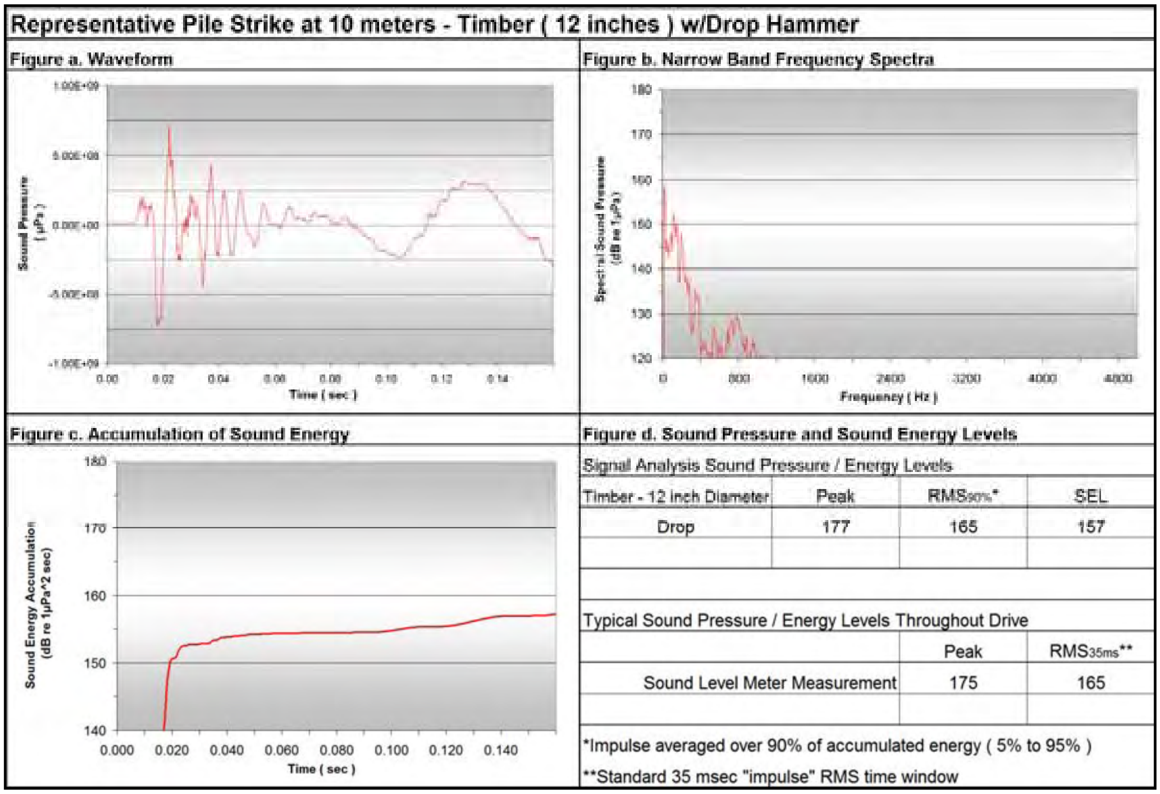
At 10 meters, peak sound pressures were generally in the range of 170 to 180 dB, and RMS sound pressure levels ranged from 160 to 168 dB. During some short periods, sound pressures exceeded 180 dB peak and 170 dB RMS at 10 meters. The highest measured levels were 191 dB peak and 176 dB RMS. Sound pressures 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.

Figure I.7-1 Driving of Timber Piles at Ballena Bay Marina Using a 3,000-Pound Drop Hammer

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

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

Signal analysis of representative pulses indicates considerable low-frequency content, compared to other impact pile driving pulses. The example shown in Figure I.7-2 is for a pulse measured at 10 meters during installation of the fourth pile. The sounds are comprised of low-frequency content and appear to include very low frequency ground-borne sound reflection that is 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.



Signal Analysis Sound Pressure / Energy Levels			
Timber - 12 inch Diameter	Peak	RMS90%*	SEL
Drop	177	165	157
Typical Sound Pressure / Energy Levels Throughout Drive			
		Peak	RMS35ms**
Sound Level Meter Measurement		175	165

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

**Standard 35 msec "impulse" RMS time window

Figure I.7-2 Representative Signal Analyses for Timber Pile Driven with a Drop Hammer at Ballena Bay Marina. Pulse received at 10 meters from the pile.

I.7.2 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 driving 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 (420,410 ft-lbs). 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 (8 feet) in diameter.

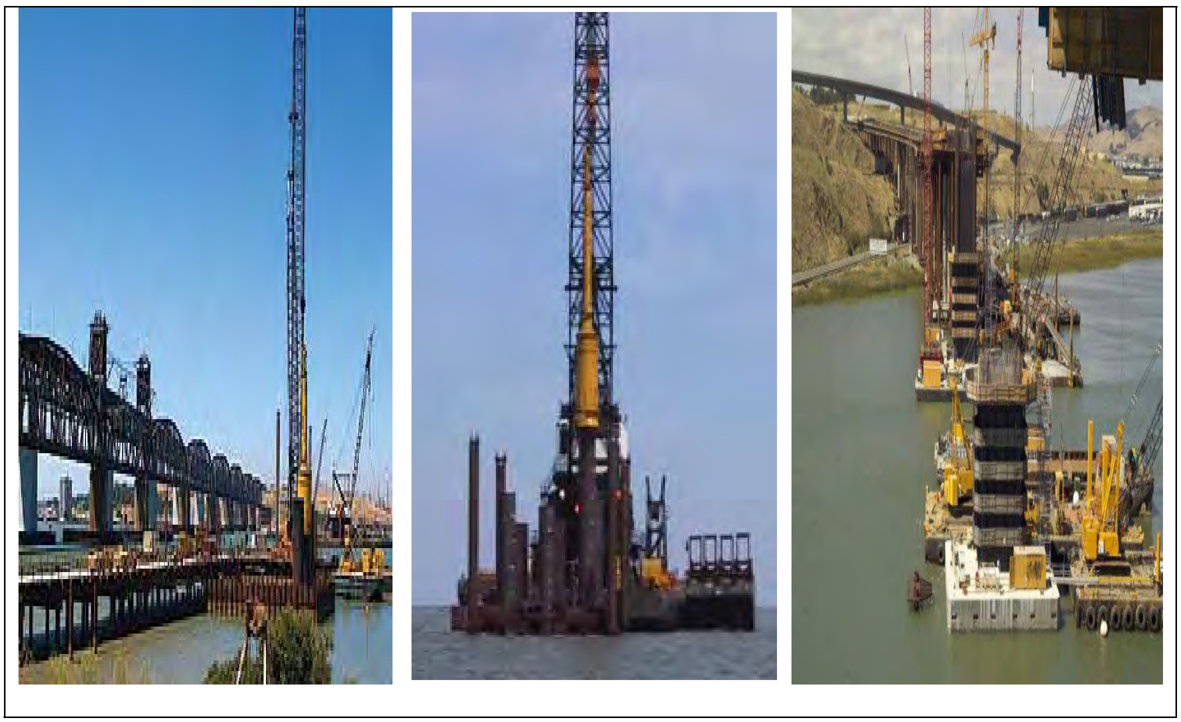


Figure I.8-1 Construction of the New Benicia-Martinez Bridge

Sound measurements were conducted during driving of 2.4-meter-diameter piles at different pier groups. Each pier group consisted of about eight piles set in a driving template. A large hydraulic hammer was used to drive the piles. During pile driving, hammer energies were typically in the range of 500 to 570 kilojoules (368,781 to 420,410 ft-lbs). 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.

I.8.2 Measurement Results

Detailed underwater sound measurements were conducted during 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-meter diameter) under different conditions (i.e., with water, bubbled, and 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 four 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., from 5 to 7 meters) from distances of 15 to 300 meters, where sound levels ranged from about 215 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, 50, and 310 meters for different depths.

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

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

* Measured from the pile at about mid depth (10–15 meters deep)

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

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

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

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.

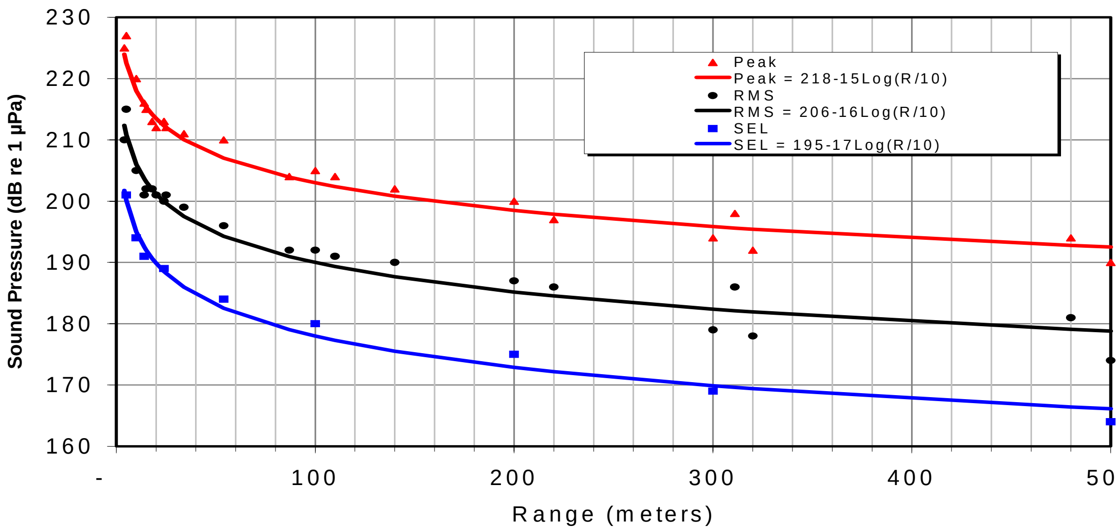
Equations that predict the received peak sound pressure level were developed for mid depth or 5-meter depth.

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

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 meters.

Analyses of the signals were not conducted; 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 Levels in dB**		
	Peak	**RMS**	**SEL**
Inside cofferdam			
5 meters	215	203	--
10 meters	208	199	--
19 meters	203	194	--
Outside cofferdam			
12 meters	193	206	--
22 meters	198	184	--
36 meters	190	170	--
54 meters N	179	162	--
54 meters 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 Levels in dB		
	Peak	**RMS**	**SEL**
Bare pile			
14 meters	216	201	191
24 meters	213	201	189
54 meters	210	196	184
100–106 meters	204	191	180
Casing with air bubbles			
14 meters	192	176	--
24 meters	189	173	
54 meters	187	174	163
100–106 meters	--	--	--
Casing dewatered			
14 meters	--	--	--
24 meters	191	175	--
54 meters	185	173	162
100–106 meters	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 meters from the pile, GS measured a 0-dB difference in the peak sound pressure levels. At 14 meters, GS measured increased sound levels; however, this unusual variability may be due to near-field effects. At 54 meters, I&R measured a 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 1,600 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 meters and 23 to 31 dB at 24 meters. I&R measured a reduction of 23 dB peak and 21 dB SEL at 54 meters (measured at mid-depth only). A close examination of the acoustical pressure waveforms recorded at 54 meters showed a fast rise time in pressure that occurred within the first 5 msec. A rapid fluctuation in underpressure to overpressure occurred within about 2 msec. The decay time of the pulse was relatively slow, lasting about 50 to 100 msec. Much of the energy associated with the pulse occurred within the first 50 msec. 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 1,600 Hz. Based on these data, the bubbled casing condition was most effective at close-in distances.

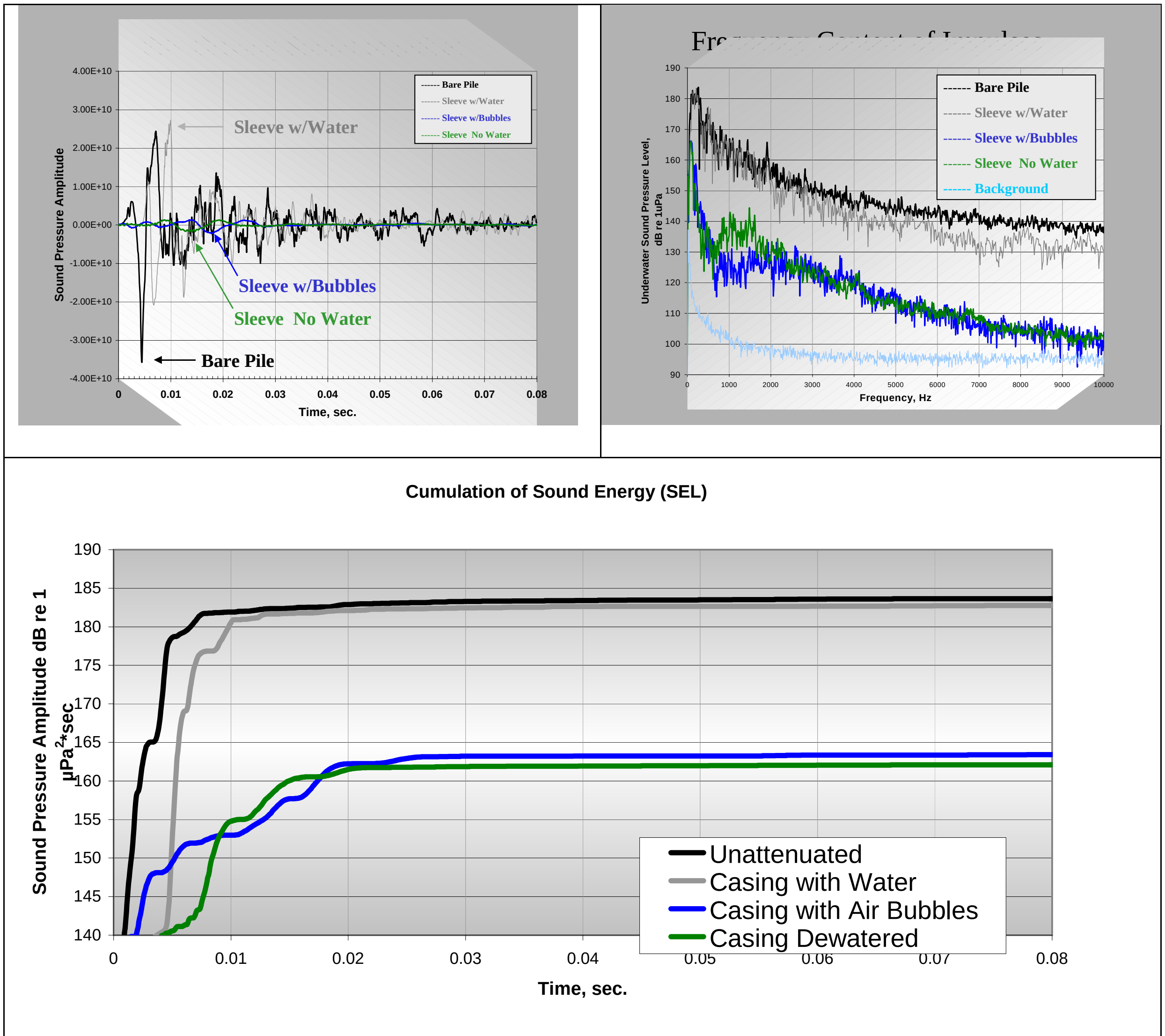


Figure I.8-5 Signal Analyses of Underwater Sound Pulses at 54 Meters – Isolation Casing Tests

Isolation Casing without Water

At the request of National Marine 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 isolation casing/air bubble curtain 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 nine stages (Figure I.8-6). Each stage or ring was open or closed. The system was designed to 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.

Prior to 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 it required redesigning and fabricating the existing pile template. 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 needing to modify the pile template.

Testing Results (Pier 13)

Plans were developed to measure at three different fixed positions approximately 100 meters from the pile (actual distances varied from 95 to 150 meters 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].

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. 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 meters 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			
	Sound Levels in dB re 1 μPa		
Position	**Unattenuated Pile**	**Isolation Casing/Air Bubble Curtain**	**Air Bubble Tree**
~50 meters	Peak = 210 RMS = 196 SEL = 184	Peak = 187 RMS = 174 SEL = 163	Peak = 182* RMS = 168* SEL = 159*
~100 meters	Peak = 204 RMS = 191 SEL=180	Peak = 181 RMS = 172 SEL=162	Peak = 185* RMS =170* SEL = 160*

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

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

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

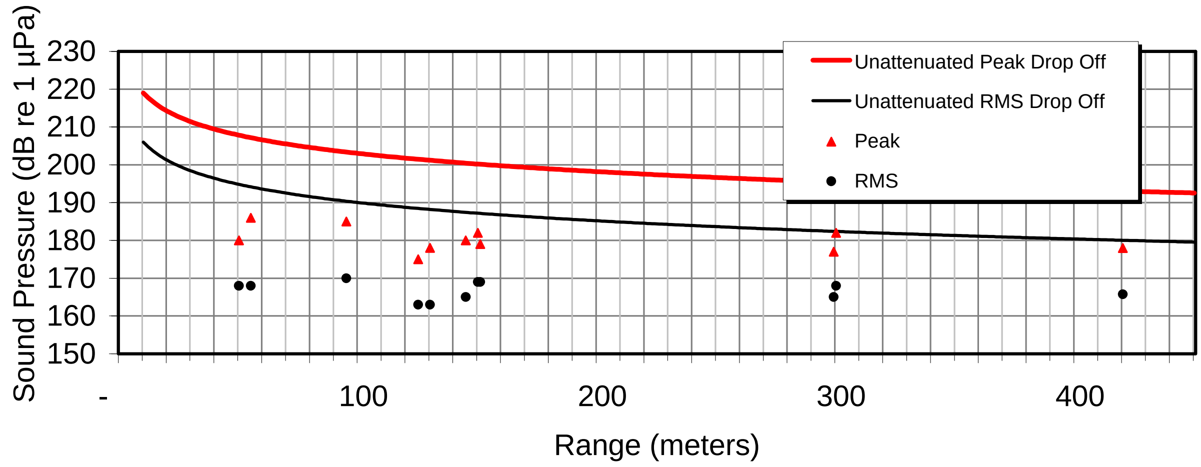
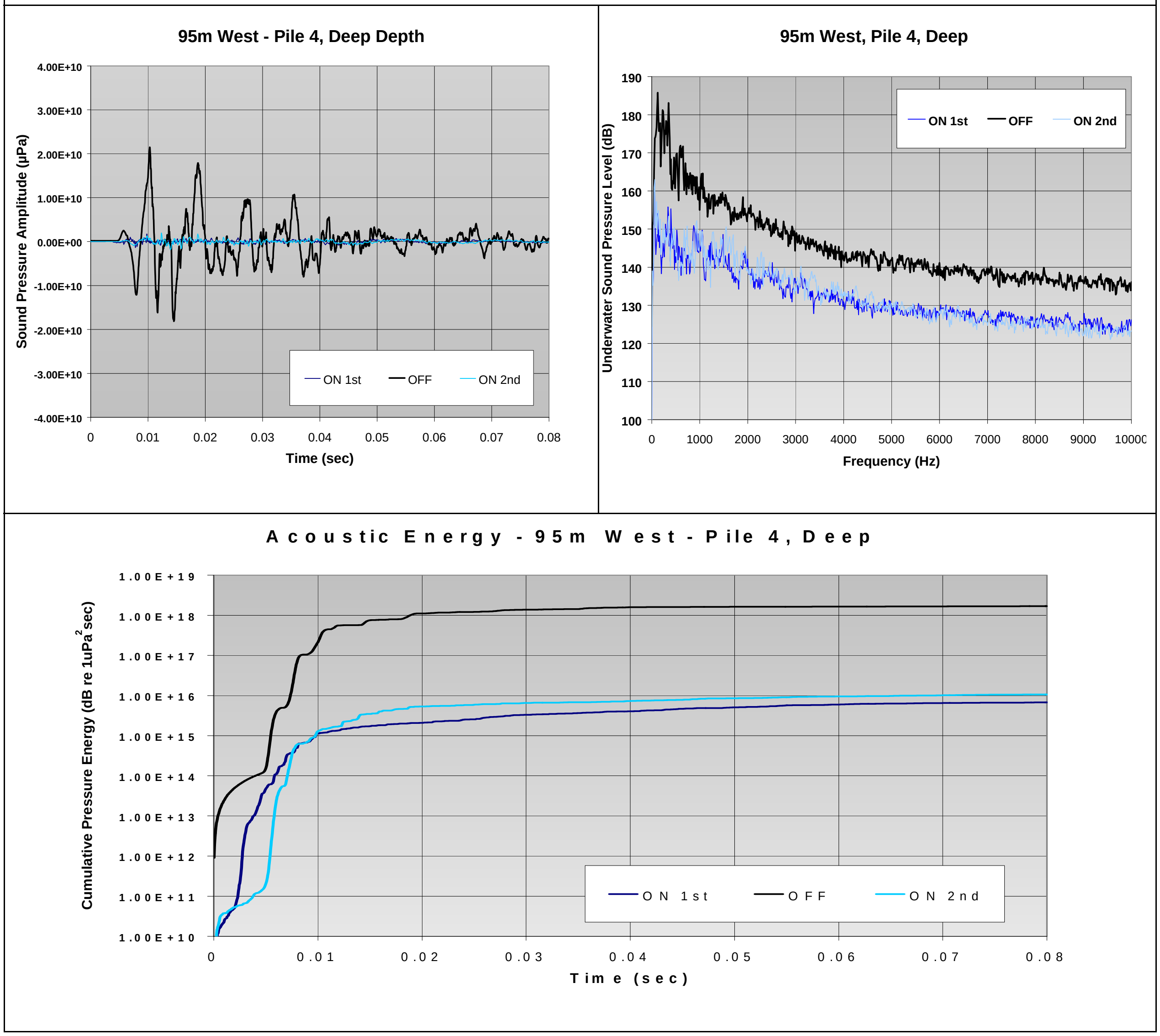


Figure I.8-8 Signal Analyses of Underwater Sound Pulses at 95 Meters West – Air Bubble Tree

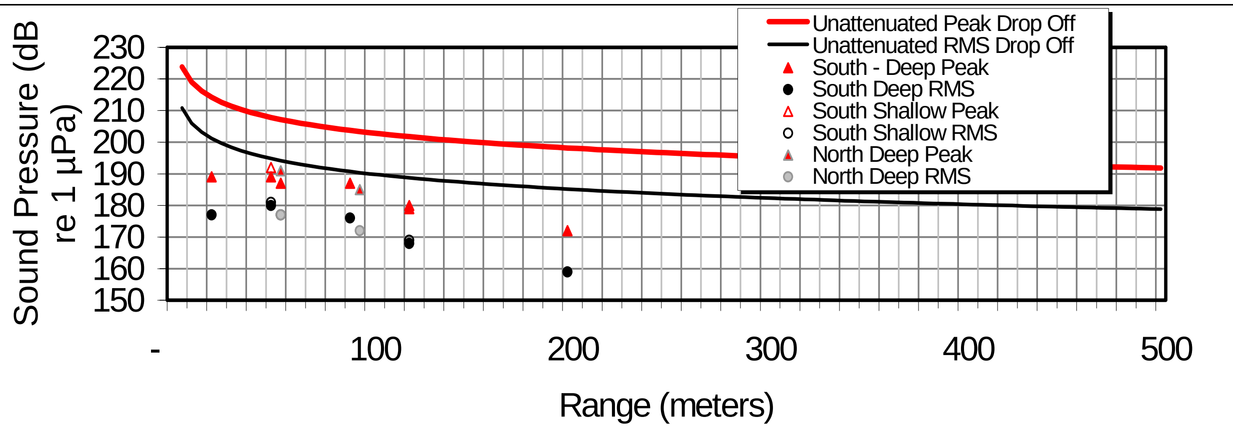


Compliance Monitoring Results
Measurements were made to document underwater sound levels and air bubble curtain performance during production pile driving. Measurements were made at Piers 7, 11, 12, and 15. Only peak and RMS sound pressure levels were reported under the compliance monitoring tasks.

<u>Pier 7</u>

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.

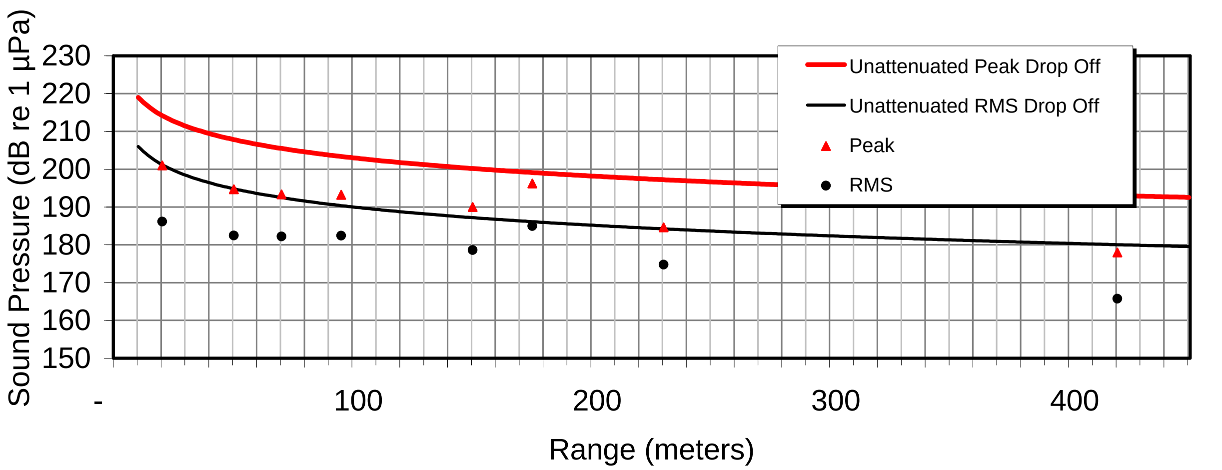
Figure I.8-9 Results of Pier 7 Measurements Compared to Unattenuated Sound Levels



Pier 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 unconfined air bubble curtain system on the west side. Results are plotted graphically in Figure I.8-10.

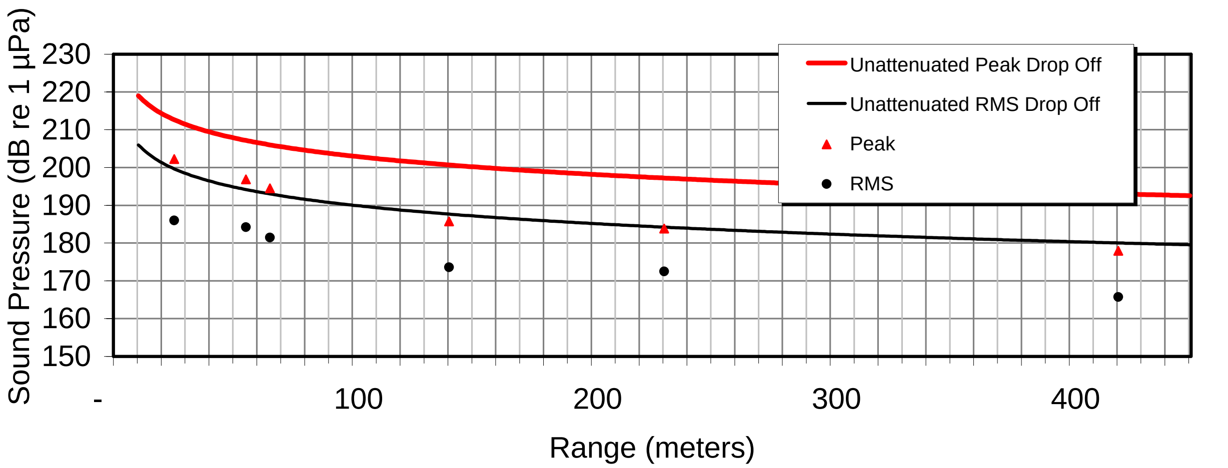
Figure I.8-10 Results of Pier 11 Measurements Compared to Unattenuated Sound Levels



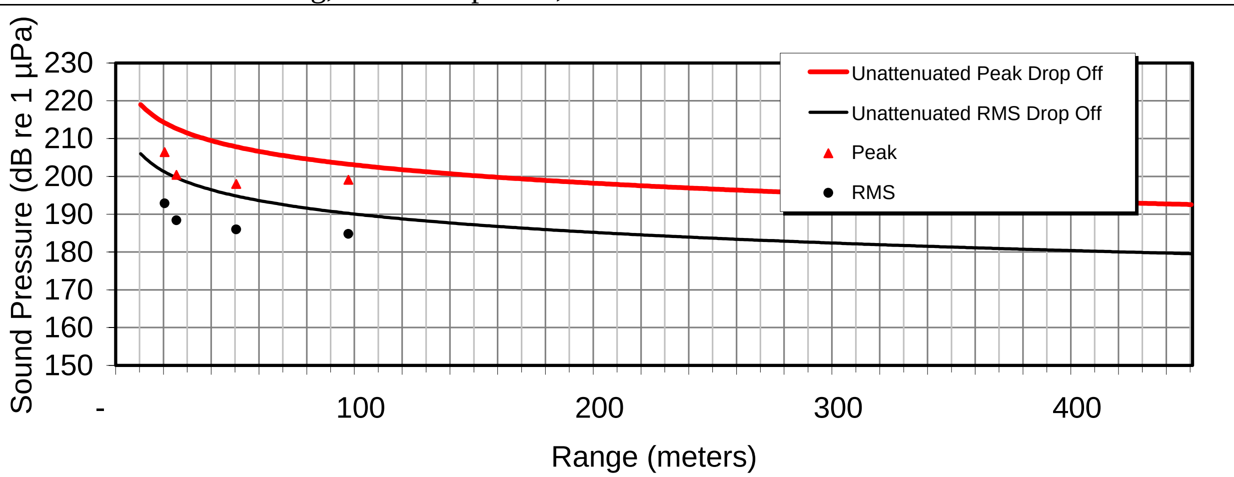
Pier 12

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.8-11) 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.8-11 Results of Pier 12 Measurements Compared to Unattenuated Sound Levels



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

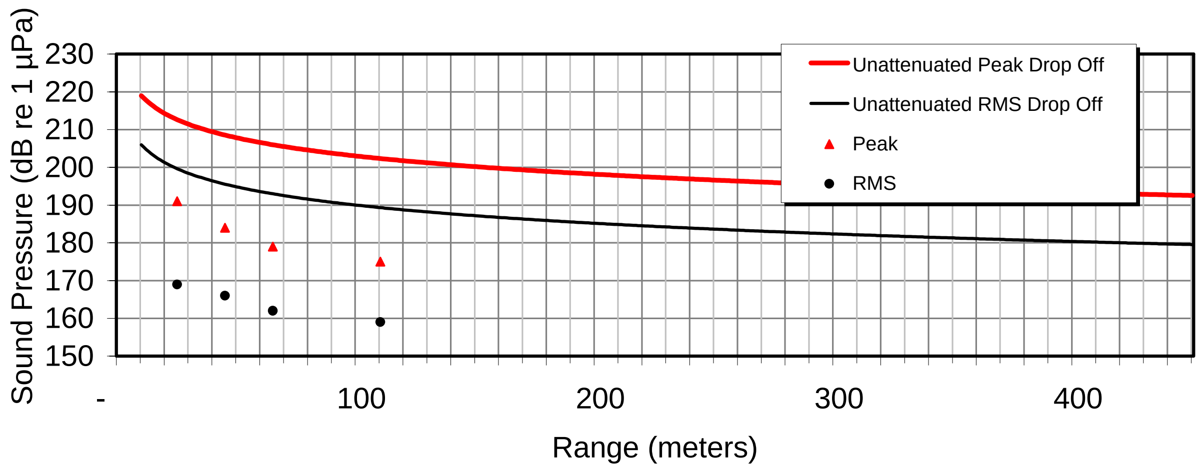


Center Relief Pile Driving, Pile 7 – May 8, 2003

Pier 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 6 meters 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.8-10 Results of Pier 15 Measurements Compared to Unattenuated Sound Levels



I.8.3 References

1. Reyff, J., P. Donavan, and 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.

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 California Department of Transportation under Contract No. 43A0063, Task Order No. 18.* April 2003.

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/Yerba Buena Island 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 Yerba Buena Island 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 Yerba Buena Island. 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 Yerba Buena Island 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.

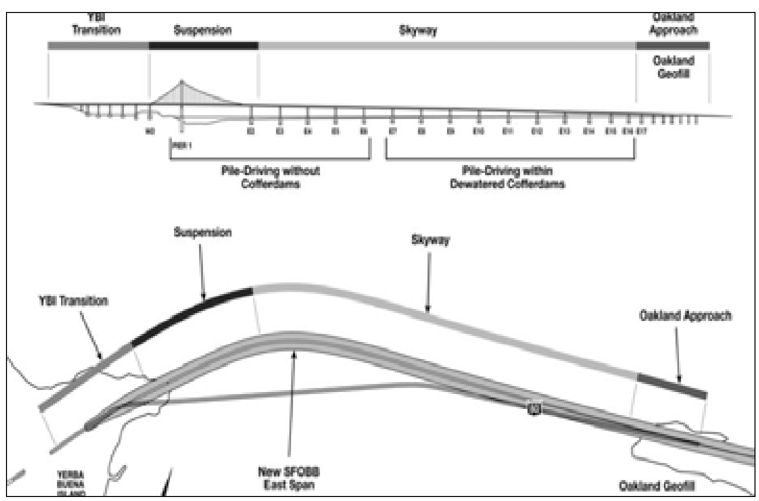


Figure I.9-2 Project Components – San Francisco-Oakland Bay Bridge East Span

The SFOBB Project included driving large piles (2.7-meter- [8-foot-] diameter) that were over 100 meters (330 feet) long. Piers that would support the new bridge include at least six of these piles, with four piles installed at an angle (battered). In addition, blasting was conducted at Yerba Buena Island 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 also were made during blasting activities at Pier W1 at Yerba Buena Island. 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 Re-Strike[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 were 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 Service 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 Yerba Buena Island near the water.

I.9.3 Hydroacoustic Measurements

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[1]. 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 meters (356 feet), long with an inside diameter of 2.4 meters (8 feet), and an outside diameter of 2.57 meters (8.5 feet). 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 also was battered, but it was angled to the west. A proprietary fabric underwater barrier attenuation system (Proprietary) 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 ft-lbs); and the MHU1700T (Figures I.9-3a and I-9.3b) had a maximum capacity of about 1,780 kilojoules (1,253,750 ft-lbs).

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 Quarter 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 meters, 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.

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 Proprietary 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.

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

Pile	Conditions	Sound Pressure Levels in dB		
		Peak	RMS	SEL
PIDP 1 Section 1D (top)	Menck1700T hammer (900 kilojoules)			
	100 meters unattenuated – 1-meter depth	197	185	~172
	100 meters unattenuated – 3-meter depth	205	192	~178
	100 meters unattenuated – 6-meter depth	207	196	~183
	360 meters unattenuated – 1-meter depth	181	167	~157
	360 meters unattenuated – 3-meter depth	188	175	~164
	360 meters unattenuated – 6-meter depth	191	179	~168
PIDP 2 Section 2D (top)	Menck500T hammer (550 kilojoules)			
	200 meters unattenuated – 1-meter depth	197	184	~172
	200 meters unattenuated – 3-meter depth	201	189	~178
	200 meters unattenuated – 6-meter depth	197	186	~174
PIDP 2 Section 2D (top)	Menck1700T hammer (1,000 kilojoules)			
	200 meters partially attenuated – 1-meter depth	199	187	~175
	200 meters partially attenuated – 3-meter depth	201	190	~177
	200 meters partially attenuated – 6-meter depth	199	188	~176
PIDP 3 Section 3D (top)	Menck1700T hammer (1,500 kilojoules)			
	100 meters east unattenuated (Proprietary OFF)– 1-meter depth	193	179	~167
	100 meters east unattenuated (Proprietary ON)– 1-meter depth	189	175	--
	100 meters west unattenuated (Proprietary ON)– 1-meter depth	188	175	~163
	100 meters west unattenuated (Proprietary OFF)– 1-meter depth	197	184	~173
	500 meters west unattenuated (Proprietary ON)– 1-meter depth	170	160	~148

Figure I.9-4a Simple Air Bubble Ring Used during Driving of PIDP Pile 2

Figure I.9-4b Proprietary Fabric Air Bubble Curtain (Proprietary) Used during Driving of PIDP Pile 3

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

Pile Installation Demonstration Project Re-Strike

The PIDP Re-Strike 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 Re-Strike Project, the Menck1700T hydraulic hammer (MHU1700T), with a capacity of 1,780 kilojoules, was used at or near full capacity. The geotechnical evaluation was intended to demonstrate the limits of pile "take-up" 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 criterion used to determine stability was 670 strikes with less than 250 millimeters (approximately 1 foot) 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 air 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-meter 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 450 meters south, the reductions were only about 2 dB. Uneven bottom topography around Pile 3, which could have compromised the air 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 ground-borne 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 for Piles 1 and 2. Measurements of peak pressures made at about 100 meters 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. Measured peak pressures were lower than the levels predicted in the Biological Opinion, except at the 450-meter south position. At this location, measured peak pressures were 5 to 8 dB higher than predicted. This was the result of the ground-borne sound generation in that direction that was not known at the time of the predictions. Conversely, unattenuated peak pressures at 450 to 500 meters north were 0 to 6 dB lower than predicted.

Table I.9-2 Summary of Sound Pressures Measured for the 2003 Pile Installation Demonstration Project (PIDP) Re-Strike Using the MHU1700T Hammer at Full Energy – San Francisco-Oakland Bay Bridge, East Span

		Sound Pressure Levels in dB		
Pile	**Conditions**	**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 north attenuated	201	189	--
	100 meters north unattenuated	207	194	--
	450 meters north attenuated	175	162	--
	450 meters north 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 north attenuated	196	184	--
	100 meters north unattenuated	205	193	--
	450 meters north attenuated	180	171	--
	450 meters north unattenuated	190	177	--
PIDP 3	100 meters south attenuated	193	182	--
	100 meters south unattenuated	199	186	--
	450 meters south attenuated	184	173	--
	450 meters south unattenuated	187	175	--
	100 meters north attenuated	179	169	--
	100 meters north unattenuated	198	184	--
	470 meters north attenuated	<180	<170	--
	470 meters north 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 msec or longer, and most of the disturbance occurred during the first 25 to 35 msec. In all cases, the reduction in acoustical energy is evident. The bubble curtain system was effective at reducing sound pressure levels above 1,000 Hz in all cases and above 300 Hz in some cases. The reductions were over 20 dB above 2,000 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 locations of Piles 1 and 2 and the location of Pile 3. At Pile 3, sound pressures were much lower even without the air 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.

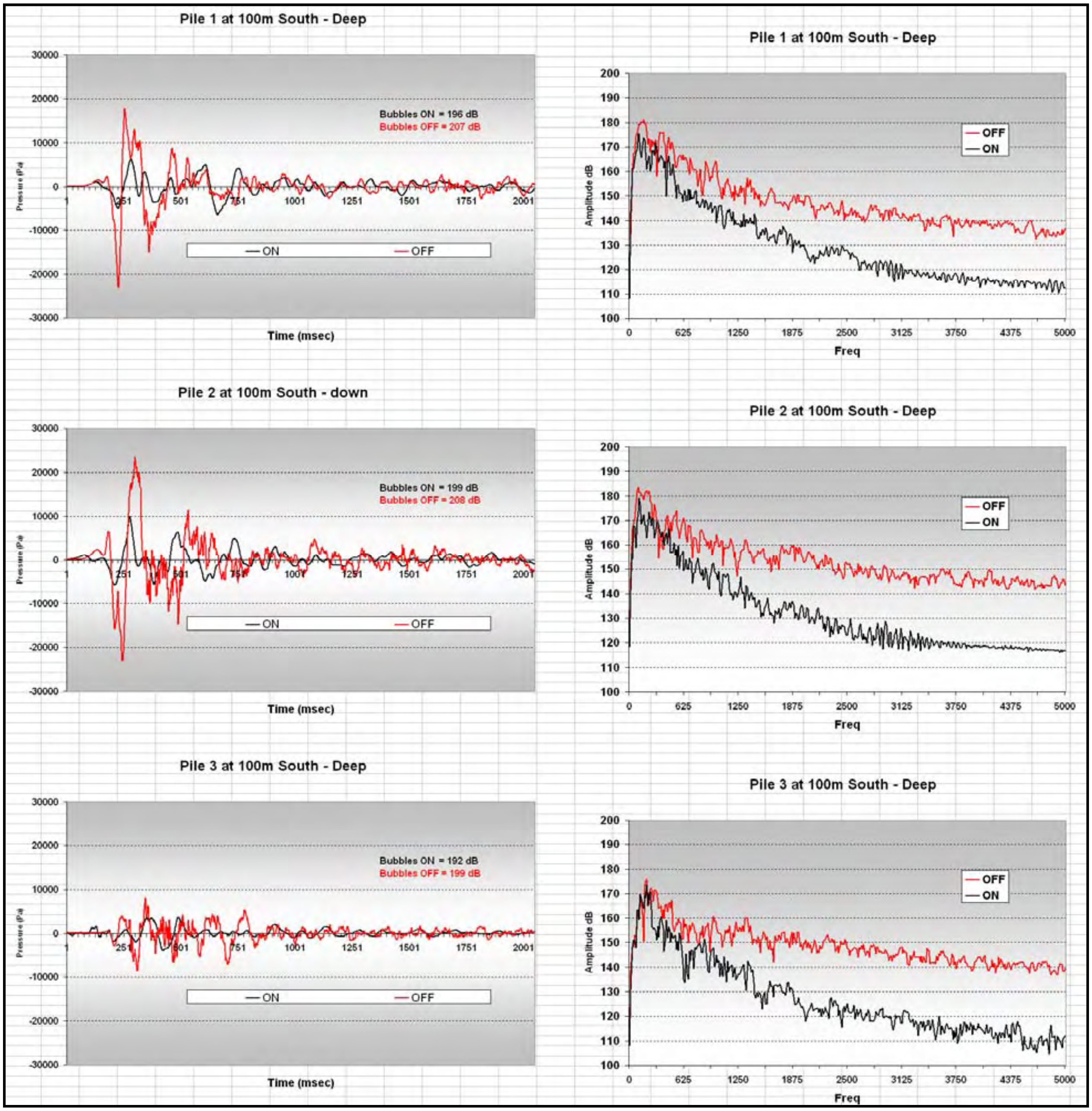


Figure I.9-6 Representative Signal Analyses for PIDP Re-Strike Measurements Made at 100 Meters from Three Different Piles with and without Air Bubble Curtain Attenuation – San Francisco-Oakland Bay Bridge, East Span

I.9.4 Production Pile Driving

As of this writing, the SFOBB 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 six 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 underwater 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 effectiveness of the air bubble curtain system. 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 Re-Strike, 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 *Hydroacoustic Monitoring Report for the Skyway Construction Project* for a full description of the data collected for this project[9].

Production – Dewatered Cofferdam

Twenty of the bridge piers were constructed in dewatered cofferdams. The dewatered cofferdam provided the greatest reduction in peak sound pressure levels created by impact pile driving into the water column. The air within the dewatered cofferdam mostly decoupled 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.

Each cofferdam included six 100-meter-long, 2.4-meter-diameter piles that were driven into the bottom of San Francisco Bay using 550-kilojoules and 1,780-kilojoules 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 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 had been driven into the ground.

Figure I.9-7 SFOBB Pile Driving in Dewatered Cofferdam at Pier E7E (Deepest Cofferdam) Using Menck 1700MHU

Measurements under similar conditions for Pier E12W found higher sound levels in fairly isolated areas. The area of elevated sound pressures was larger 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 rated at 1,750 kilojoules was used. Measurements were made at Pier E11W when the bottom pile sections (i.e., the 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 to 195 dB peak, 180 to 183 dB RMS, and 170 to 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. SELs analyzed for individual strikes showed roughly a 10-dB relationship to RMS levels.

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 attenuated only by about 5 to 10 dB. In fact, peak pressures as high as 204 dB were measured at 120 meters 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 meters [6,560 feet] west)* while measurements at 100 meters (328 feet) west were 187 dB peak. More limited measurements were made at Pier E7E, 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 in the southerly direction. However, higher levels were seen to the southeast. The highest level measured in that direction was

* 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.

about 195 dB peak at 220 meters (720 feet). At 100 meters (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 500 meters (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 200 meters (656 feet) north, the cofferdam levels were about 2 dB lower than the air bubble curtain "ON" conditions with PIDP Re-Strike Pile 3.

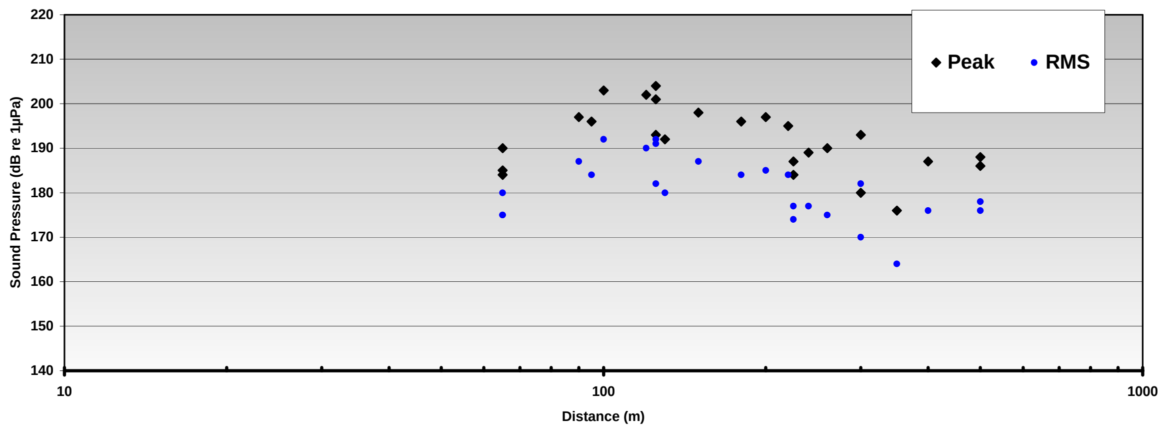


Figure I.9-8a Drop Off in Sound Pressure Levels with Dewatered Cofferdam in Southerly (Louder) Direction

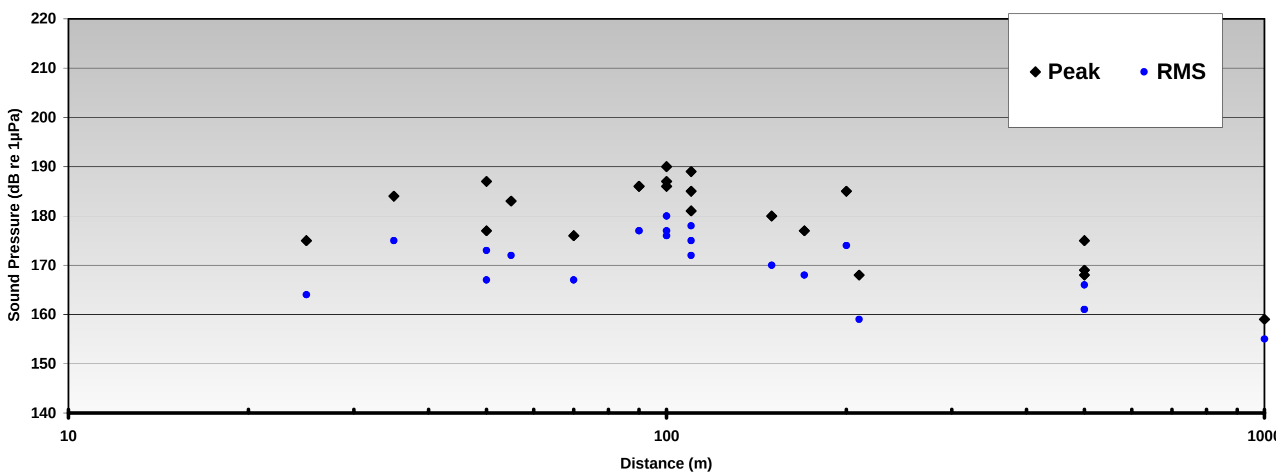


Figure I.9-8b Drop Off in Sound Pressure Levels with Dewatered Cofferdam in Other (Quieter) Directions

<u>Signal Analysis for Dewatered Cofferdam Measurements</u>

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 3 meters (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 at 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 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.

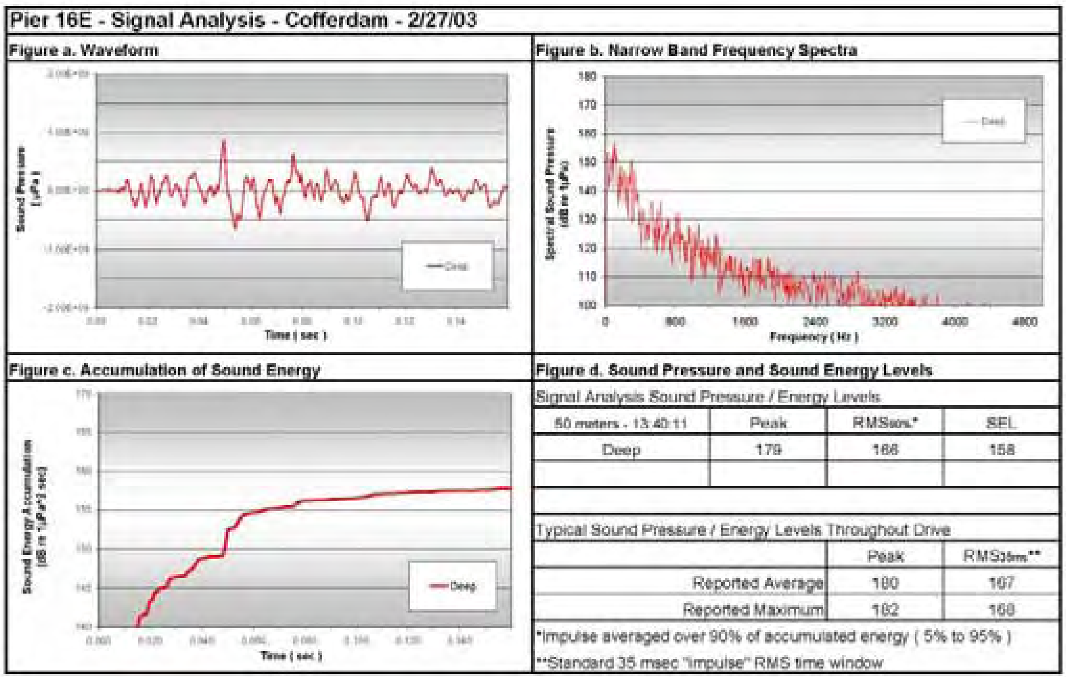


Figure I.9-9 Pulse from Pile Driven in Dewatered Cofferdam at Pier E16E (Very Shallow Water) Measured 50 Meters from Pile – San Francisco-Oakland Bay Bridge East Span Replacement Project

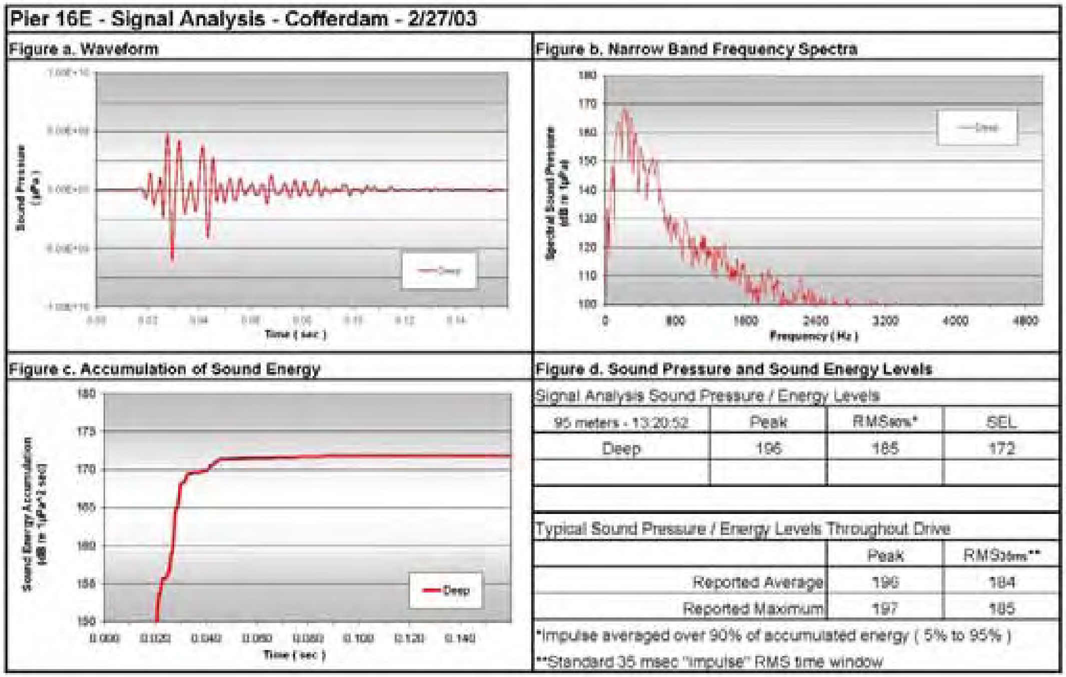


Figure I.9-10 Pulse from Pile Driven in Dewatered Cofferdam at Pier E16E (Very Shallow Water) Measured 95 Meters from Pile – San Francisco-Oakland Bay Bridge East Span Replacement Project

Time History of Sound Pressures – Dewatered Cofferdam

Sound pressures varied throughout the driving of a particular pile. The variability in amplitude and duration of driving events at one location for Pier E10 are illustrated in Figure I.9-11. Peak pressures were 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 of piles at Pier E10E were measured at three distances (about the 50-meter [164-foot] north, 100-meter [328-foot] north, and 120-meter [394-foot] 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 50 meters (164 feet) and 100 meters (328 feet) varied, and 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, with some 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.

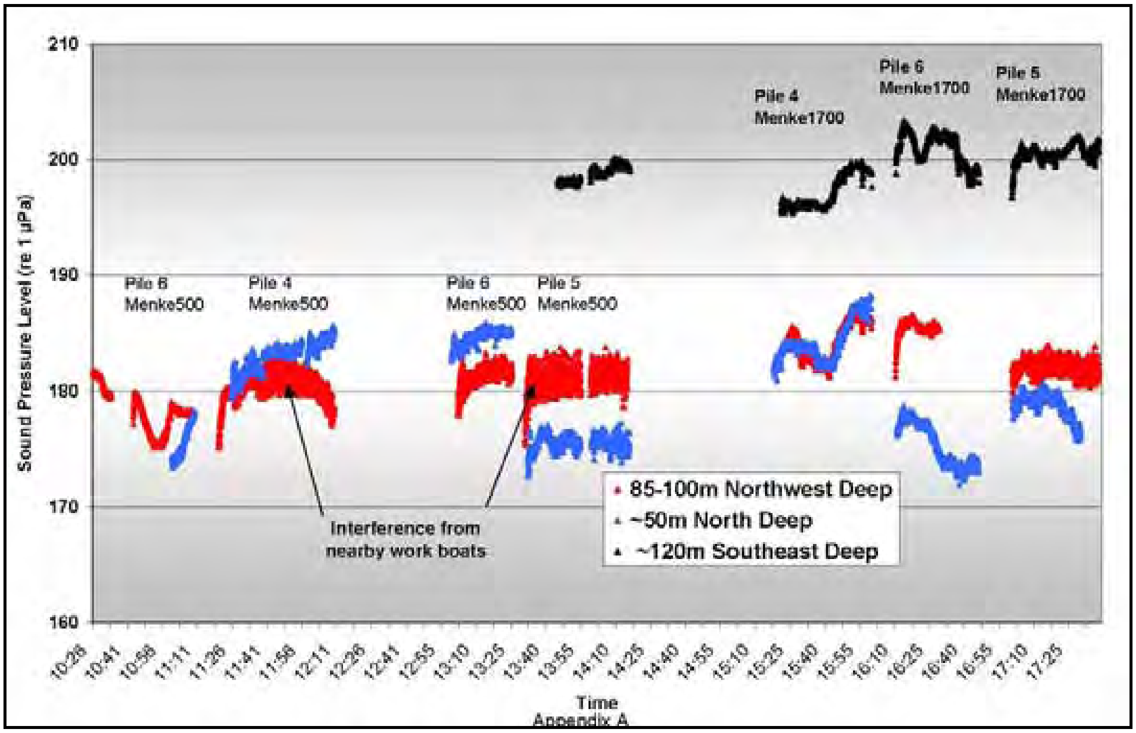


Figure I.9-11 Peak Pressures Measured at Three Different Positions during the Course of Pile Driving in 1 Day at Pier E10E (Dewatered Cofferdam) – San Francisco-Oakland Bay Bridge East Span Replacement Project

Production – In-Water

The air bubble curtain system was used to attenuate underwater noise levels for the eight 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 to193 dB RMS at 50 meters, to 190 to 200 dB peak and 180 to 185 dB RMS at 100 meters. 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 500 meters, 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 meters (1,640 feet) or farther 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 air 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 air 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 tenfold 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 ground-borne 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.

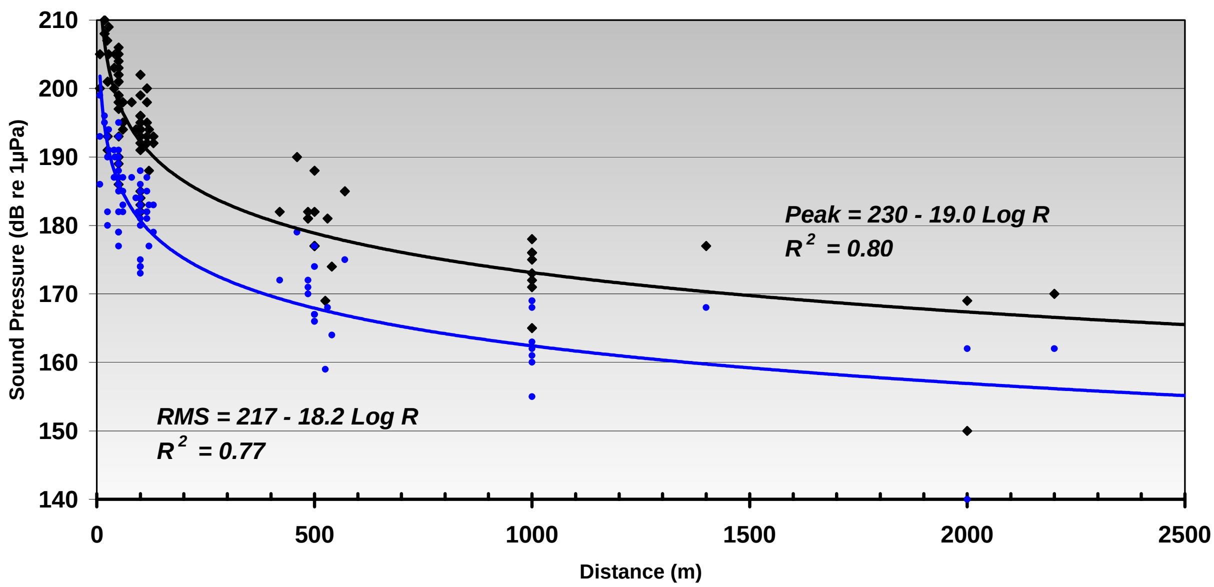


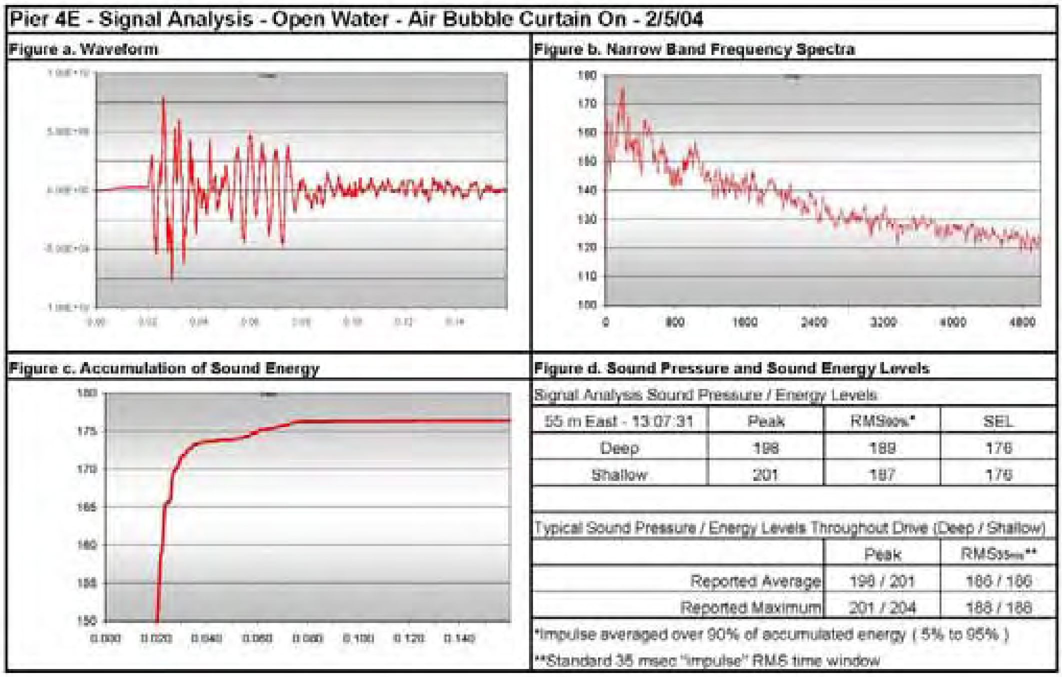
Figure I.9-12 Drop Off in Sound Pressure Levels with the Air Bubble Curtain System during In-Water Pile Driving – San Francisco-Oakland Bay Bridge East Span Replacement Project

Since currents usually ran north-south, measurements to the east or west were generally unaffected by the effect of the current 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 upward to 20 dB.

Most measurements were made at two depths: 2 meters below the water surface and 2 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 were 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 to almost 1 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, 110, 570, 1,400, and 2,200 meters—generally to the north of the pile driving. These illustrate the attenuation of these pulses as one moves farther from the pile. These examples were chosen for the direction with the lowest rate of attenuation, which appears to be caused by the pulse transmitted through the ground.



55 m East - 13:07:31	Peak	RMS90%*	SEL
Deep	198	189	176
Shallow	201	187	176

Typical Sound Pressure / Energy Levels Throughout Drive (Deep / Shallow)

	Peak	RMS35ms**
Reported Average	198 / 201	186 / 186
Reported Maximum	201 / 204	188 / 188

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

**Standard 35 msec "impulse" RMS time window

Figure I.9-13 Pulse from Pile Driven in Water with Air Bubble Curtain at Pier E4E Measured 55 Meters from Pile – San Francisco-Oakland Bay Bridge East Span Replacement Project

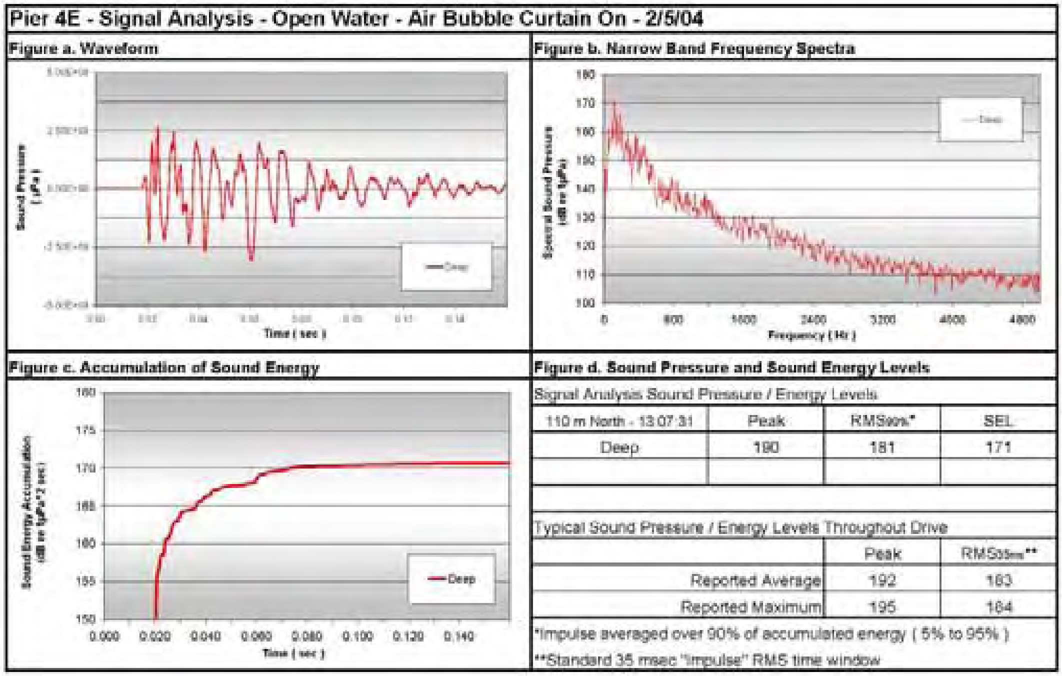


Figure I.9-14. Same as Figure I.9-13, Except 110 Meters from Pile – San Francisco-Oakland Bay Bridge East Span Replacement Project

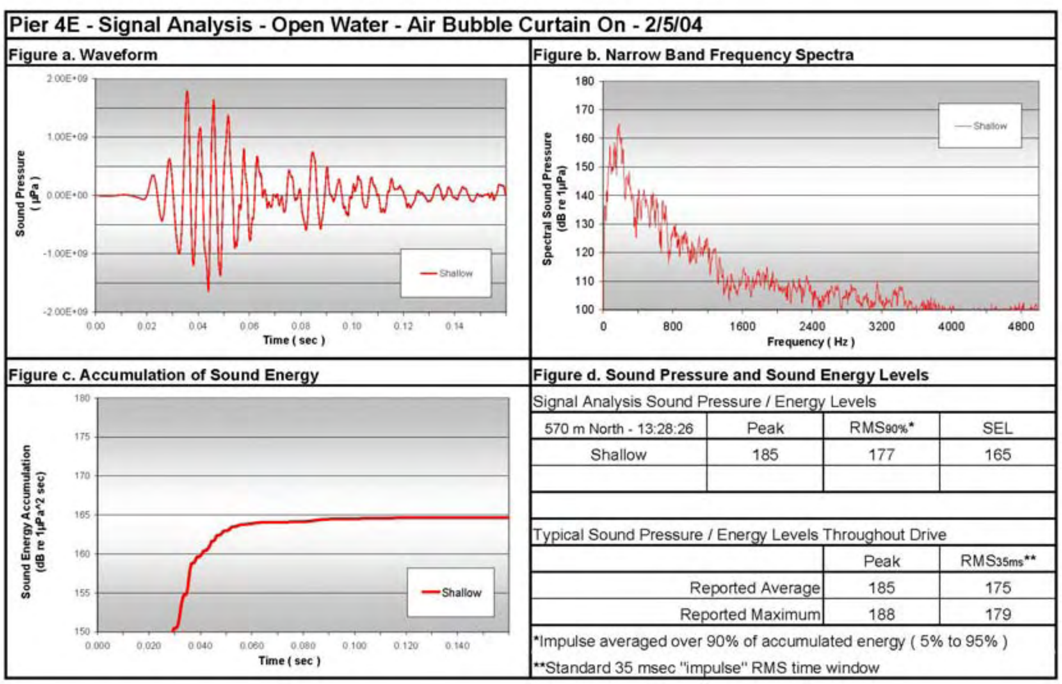


Figure I.9-15 Same as Figure I.9-13, Except 570 Meters from Pile – San Francisco-Oakland Bay Bridge East Span Replacement Project

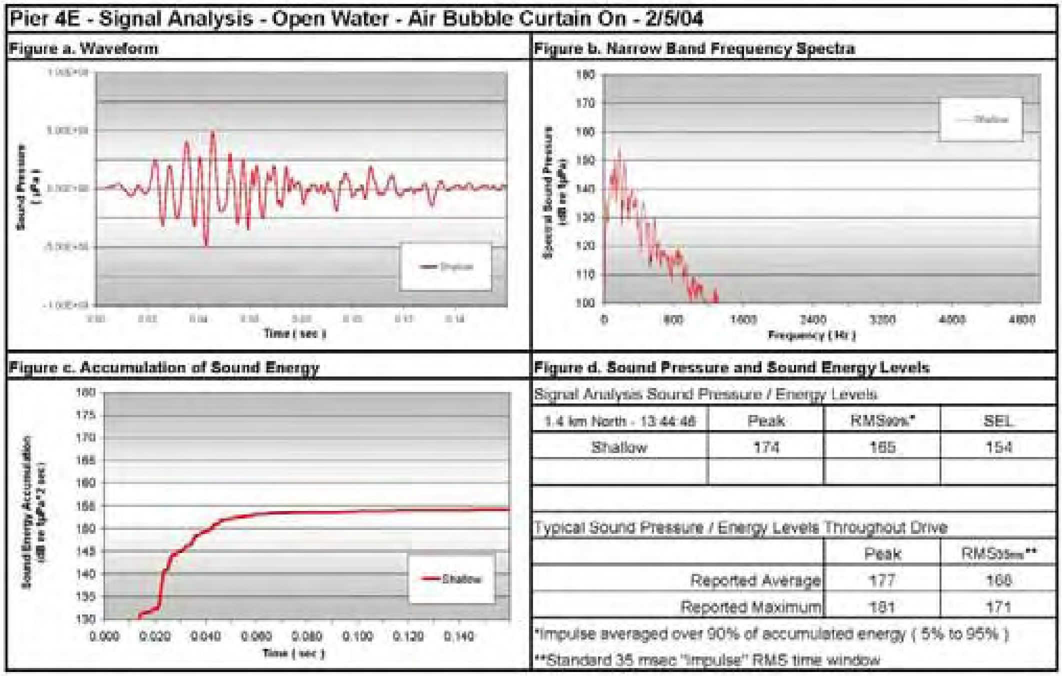


Figure I.9-16 Same as Figure I.9-13, Except 1,400 Meters from Pile – San Francisco-Oakland Bay Bridge East Span Replacement Project

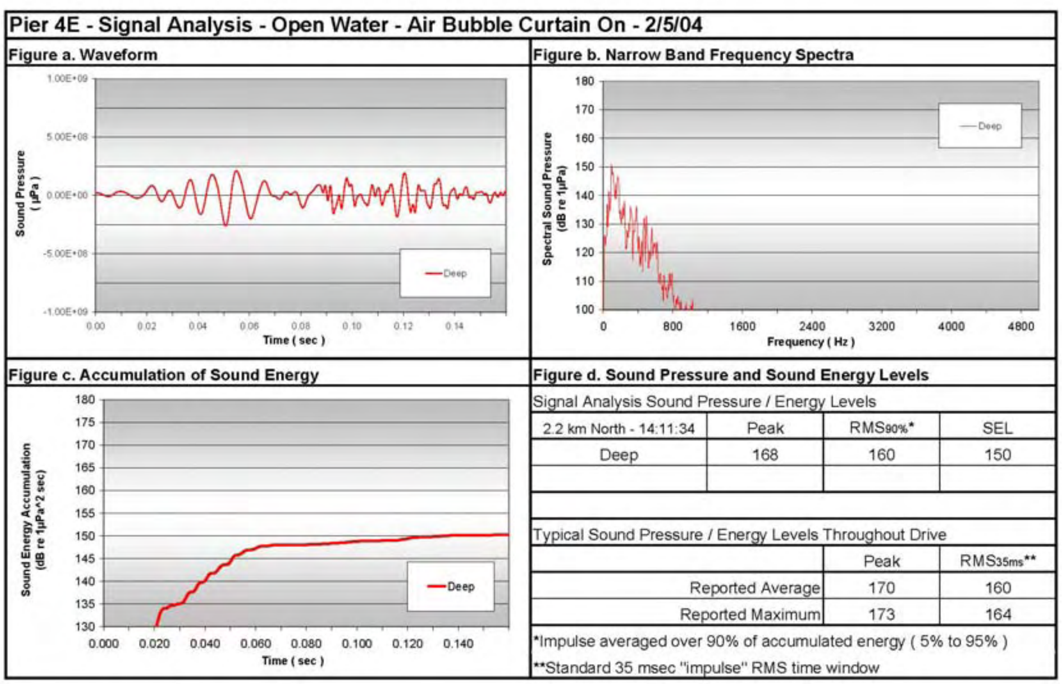


Figure I.9-17 Same as Figure I.9-13, Except 2,200 Meters from Pile – San Francisco-Oakland Bay Bridge East Span Replacement Project

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 farther 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 affected the attenuation performance. The air 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 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 two-thirds of the way from the water surface to the bay bottom, leaving only one-third 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 air 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 air bubble curtain performance in the upstream side; however, the overall unattenuated level was 3 dB lower than the first test. A 1- to 2-dB difference was measured at about 500 meters (1,640 feet) south and 400 meters (1,312 feet) west.

A brief test with the air bubble curtain off for 1 minute of hammer strikes was conducted at Pier E3E. Pier E3E was in water about 12 to 15 meters deep. Measurements were made at 25 meters (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- to 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 showed 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 air 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.9-3 Summary of Measurements – Pier E6E Bubble Curtain On/Off Test, 11/21/2003

Position	Water Depth	ON		OFF	
		RMS	Peak	RMS	Peak
North pile					
45 meters west	6 meters	187	200	196	210
50 meters north	6 meters	191	203	196	210
100 meters west	6 meters	182	194	188	201
120 meters north	6 meters	177	188	184	196
485 meters south	8 meters	172	182	174	182
South pile					
45 meters west	6 meters	191	203	196	210
50 meters north	6 meters	195	206	197	208
100 meters west	6 meters	184	194	190	203
420 meters west	7 meters	171	181	173	183
485 meters south	8 meters	172	182	173	184

Table I.9-4 Summary of Measurements – Pier E3E Bubble Curtain On/Off Test, 1/24/2004

Position	Water Depth	ON		OFF	
		RMS	Peak	RMS	Peak
Center pile					
50 meters north	11 meters	187	199	197	212
25 meters north	11 meters	190	201	199	212
25 meters south	11 meters	182	193	198	211
25 meters west	11 meters	180	191	195	209

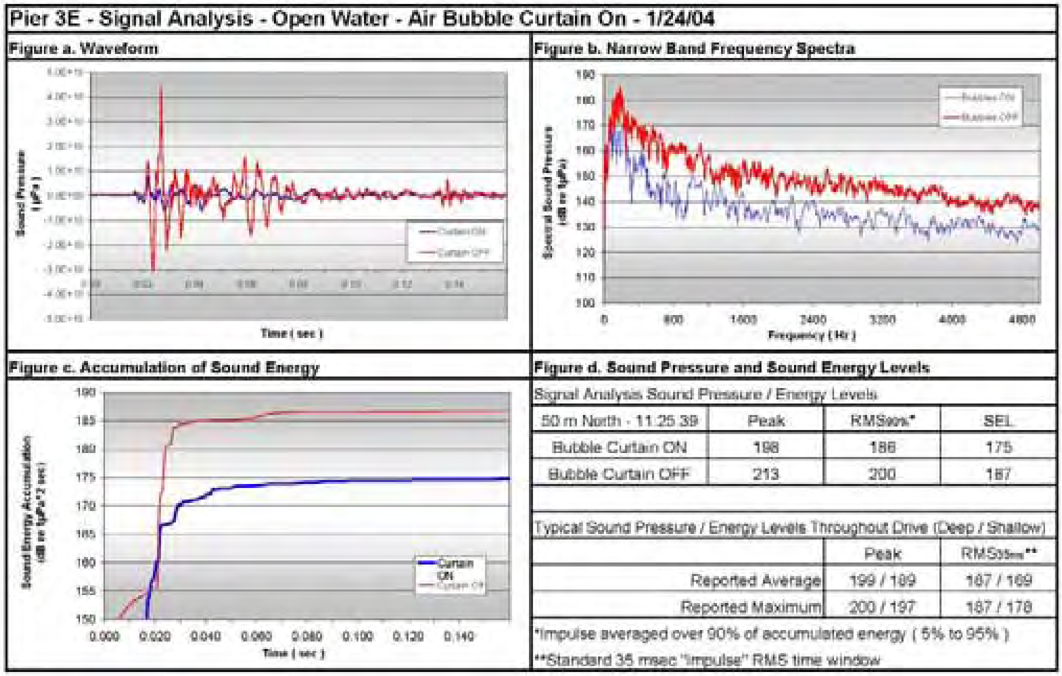


Figure I.9-18 Pulse for Attenuated and Unattenuated Piles Strikes during Air Bubble Curtain Test at Pier E3E Measured 50 Meters from Pile – San Francisco-Oakland Bay Bridge East Span Replacement Project

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 toward 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 air 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 for other in-water piles with the air bubble curtain operating. The subsequent hydroacoustic characterization for Pier E3W indicated much better air 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 meters (25 feet) north and 7 meters (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 air bubble curtain system.

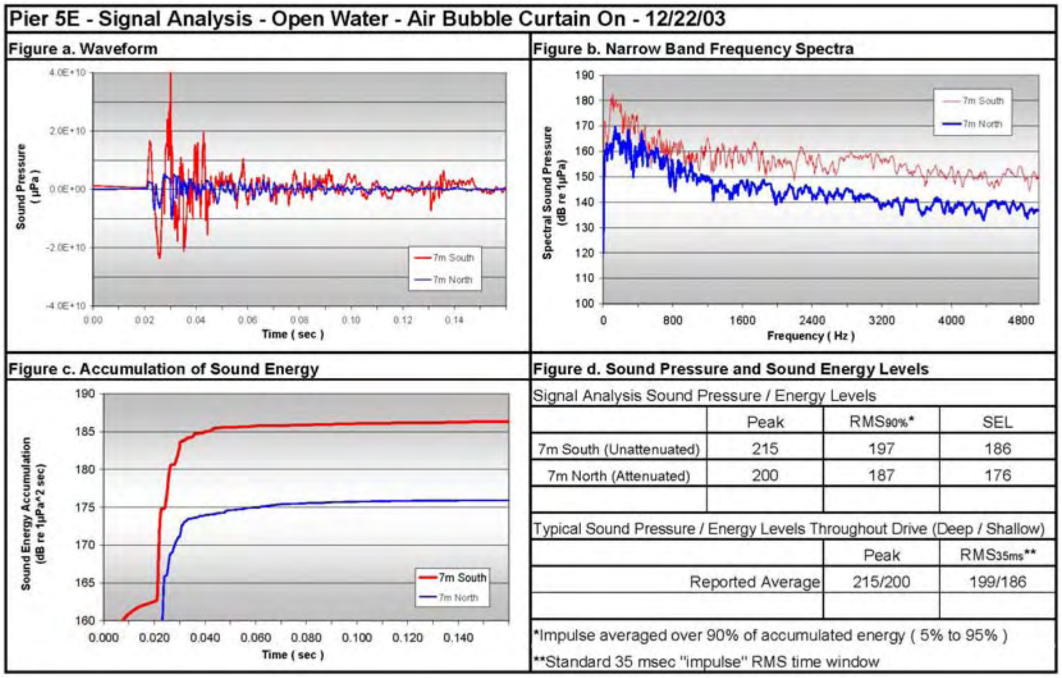


Figure I.9-19 Pulses for Attenuated and Unattenuated Pile Strikes at Edge of Air Bubble Curtain System at Pier E5E Measured 7 Meters from Pile – San Francisco-Oakland Bay Bridge East Span Replacement Project. Bubbles to south of pile were being washed away by tidal current.

I.9.5 Greeneridge Sciences Measurements at Pier E6E

Greeneridge Sciences, Inc. (GS) also made underwater recordings during driving of piles at Pier E6E. The piles driven were the top sections of the piles. The GS measurements were conducted independently of the Illingworth & Rodkin, Inc. (I&R) measurements to provide an independent check, to provide supplemental data, and to gain 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.

With the air bubble curtain system operating, GS measured peak sound pressures of 197 dB (SPL of 185 dB) at 100 meters (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 percent and 95 percent of the total energy) was about 0.08 second. 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 100 meters (328 feet) west. GS found the air bubble curtain system to reduce peak sound pressures by 7 dB at 100 meters (328 feet) and from 2 to 3 dB at 500 meters (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 meters (328 feet) and 2 dB at 500 meters (1,640 feet). The corresponding reductions in RMS levels were 6 and 2 dB.

Table I.9-5. Comparison of I&R and GS 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
100 meters west						
MHU 500T bubble ON	196	196	183	184	--	172
MHU1700T bubble ON	194	197	184	185	172	174
MHU1700T bubble OFF	203	204	190	191	178	180
485 to 500 meters south						
MHU 500T bubble ON	180	181	170	169	160	160
MHU1700T bubble ON	181	182	171	170	161	161
MHU1700T bubble 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.

1.9.6 References

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2. Reyff, J. 2003. Underwater Sound Pressures Associated with the Re-Strike of the Pile Installation Demonstration Project Piles - Measurements Results for the PIDP Re-Strike – East Span Seismic Safety Project on the SFOBB. *Submitted to the State of California Department of Transportation, District 4, Toll Bridge Program.* July 2003.
3. California Department of Transportation (Caltrans). 2002. Fisheries and Hydroacoustic Monitoring Program – Work Plan. September 2002.
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8. Caltrans 2004. Fisheries and Hydroacoustic Monitoring Program Compliance Report. June 2004
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11. Caltrans 2006. Hydroacoustic Measurements at Piers T1 and E2. August 2006.

I.10 Richmond-San Rafael Bridge Project

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 installation of over 760 cylindrical steel piles over the 3-year period using impact pile drivers. The piles ranged in size from 0.3 meter (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 0.36-meter (14-inch) diameter steel pipe piles (fender piles)
- Temporary 0.76-meter (30-inch) diameter steel pipe trestle piles
- Permanent 1.7-meter (66-inch) diameter steel pipe trestle piles
- Permanent 3.2-meter (126-inch) diameter steel pipe piles
- Permanent 3.8-meter (150-inch) diameter steel pipe piles

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

The 30- and 66-inch diameter piles were driven along the trestle part of the bridge in relatively shallow water (about 2 to 5 meters deep). These piles were driven only at night due to the need for traffic control and lane closures. The permanent 14-inch fender, 126-inch, and 150-inch 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 cast-in-drilled hole (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 30-inch steel pipe and 66-inch CIDH piles along the trestle section could be measured only 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.

1.10.1 Permanent 0.2-Meter- (14-Inch-) Diameter Steel Pipe Fender Piles

Because access to the construction area was difficult, measurements were conducted in only 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; results are summarized in Table I.10-1.

Figure I.10-2 14-Inch-Diameter 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 for the Richmond-San Rafael Bridge

	Sound Pressure Measured in dB		
Position	**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. Because the piles were driven adjacent to a pier, the 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 5,000 Hz). This ringing that occurred resulted in pulse duration that exceeded 100 msec, and 90 percent of the acoustical energy was contained within 60 to 80 msec. The high-frequency content of this pulse is evident from the waveform.

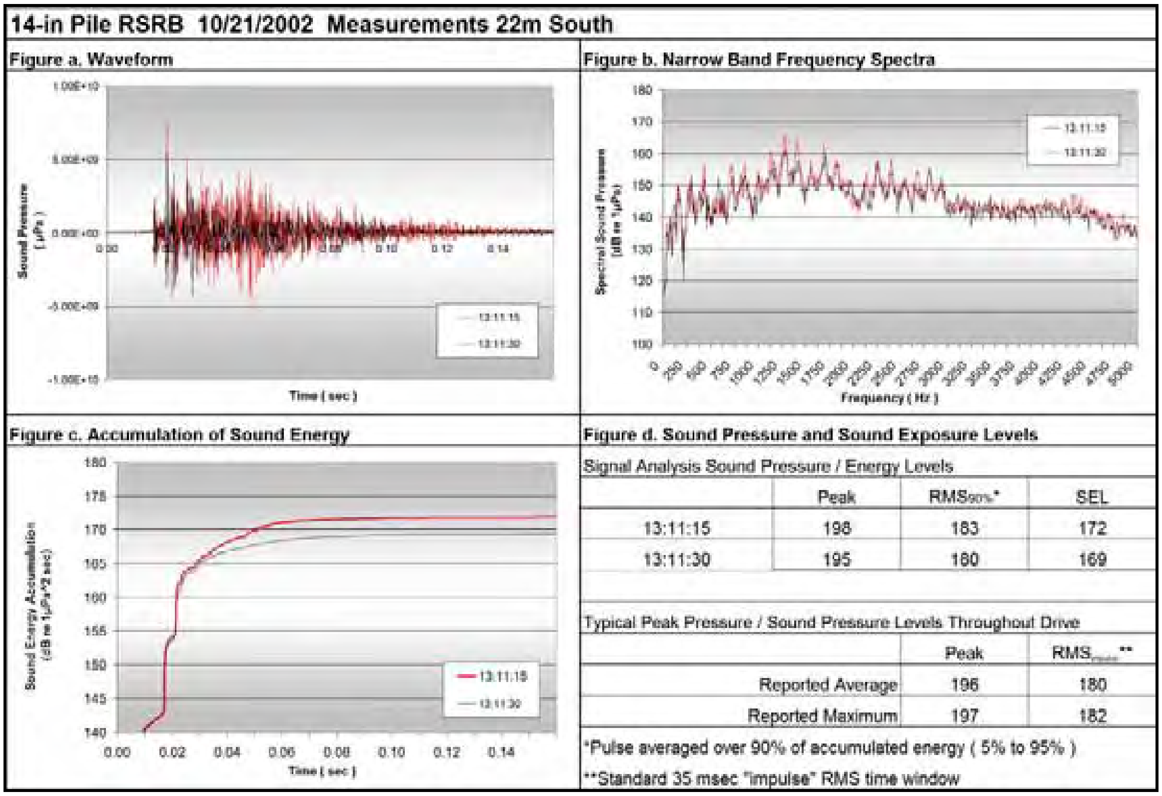


Figure I.10-3 Representative Signal Analyses for 14-Inch-Diameter Pile. Pulse received at 22 meters from the pile at Richmond-San Rafael Bridge.

1.10.2 Temporary 0.9-Meter- (30-Inch-) Diameter Steel Pipe Trestle Piles

The 30-inch-diameter 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 from 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 10:00 p.m. and 4:00 a.m. 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 from 2 to 3 meters. The continuous driving events were relatively short, lasting 2 to 4 minutes or less. During two of the events, periods of several minutes prior 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 10 meters, to 195 dB peak and 169 dB RMS at 60 meters. Measurements for all four pile driving events were made at 20 meters; all indicated unattenuated peak pressures of 200 dB. The measurements were made in relatively shallow water (about 3 meters deep); therefore, levels lower than those from deeper-water piles were expected.

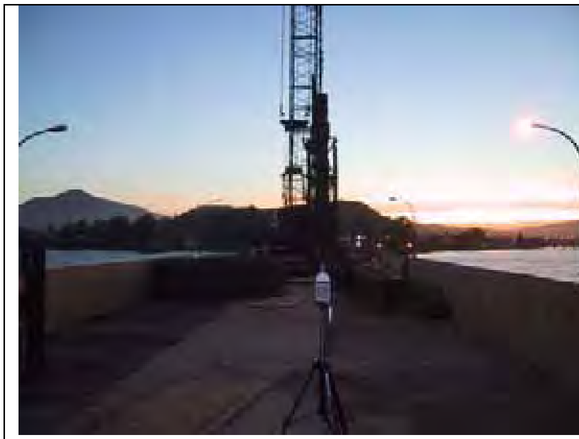


Figure I.10-4 30-Inch-Diameter Pile Being Driven for Temporary Trestle at Richmond-San Rafael Bridge

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 msec. 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.

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 that about 10 dB of reduction was provided. In two of the tests, peak sound pressures were reduced below 190 dB at 20 meters.

30-in Pile RSRB 11/12/2002 Measurements 30m East

Figure a. Waveform

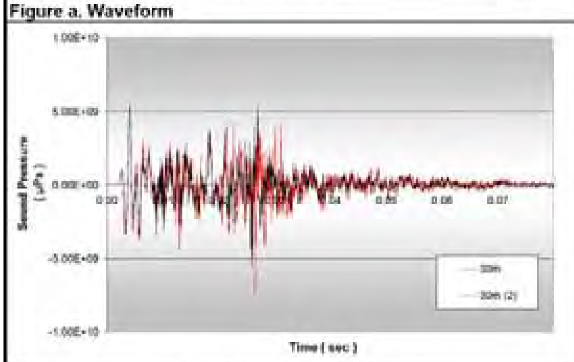


Figure b. Narrow Band Frequency Spectra

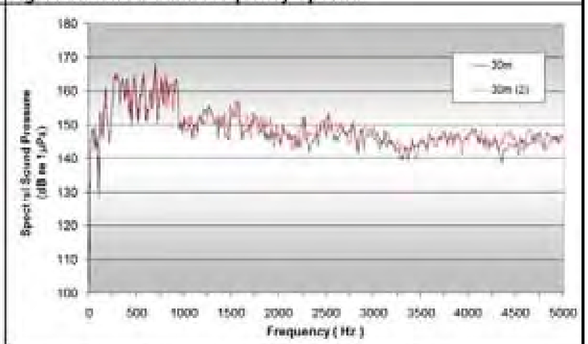


Figure c. Accumulation of Sound Energy

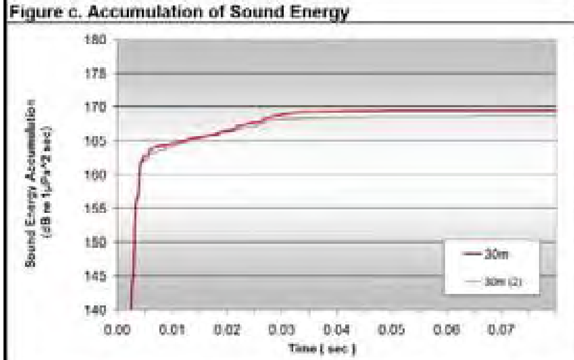


Figure d. Sound Pressure and Sound Exposure Levels

Signal Analysis Sound Pressure / Energy Levels

30meters 11/12/2002	Peak	$RMS_{90\%}$*	SEL
Strike 1	197	181	169
Strike 2	195	180	169

Typical Peak Pressure / Sound Pressure Levels Throughout Drive

	Peak	RMS**
Reported Average	199	181

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

**Standard 35 msec "impulse" RMS time window

Figure I.10-5 Representative Signal Analyses for 30-Inch-Diameter Pile. Pulse received at 30 meters from the pile at the Richmond-San Rafael Bridge.

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-Diameter Piles

1.10.3 Permanent 1.7-Meter- (66-Inch-)-Diameter CIDH Trestle Piles

The 66-inch-diameter piles were CIDH piles 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 to the plywood barriers along the trestle. At most, two piles were driven at night, between 10:00 p.m. and 4:00 a.m. 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-Diameter 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 msec, with most energy contained within 20 msec (very fast). Analyses of strikes farther 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 msec into the event). SEL accumulates quickly with this pulse.

An air bubble curtain test also was performed for these piles, similar to the test conducted for the 30-inch diameter piles. This system was tested for two of the 66-inch-diameter 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 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 effects of the current 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.

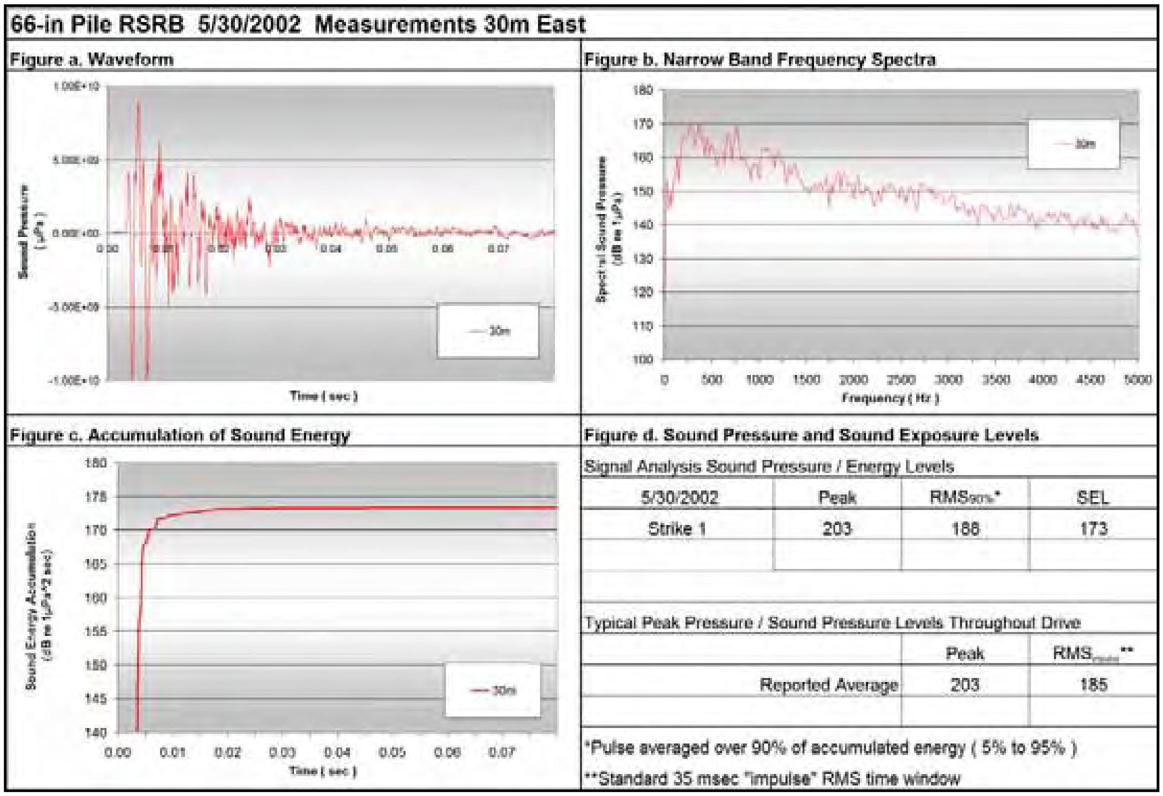


Figure I.10-8 Representative Signal Analyses for 66-Inch-Diameter CIDH Pile. Pulse received at 30 meters from the pile at the Richmond-San Rafael Bridge.

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 – current	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-Diameter CIDH Pile during Tidal Currents

1.10.4 Permanent 3.2-Meter- (126-Inch-) Diameter CISS Piles

These 126-inch-diameter 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 1.5-hour period. The hammer strikes the pile frequently at the beginning (about once per second), but less frequently as the stroke increases. The frequency of pile strikes was about once every 2 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 the 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.

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 m meters. The entire pile driving event was measured at the 10-meter location, while most of the event also was measured at the 230-meter 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 that the primary sound source was through the substrates.

Figure I.10-10 126-Inch-Diameter CISS Pile Being Driven Underwater at the 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

	Sound Pressure Measured in dB		
Position	**Peak**	**RMS**	**SEL**
10 meters	218–208	206–197	--
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 the pile extended through the water column and decreased as the pile was driven closer to the mud line. This variation was less at distant positions.

Interpolations of the data are difficult because measurements were made at only four distances, and two of those were made late in the driving period when close-in levels were lower. The data do indicate that the maximum peak levels of 190 dB and RMS levels of 177 dB occurred at 230 meters 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 msec (see Figure I.10-11). The rise time from the initial disturbance to the peak (or near peak) pressure was about 3 to 5 msec close in, at 10 meters. The rise time at 230 meters was about 6 to 7 msec; however, the peak pressure occurred about 10 msec into the disturbance. Most energy, which makes up the RMS level, occurred during the first 45 to 50 msec. 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.

1.10.5 Permanent 3.8-Meter- (150-Inch-) Diameter CISS Piles

These piles were similar to the 126-inch-diameter piles; they also were 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 22 meters 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 65 meters from the pile.

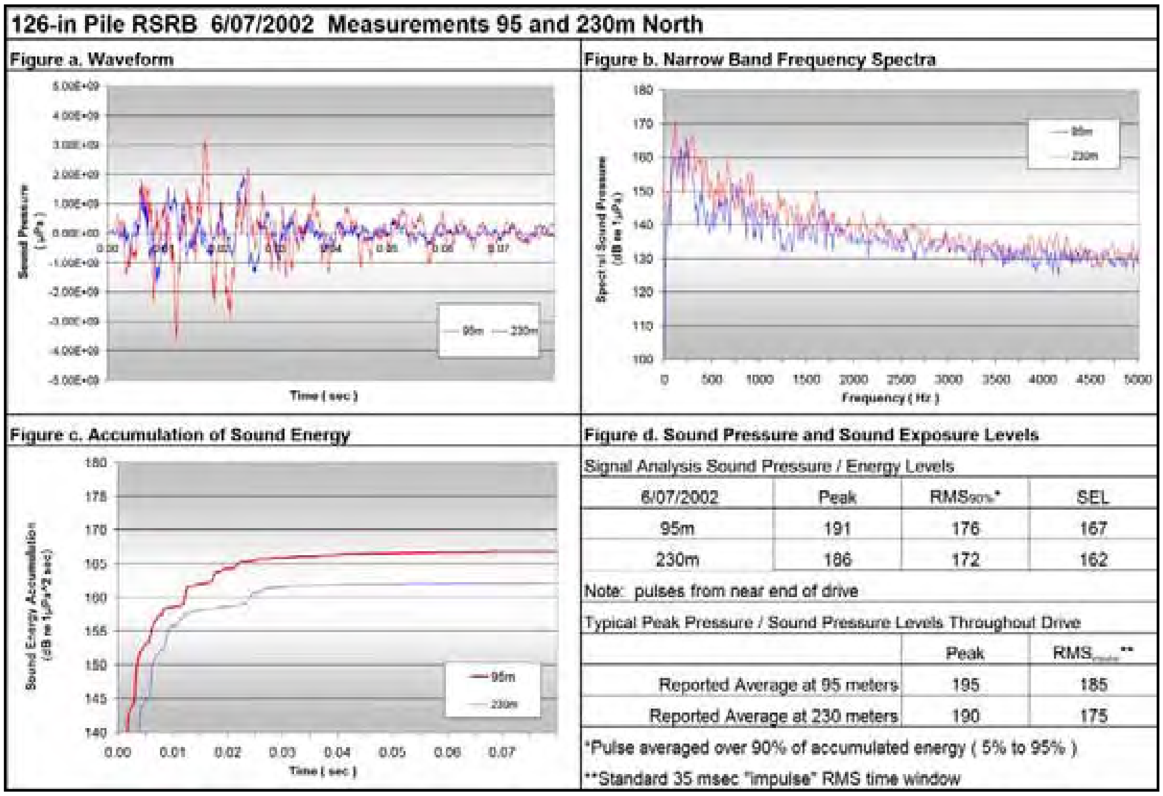


Figure I.10-11 Representative Signal Analyses for 126-Inch-Diameter CISS Pile. Pulse received at 95 and 230 meters from the pile near end of driving event at the Richmond-San Rafael Bridge.

Figure I.10-12 150-Inch-Diameter CISS Pile Being Driven Underwater at the Richmond-San Rafael Bridge

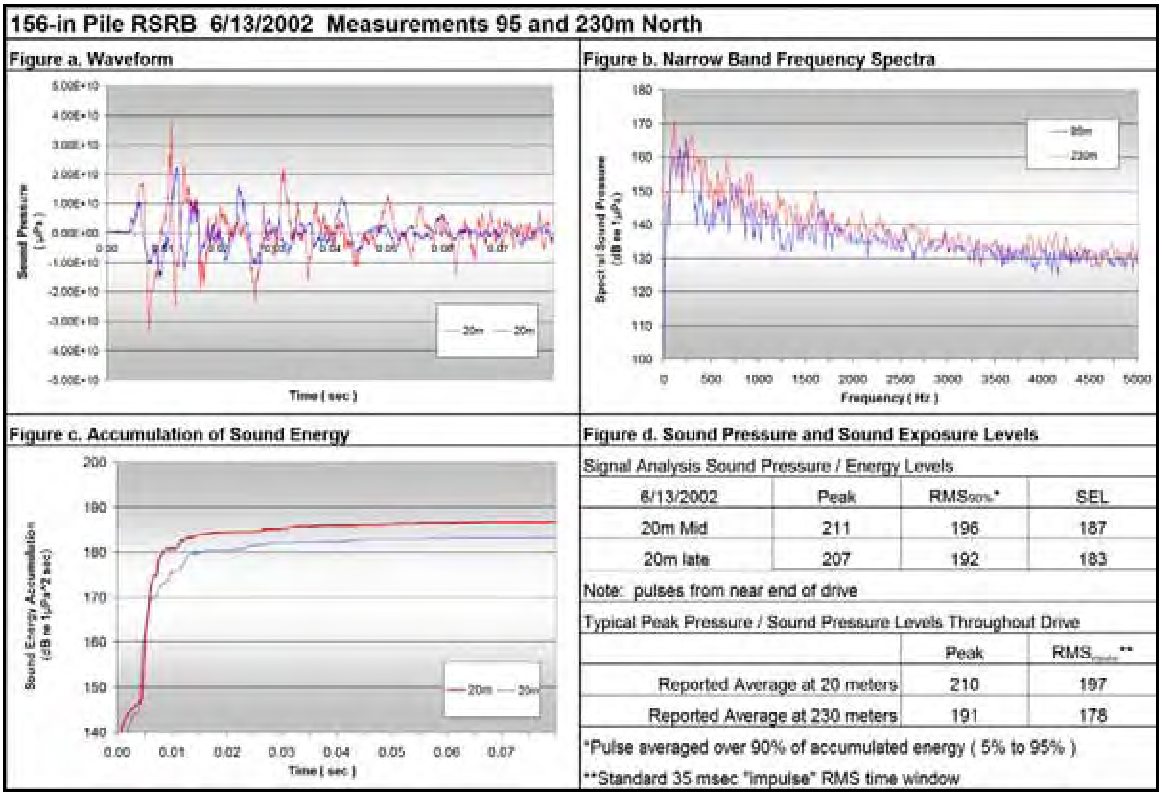
Table I.10-7 Typical Range of Sound Pressures Measured for 150-Inch-Diameter CISS Piles – Unattenuated – Richmond-San Rafael Bridge

Position	Sound Pressure Measured in dB		
	Peak	**RMS**	**SEL**
20 meters	215–205	206–197	--
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 the pile extended through the water column and decreased as the 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 to 189 dB peak and 178 to 180 dB RMS. For the other pile, peak sound pressures were about 203 dB at 50 meters. Underwater sound levels were generally similar to those measured for the 126-inch-diameter 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 is relatively low frequency, similar to the 126-inch-diameter piles measured at 95 meters. The events last over 80 msec, with much of the energy contained in 60 msec.



6/13/2002	Peak	RMS90%*	SEL
20m Mid	211	196	187
20m late	207	192	183

Note: pulses from near end of drive

Typical Peak Pressure / Sound Pressure Levels Throughout Drive

	Peak	RMSimpulse**
Reported Average at 20 meters	210	197
Reported Average at 230 meters	191	178

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

**Standard 35 msec "impulse" RMS time window

Figure I.10-13 Representative Signal Analyses for 150-Inch-Diameter CISS Pile. Pulse received at 20 meters midway and near the end of the driving event at the Richmond-San Rafael Bridge.

1.10.6 References

1. Reyff, J. A. 2003. Underwater Sound Levels Associated with Seismic Retrofit Construction of the Richmond-San Rafael Bridge - Measurements Results for the Driving of Temporary and Permanent Piles. January 31, 2003.

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.

4. Reyff, J. A. 2006. Richmond-San Rafael Bridge Seismic Safety Project – Extent of 208-dB Peak Sound Pressures. June 16, 2006.

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 installation of 0.65-meter- (24-inch-) diameter steel pipe piles for the construction of a temporary construction trestle and 0.91-meter- (36-inch-) diameter and 1.52-meter- (60-inch-) diameter 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 driving of the larger permanent piles; the temporary 24-inch temporary piles were driven without any attenuation. The project tested various sound attenuation systems.

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 an isolation casing/air bubble curtain. Finally, measurements were made at Pier 2 on the Middle Channel Bridge, and Pier 3 of the Samoa Channel.

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

I.11.1 36-Inch-Diameter 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 restruck to perform the various tests. Unattenuated 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.

Figures 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-Diameter 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 – Humboldt Bay Bridges, Eureka, CA

Figure I.11-2c Double-Walled Attenuator – Humboldt Bay Bridges, Eureka, CA

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 the results of underwater 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 also were 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-Diameter CISS Piles during Attenuator Testing – Humboldt Bay Bridges, Eureka, CA

Pile	Position	Sound Pressure Measured in dB		
		Peak	RMS	SEL
Test 1 – Flooded double-walled 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 – Dewatered double-walled attenuator flooded with bubble ring	10 meters	199	188	176
	50 meters	187	176	--
Test 4 – Dewatered double-walled 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 and 8 – 5-foot-diameter single-walled isolation casing bubbled*	10 meters	196	185	174
	100 meters	178	165	153
Test 9 – Unconfined 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 a reduced rate, while Test 8 was bubbled at maximum flow. There was no difference in the sound levels measured.

Signal analyses for the unattenuated pile strikes recorded at 10 meters are shown in Figure I.11-3. These signals were characterized as having a fairly short duration of about 40 msec with a rapid rise time, which is indicated by the fast rate that SEL accumulates. The frequency spectra indicate 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.

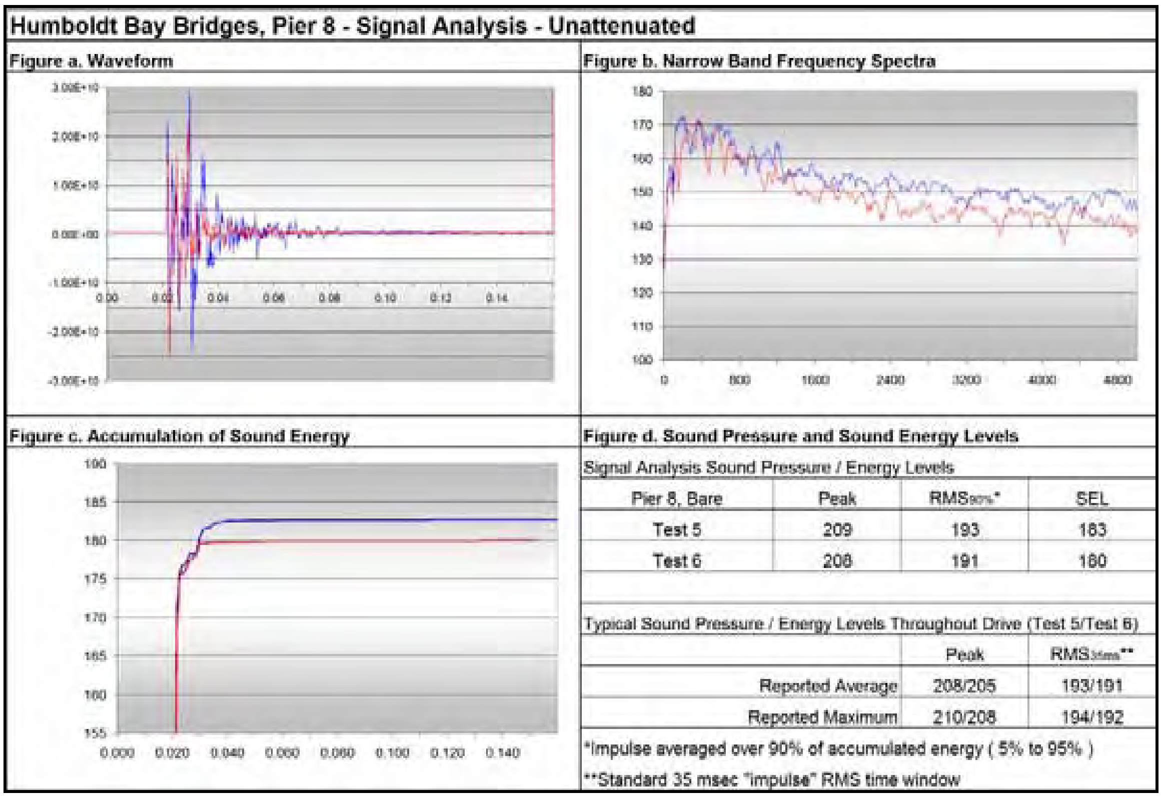


Figure I.11-3 Representative Signal Analyses for Unattenuated 30-Inch-Diameter Pile at 10 Meters – Humboldt Bay Bridges, Eureka, CA

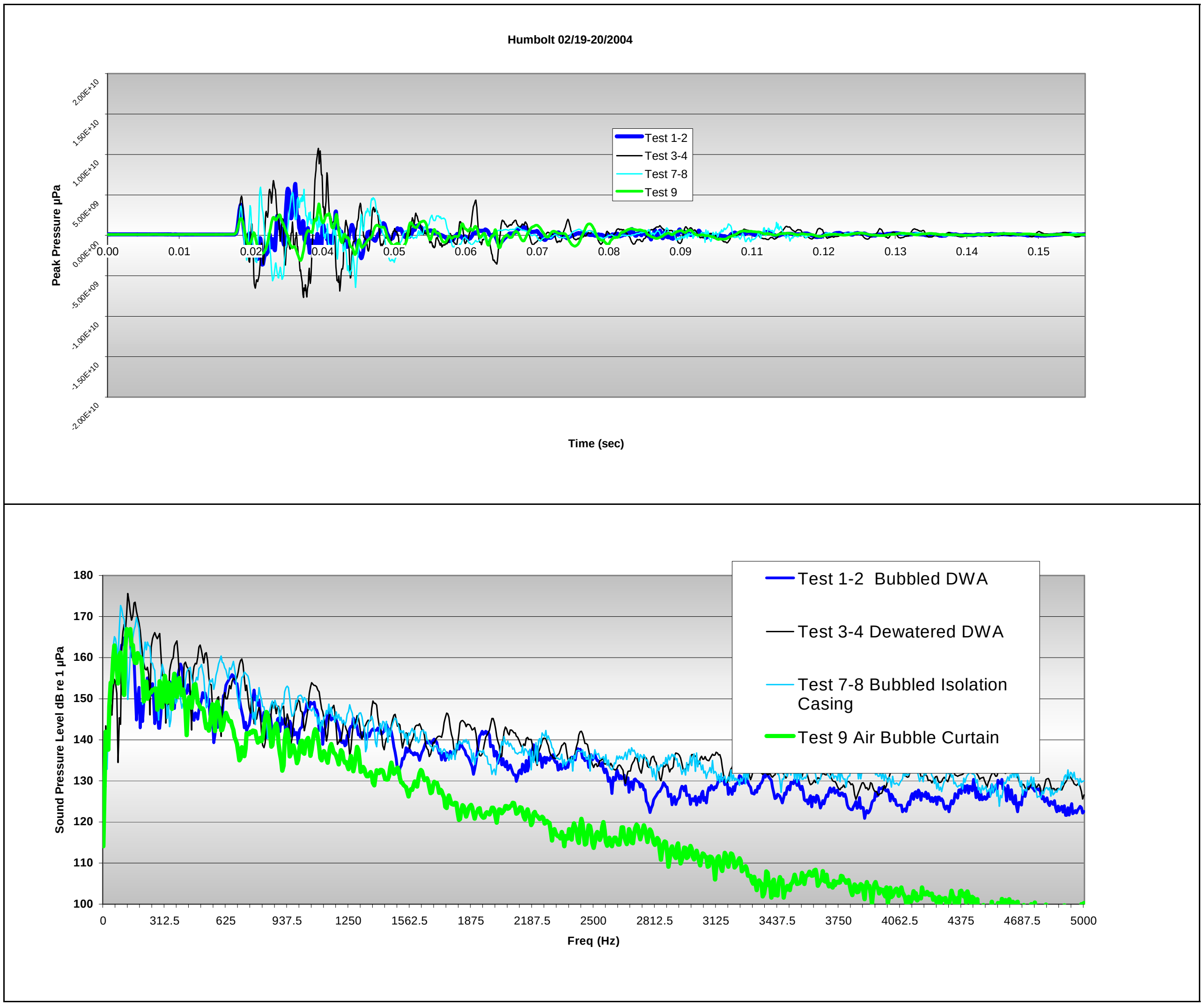


Figure I.11-4 Representative Signal Analyses for Attenuated 30-Inch-Diameter Pile at 10 Meters – Humboldt Bay Bridges, Eureka, CA

I.11.2 60-Inch-Diameter 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 large-diameter isolation casings that were bubbled, as described in Section 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 Diameter Piles – Pier S12, Samoa Channel at Humboldt Bay, Eureka, CA

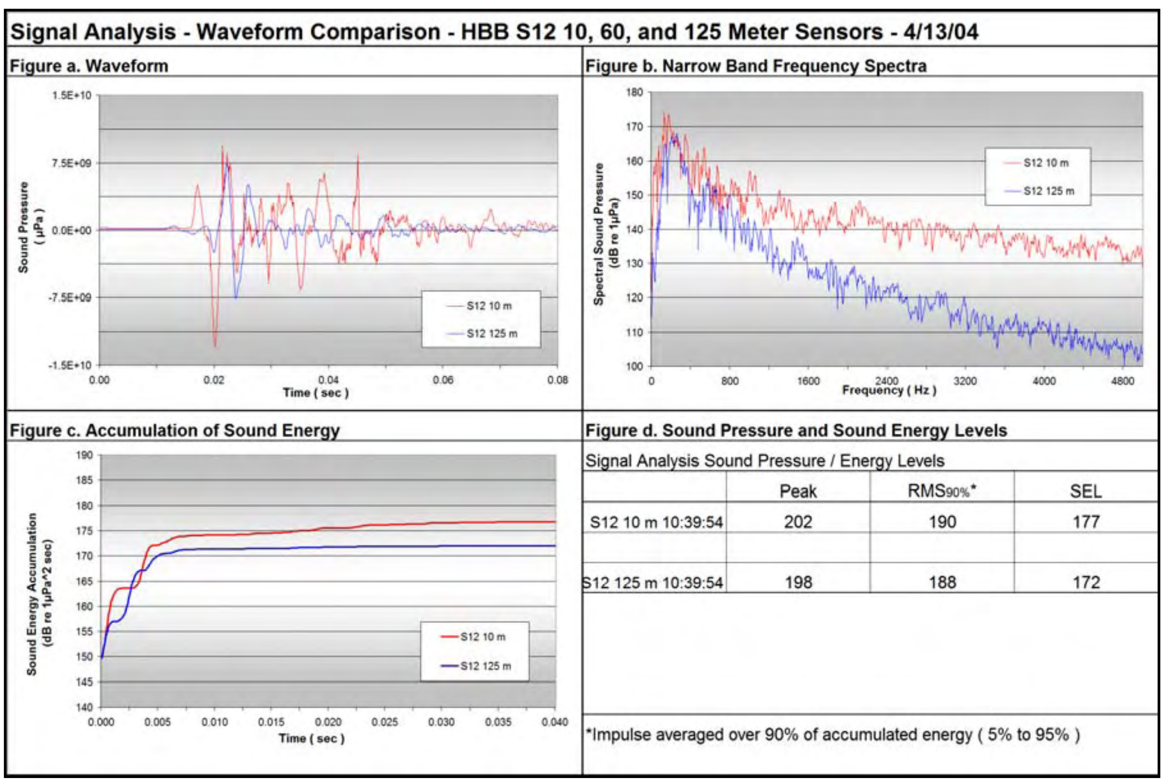
Sound levels varied by about 4 dB throughout the driving event. Figure I.11-6 shows the trend in measured sound pressure levels over the course of the pile-driving event. Sound pressures were highest at the beginning of pile driving and lowest at the end. For the most part, measurements at 10 meters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

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

Conditions	Position	Sound Pressure Measured in dB		
		Peak	RMS	SEL
First part of pile driving ~4 minutes	10 meters west	203	188	177
	10 meters east	202	188	--
	125 meters	197	185	172
Second part of pile driving ~7 minutes	10 meters west	201	198	174
	10 meters east	198	176	--
	125 meters	194	181	169
Third (last) part of pile driving <2 minutes	10 meters west	199	186	--
	10 meters east	199	186	--
	125 meters	194	181	--

The signal analyses 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-diameter 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 Section I.5.5). The 60-inch-diameter 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-Diameter Pile at 10 and 125 Meters – Pier S12, Humboldt Bay Bridges, Eureka, CA



	Peak	RMS90%*	SEL
S12 10 m 10:39:54	202	190	177
S12 125 m 10:39:54	198	188	172

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

Figure I.11-7 Representative Signal Analyses for Attenuated 60-Inch-Diameter Pile at 10 and 125 Meters – Pier S12, Humboldt Bay Bridges, Eureka, CA

I.11.3 36-Inch-Diameter 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 ft-lbs, 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-Diameter 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-Diameter CISS Piles at Pier M2, Middle Channel – Humboldt Bay Bridges, Eureka, CA

Conditions	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 Section 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 compared to the unattenuated signals shown in Figure I.11-3.

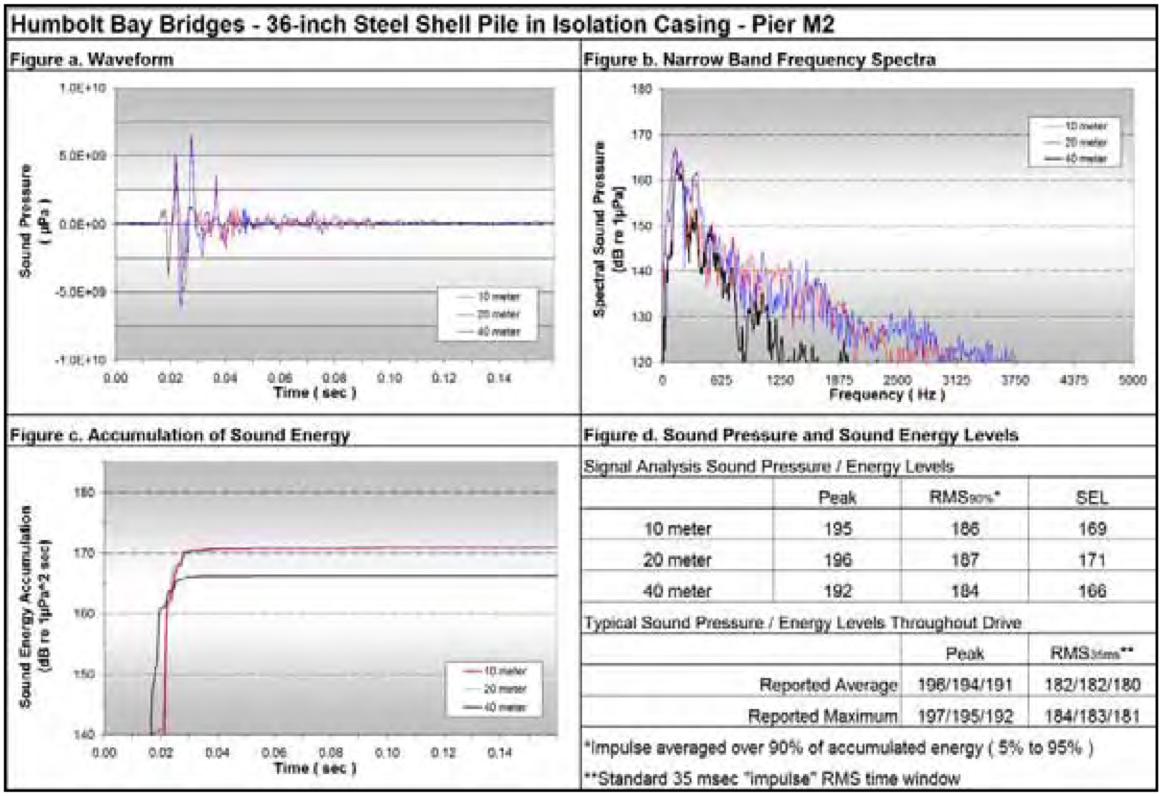


Figure I.11-9 Representative Signal Analyses for Attenuated 36-Inch-Diameter Pile at 10, 20, and 40 Meters – Pier S12, Humboldt Bay Bridges, Eureka, CA

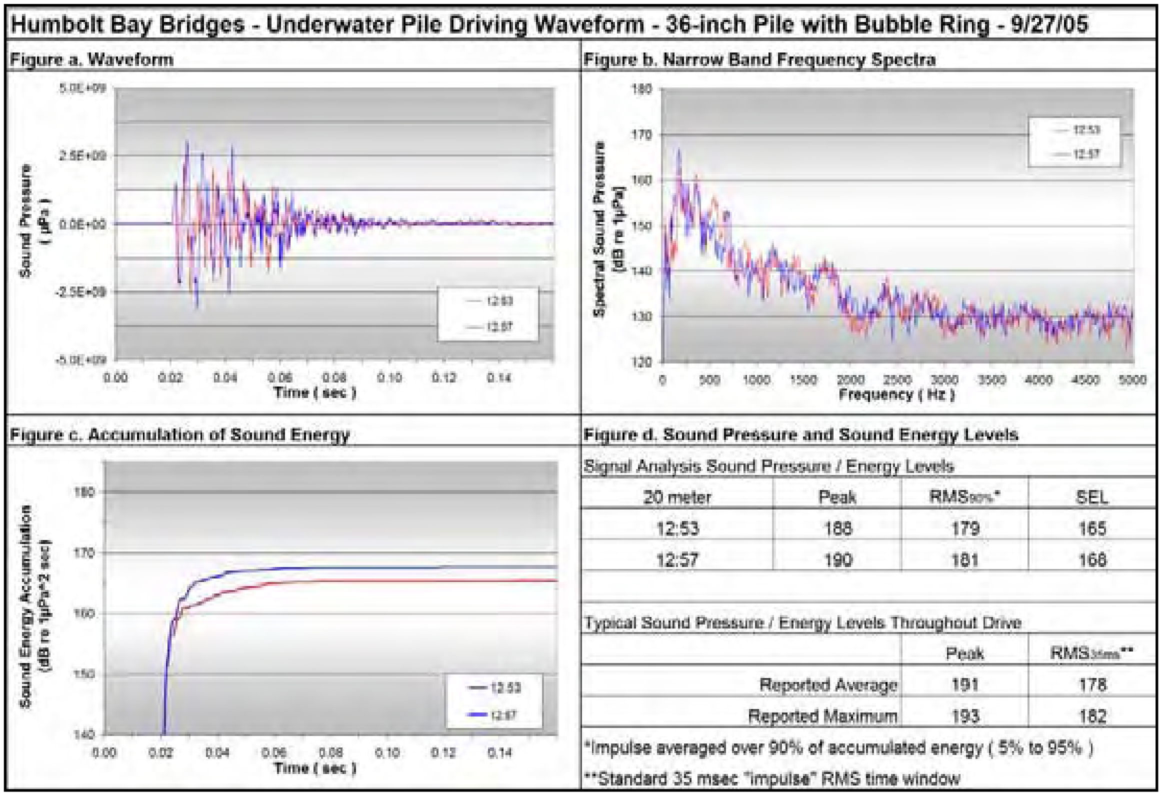
I.11.4 36-Inch-Diameter CISS Piles at Pier S3, Samoa Channel – Production Driving

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, as 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 approximately 7-minutes of pile driving.

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

Conditions	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 performed only 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 msec, while the pulses at Pier S3 had most energy in about 40 msec. The amplitude of the Pier S3 pulses was generally lower.



Signal Analysis Sound Pressure / Energy Levels

20 meter	Peak	$RMS_{90\%}$*	SEL
12:53	188	179	165
12:57	190	181	168

Typical Sound Pressure / Energy Levels Throughout Drive

	Peak	RMS_{35ms}**
Reported Average	191	178
Reported Maximum	193	182

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

**Standard 35 msec "impulse" RMS time window

Figure I.11-10 Representative Signal Analyses for Attenuated 36-Inch-Diameter Pile at 20 Meters – Pier S3, Humboldt Bay Bridges, Eureka, CA

I.11.5 References

1. Reyff, J. and Rodkin, R. 2004. An Assessment of Underwater Sound Impulses Generated from Humboldt Bridge Pile Driving Tests. March 18, 2004.

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

3. Illingworth & Rodkin, Inc. *Data files of unpublished measurements for pile driving at Pier M2, Humboldt Bay Bridges on June 7 and 8, 2005*.

4. Illingworth & Rodkin, Inc. *Data files of unpublished measurements for pile driving at Pier S2, Humboldt Bay Bridges on September 27, 2005.*

Appendix II Procedures for Measuring Pile Driving Sound

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List of Acronyms

µPa	micro-Pascal(s)
dB re: 1µPa	decibel(s) referenced to 1 micro-Pascal
dB	decibel(s)
Department	California Department of Transportation
FFT	Fast-Fourier Transform
Hz	hertz
kHz	kilohertz
RMS	root mean square
$RMS_{90\%}$	effective root mean square sound pressure level
SEL	sound exposure level
TeNS	*Technical Noise Supplement*
TNAP	*Traffic Noise Analysis Protocol*

Appendix II Procedures for Measuring Pile Driving Sound

II.1 Introduction

This appendix describes a proposed methodology for measuring the sounds associated with underwater pile driving. Several key issues complicate the measurement of pile driving noise, including:

- A lack of uniform terminology,
- Variables in oceanic conditions during surveys and monitoring, and
- Differing approaches to field measurement and resultant data.

Different measurement descriptors are used to describe underwater sounds as they may affect marine resources. Accordingly, it is critical when making underwater sound measurements to adequately define the descriptors. It is useful, and sometimes required, to collect "real-time" data and report it immediately after a monitoring event. If this is necessary, it is important to select a descriptor that can be readily measured in the field. The underwater noise environment surrounding pile driving is typically very complex because of variable water depths and currents, combined with numerous physical obstructions and interfering noise sources that can affect noise measurements.

Researchers and resource agencies are trying to understand the impacts of pile driving in marine environments through use of field measurement data gathered from various projects and from a variety of research agencies. It is therefore imperative that the data arising out of such field measurements are consistent in terms of quality and content to allow meaningful comparisons between projects.

Since 2000, numerous measurements of underwater sound from pile driving have been collected at the request of the California Department of Transportation (the Department), constructors, and other stakeholders. Experiences and the data obtained from these measurements have provided a basis for development of a standardized measurement methodology. Proper, safe, and efficient methods were established based on familiarity with the many problems associated with conducting such measurements in a marine construction environment. The methodology outlined in this document establishes standard measurement distances and depths for hydroacoustic monitoring, monitoring durations, proper calibration, and field documentation methods. In addition, requirements for the analysis of underwater signals are described, including the capability requirements for the instrumentation, noise metrics that must be evaluated both in the time and frequency domains, and suggested data presentation templates. A range of information is provided so that instrumentation specifications necessary to accurately measure underwater sound levels from pile driving can be developed.

This appendix contains the following sections:

- Noise Descriptors,
- Underwater Sound Measurement Methodology,
- Analysis of Data and Recorded Sounds,
- Quality Control, and
- Reporting.

II.2 Noise Descriptors

Various descriptors are used to characterize noise levels, depending on the noise source and environment. The Department *Traffic Noise Analysis Protocol* (TNAP) and the *Technical Noise Supplement* (TeNS) contain explanations of the noise descriptors normally associated with traffic noise. Common descriptors used in environmental noise studies evaluating airborne noise are shown in Table II-1.

Table II-1. Common Airborne Noise Descriptors

Noise Descriptor	Definition
$\mathbf{L_{max}}$ (maximum noise level)	The highest instantaneous noise level during a specified period. This descriptor is sometimes referred to as “peak (noise) level.” The use of “peak” level should be discouraged because it may be interpreted as a non-RMS value noise signal (see Sec. N-2133 of TeNS for difference between peak and RMS noise signals).
$\mathbf{L_x}$ (a statistical descriptor)	The noise level exceeded X percent of a specified time period. The value of X is commonly 10. Other values of 50 and 90 are also used. Examples: L_{10}, L_{50}, L_{90}.
$\mathbf{L_{eq}}$ (equivalent noise level) – routinely used by the California Department of Transportation and the Federal Highway Administration to address the worst noise hour ($L_{eq}^{[h]}$)	The equivalent steady-state noise level in a stated period of time that would contain the same acoustic energy as the time-varying noise level during the same period.
$\mathbf{L_{dn}}$ (day/night noise level) – commonly used to describe the community noise level	A 24-hour average with a “penalty” of 10 dBA added during the night hours (2200–0700). The penalty is added because this time is normally sleeping time.
CNEL (community noise equivalent level) – a common community noise descriptor; also used to describe airport noise	Same as the L_{dn} with an additional penalty of 4.77 dBA (or 10 Log3) for the hours 1900–2200, which are usually reserved for relaxation, TV, reading, and conversation.
SEL (single-event level) – used mainly for aircraft noise; it enables comparing noise created by a loud but fast overflight with that of a quieter but slow overflight.	The acoustical energy during a single noise event, such as an aircraft overflight, compressed into a period of 1 second, expressed in decibels.

Airborne environmental noise descriptors typically are based on human hearing. The A-scale frequency-weighting network, abbreviated dBA, was developed to provide a single-number measure of a sound level in air across the human audible frequency spectrum. The A-weighting filter network has no direct application to assessing the effects of underwater pile driving noise on fish and marine mammals. The noise descriptors that are used to assess hydroacoustic noise are based on the linear (un-weighted) frequency spectrum, abbreviated dB. Given the frequency content of the pile driving pulses and the limitations of instrumentation that is commonly available to noise analysts, the un-weighted frequency spectrum is limited to the frequency range of 20 hertz (Hz) to 10 kilohertz (kHz) to accommodate the data acquisition of pile driving pulses from a wide variety of pile types and conditions.

All sound levels represented in decibels are related to a reference pressure. For airborne sound, the reference pressure is 20 micro-Pascals (µPa) (threshold of hearing human). For underwater sound, the reference pressure is 1 µPa. The 1- µPa reference pressure is mathematically convenient but results in a mathematical offset of +26 dB when compared to decibels based on the 20-µPa reference pressure.

When a pile driving hammer strikes a pile, a vibratory motion is created that propagates through the pile and radiates a pulse into the water and the ground substrate, as well as into the air. The rise and fall of the sound pressure pulse, represented in the time domain, is referred to as the *waveform*. The *peak pressure* is the highest absolute value of the measured waveform, and can be a negative or positive pressure peak. The root mean square (RMS) level for the pulse is calculated by computing the average of the squared pressures over the time that comprises the portion of the waveform containing 90 percent of the sound energy.[1] This RMS term is described as the *effective RMS level* and is abbreviated $RMS_{90\%}$ in this report. The $RMS_{90\%}$ level can be approximated for impact pile driving by measuring the signal with a precision sound level meter set to the "impulse" RMS setting All peak pressures and RMS sound pressure levels are expressed in decibels referenced to 1 µPa (dB re: 1µPa). Another measure of the pressure waveform that can be used to describe the pulse is the sound energy in the pulse. The total sound energy in the pulse is described using various terms. Assuming plane wave propagation, the total sound energy can be considered equivalent to the un-weighted sound exposure level (SEL), a common unit of sound energy used in airborne acoustics to describe short-duration events. The unit for SEL is dB re: $1\mu Pa^2$-sec.

Figure II-1 shows a sample pile driving waveform and the various acoustical descriptions associated with the signal.

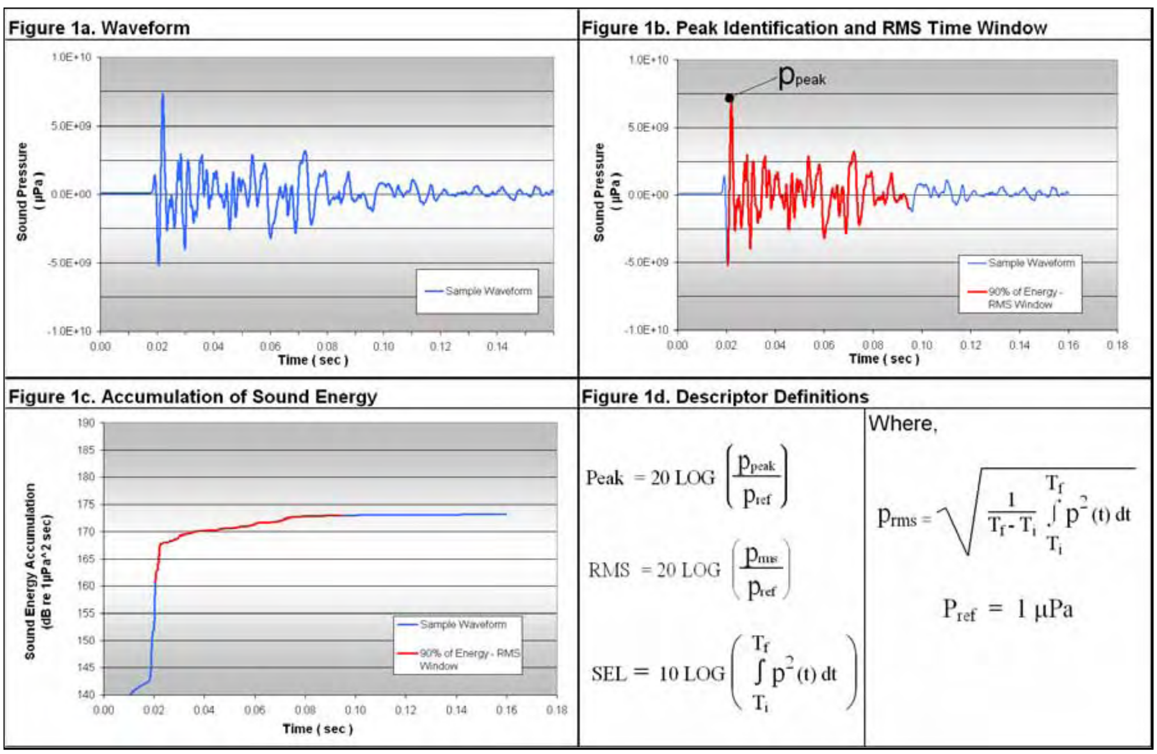

Figure II-1. Acoustical Descriptors Associated with a Pile Driving Waveform

The waveform, or time history, shown in the first panel of Figure II-1 presents the variation in pressure over time from a single pulse. The pressure is shown in micro-Pascals, and the time shown is in hundredths of a second (Figure 1a). Figure 1b shows the peak pressure for this sample pulse and the portion of the waveform from which the effective pressure ($RMS_{90\%}$) is calculated. Figure 1c shows how

[1] Richardson, Greene, Malone & Thomson, *Marine Mammals and Noise*, Academic Press, 1995; and Greene, personal communication.

acoustical energy accumulates over the duration of the pulse. It can be seen that the energy accumulates most rapidly at the beginning of the pulse, coinciding with the time when the peak pressure occurs. The rate of accumulation of energy varies, depending on the rise time to the peak pressure and the frequency content in the pulse. The resultant level in the sample shown in the Figure 1c (173 dB re: 1μPa^2 -sec) is the sound exposure level for this sample. Figure 1d summarizes the equations used to calculate the descriptors. The procedure for analyzing the signals and calculating the noise descriptors will be described later in this appendix.

To summarize, the three relevant single-number descriptors used to describe the acoustical pulse resulting from an impact pile driver are:

- **Peak/Sound Pressure Level:** The maximum absolute value of the instantaneous sound pressure that occurs during a specified time interval, measured in dB re: 1μPa (e.g., 198 dB Peak).

- **Effective Root Mean Square Sound Pressure Level:** A decibel measure of the square root of mean square (RMS) pressure. For pulses, the average of the squared pressures over the time that comprises that portion of the wave form containing 90 percent of the sound energy of the impulse in dB re: 1μPa is used (e.g., 185 dB RMS).

- **Sound Exposure Level:** The integral over time of the squared pressure of a transient waveform, in dB re: 1μPa2–sec. (e.g., 173 dB SEL). This is an approximation of sound energy in the pulse.

Most sounds, including the sound of a pile driving pulse, are composed of many different frequencies, referred to as the *frequency spectrum* of a sound. This concept is discussed in Section N-2137 of TeNS[2]. In hydroacoustics, frequency spectra are usually presented in 1/3 octave bands or “narrow bands” that normally have a constant bandwidth of 6 or 12.5 Hz. An example 6-Hz narrowband frequency spectrum is shown in Figure II-2. Frequency is measured in cycles per second, designated as Hz. When characterizing a sound pressure spectrum for a waveform, the unit of amplitude is typically the RMS pressure measured over a defined frequency bandwidth.

Frequency spectra are important because the frequency content of the sound may affect a species response to the sound (for physical injury as well as hearing loss). From an engineering standpoint, the frequency spectrum is important because it affects the expected sound propagation and the performance of sound attenuation systems, which are also frequency dependent. The frequency content of pulses is often requested by resource agencies.

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[2] *Technical Noise Supplement* (TeNS). A technical noise supplement to the *Traffic Noise Analysis Protocol*. California Department of Transportation. October 1998.

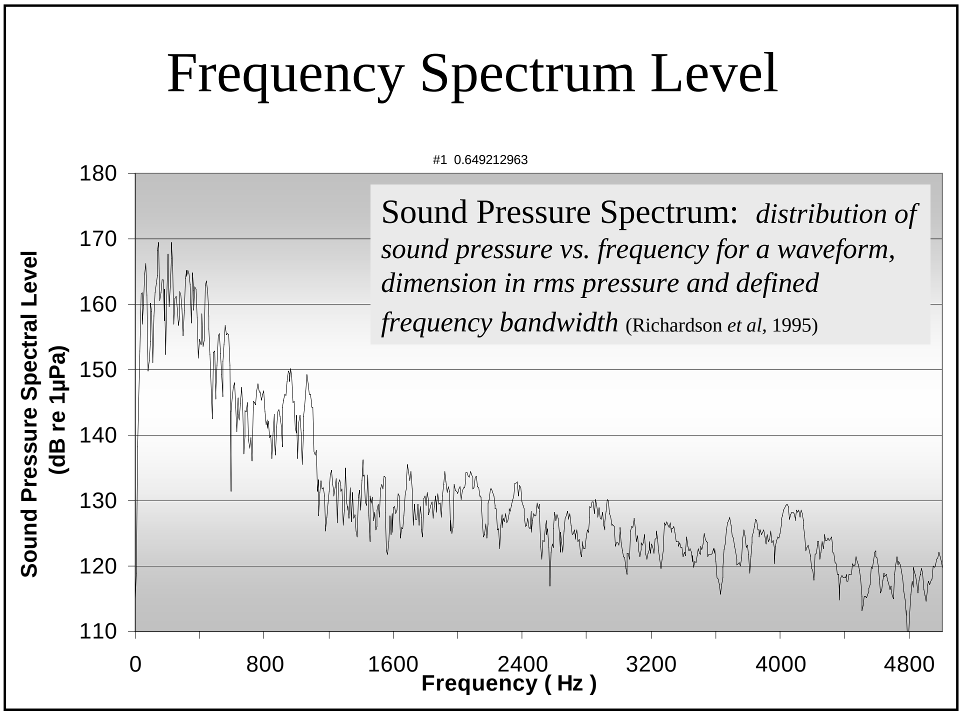

Figure II-2. Sample Narrowband Frequency Spectrum

II.3 Underwater Sound Measurement Methodology

II.3.1 Measurement Equipment

The instruments used for measuring, recording, and analyzing hydroacoustic data from pile driving are available from a wide variety of manufacturers, and different types of systems can be used to accomplish the task. Following the recommendations in TeNS, this guidance manual does not provide detailed information regarding the instrumentation used to collect and analyze hydroacoustic data nor endorse certain manufacturers. It is strongly recommended that the Department Headquarters Noise and Vibration unit be consulted before purchasing or using any noise instrumentation for the collection of hydroacoustic data.

Figure II-3 depicts a typical setup using a single hydrophone, single-channel system. A photograph of an actual field measurement system is included as Figure II-4. The signal is detected with a hydrophone, which serves the same function as the microphone on a sound level meter and is constructed like an accelerometer used for vibration measurements. Some examples of pressure sensors, including a blast transducer and two hydrophones that would be appropriate for this type of measurement system, are shown in Figure II-5. The hydrophone must be completely waterproof and corrosion resistant, electrically stable, rugged enough to withstand pile driving site conditions, and sufficiently sensitive to produce a signal that can be measured and analyzed. To maintain a waterproof seal, the hydrophone and cable are an integral assembly, which is supplied by the manufacturer. Extension cables with waterproof connectors are available. A 100-foot (30-meter) cable has proven to be adequate for all projects that have been completed to date. The electrical signal generated by the hydrophone is passed through a charge converter and then to a power supply that acts as a pre-amplifier; consequently, a strong, clear signal can be sent to the data recorder and real-time measurement system.

General performance standards are recommended based on the experience gained through measurements on numerous projects. Peak sound pressure levels generated by marine pile driving at measurement positions close-in to the pile and out to distances of several hundred meters normally fall within the 140 to 230 dB re: 1µPa (a dynamic range of 90 dB). Conditions are rugged; therefore, the selected hydrophone should be of medium sensitivity and resistant to damage. Based on these two criteria, and the possibility that it may be desirable to standardize around a single sensor for ease of calibration and analysis, a "miniature type" hydrophone has been found to serve very well. This hydrophone is available from different manufacturers, including Bruel & Kjaer (Type 8103), Reson (Type TC4013), and G.R.A.S. (Type 10CT). These hydrophones have a flat frequency response from less than 1 Hz to at least 170 KHz, meaning there is no correction necessary for signals that contain data over this frequency range. As previously noted, the sound energy in pile driving pulses is concentrated between 20 Hz and 10 KHz, which falls well within the measuring range of these hydrophones. The sensitivity of these hydrophones is about -211 dB re: 1 volt per µPa (the exact sensitivity varies with manufacturer). Experience has proven that the measuring system can accept up to about 1 volt before saturating (or overloading). The measurement system with a hydrophone of this sensitivity can measure pulses with a peak pressure of up to about 212 dB re: 1µPa with a uni-gain (one-to-one) charge converter. To measure higher peak pressures, it is recommended that a charge converter or charge amplifier be used that can attenuate the signal from the hydrophone. An inexpensive charge converter with 20-dB step attenuation built into it can replace the uni-gain charge converter and accomplish this task. The power supply should include amplifiers that can be adjusted in accurate discrete steps (e.g., 6 dB or 20 dB) to amplify the signal. This allows low-level signals to be accurately recorded. Suitable power supplies are available from Bruel & Kjaer, G.R.A.S., PCB, and other manufacturers.

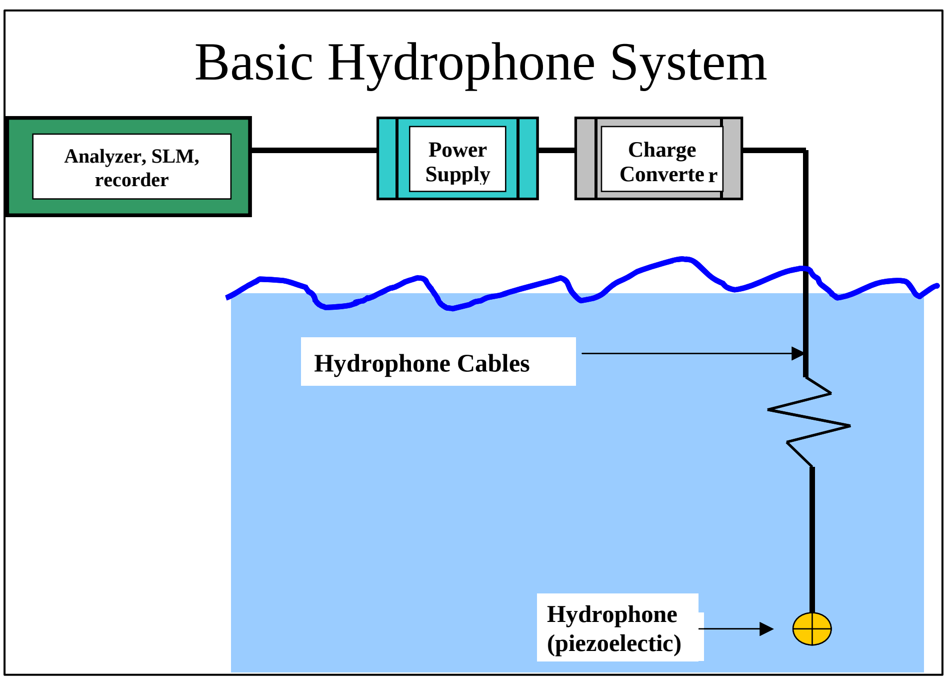

Figure II-3. Schematic of a Basic Hydrophone System

Figure II-4. Example of a Field Measurement Setup

Figure II-5. Example of Different Pressure Sensors

It is important to record the hydroacoustic data from a pile driving project so that subsequent detailed analyses of the signals can be completed. An accurate real-time measurement of the peak pressure and an estimate of the effective RMS pressure during the pile driving also should be made. These data are used as a point of reference when subsequently analyzing signals and are sometimes of critical interest to (for example, to determine the effectiveness of mitigation measures in the field, or the size of the area where marine mammal monitoring is required). Traditionally, data have been tape-recorded on digital audiotape recorders to provide an accurate recording over the frequency range of interest. Digital solid state recorders that record directly to a hard drive or flash card are now available and should be given serious consideration when purchasing new instrumentation, as digital audiotape recorders may soon become obsolete. The recording system should sample at a rate of at least 44 KHz, have a dynamic range of at least 80 dB, and meet numerous other specifications for precision professional data recording. To provide real-time information, a precision integrating sound level meter (such as the Larson-Davis 820, which is used routinely in highway noise measurement) has proven to be an excellent measurement system for spot-checking data in the field. To be useful, the real-time instrument must be able to measure in sequential one-second or shorter intervals, measure the linear (un-weighted) peak pressure accurately, and measure either the un-weighted or C-weighted (RMS) sound pressure level using the standard "impulse" time constant. The C-weighted impulse RMS time constant setting has proven to provide a good estimate of the un-weighted RMS 90 % sound pressure level (i.e., the effective RMS).

Note: It is critical that the power consumption of the instrumentation is well understood and that the battery life of all the batteries is known so that batteries may be replaced, if necessary, during the measurements. In addition, the instruments used must have sufficient memory storage.

II.3.2 Measurement Sampling Positions

There are several considerations in the selection of sampling positions:

- Location of species of interest,
- Safety for the operator and instrumentation,
- Consistency with other studies,
- Environmental factors at the job site,
- Pile driving scenario, and
- Meeting threshold requirements.

Before 2000, no protocols existed for conducting hydroacoustic measurements of underwater pile driving projects. Limited work had been done at only a few locations in the world. In conversations with the National Marine Fisheries Service, it was agreed that a sampling position 10 meters from the pile would be established as a standard reference distance for small piles. This distance was selected because it was believed to be safe for instrumentation and the noise analyst. For large-diameter steel pipe piles, jobsite conditions sometimes dictate a distance farther from the pile. The number of sampling positions depends on the characteristics at the job site. These characteristics include whether the site is adjacent to shore or in open water, whether the effects of water currents are important at a particular site, and whether a noise abatement system is in place. The presence of a noise abatement system sometimes complicates the feasibility of obtaining measurements at the 10-meter reference position. For example, the dimensions of a cofferdam may exceed 10 meters or place the cofferdam walls very close to a 10-meter distance from the pile. A bubble curtain system can create water turbulence at distances of 10 meters that render the environment unsuitable for hydroacoustic measurement. Under these conditions, a site-specific close-in reference position must be found and specified. Normally, a secondary distance of 20 meters can be accommodated within the constraints imposed by site conditions.

Additional measurements at greater distances are sometimes required by regulatory agencies. The measurement positions are normally specified in the orders or developed as part of a Noise Monitoring Work Plan. To establish attenuation rates, at least three positions at different distances should be used.

The depth of the hydrophone in the water column also must be considered at each location. Several factors must be considered when determining the depths at which the measurements would be made.

These include the depth at which the fish species of concern (or marine mammals) may be found most frequently, the depth of the water at the measurement location, and the effects of proximity to the surface or bottom on the accuracy of the noise measurement. Small changes in hydrophone depth within about 1 meter of the water surface cause large changes in measured noise levels. This makes repeatable measurements difficult to obtain, so measurements at depths of less than 1 meter are not recommended. In water that is more than 1 meter deep and less than 3 meters deep, a single measurement at low-depth is appropriate to characterize hydroacoustic pressures in the water column. Currently, regulatory agencies have requested hydroacoustic data at a depth of 3 meters. Two measurements, one at 1 meter below the surface and one positioned 1 meter from the bottom are normally sufficient to characterize acoustic pressures in the water column. A third measurement at mid-depth may be added or may be used as an alternative to the position 1 meter from the surface, depending on the depth of the water and the expected location of fish in the water column.

II.3.3 Procedures

The measurement and analysis of underwater noise from pile driving requires a thorough understanding of basic acoustic principles and specific training in the use of the instrumentation described above. This discussion assumes that the noise analyst is trained in and proficient with the use of acoustical instrumentation and recording systems.

II.3.3.1 Instrumentation Field Calibration

The measurement system must be calibrated prior to conducting a field measurement. Hydrophones are shipped from the manufacturer with a specified sensitivity. Using this sensitivity it is possible, but difficult, to measure correct levels from the real-time and recorded signals. Acoustical calibrators, therefore, must be used to calibrate the instrumentation system. The calibration should first be conducted in the office or lab prior to going to the job site. A second calibration should be conducted after transportation to the field, to confirm that the systems are correctly working and are still in calibration.

At low frequencies, the sensitivities of the recommended hydrophones are the same in air as they are in water. Calibration at a single calibration frequency is a valid method to use.[3] Hydrophone calibrators are available from various manufacturers. These are similar to standard acoustical calibrators but are normally of the pistonphone type rather than the electronic tone type of calibrator. The pistonphone generates a signal at 250 Hz. Because hydrophones come in different shapes and sizes, the appropriate coupler must be attached to the pistonphone. The relationship of the coupler volume to the hydrophone size affects the dB level of the calibration tone. The corrected calibration level must be supplied by the manufacturer for the specific calibrator, coupler, and hydrophone to be used. Pistonphones are typically rated in dB re: 20µPa. As an example, a pistonphone may be rated at 114, 124, or 134 dB re: 20µPa. This must be adjusted for the reference pressure of water by adding 26 dB, so that the rated calibration level would become 140, 150, or 160 dB re: 1µPa, respectively. The adjustment to correct for the coupler/hydrophone volume is then added. The system shown in Figure II-6 utilized a 114 dB re: 20µPa (140 dB re: 1µPa) pistonphone, and the manufacturer-supplied coupler with a “miniature hydrophone” has a coupler correction of +5.3 dB, so the calibration level is 145.3 dB (114 dB + 26 dB + 5.3 dB) re: 1µPa at 250 Hz. The instrumentation can be calibrated to the known calibrator signal level. Any attenuation or amplification that is supplied by the charge converter/amplifier or power supply must be accounted for when calibrating the sound level meter or data recorder and noted in the field logbooks. It

[3] Application Notes, *Introduction to Underwater Acoustics*, Bruel & Kjaer.

is recommended that all gain settings be set to uni-gain for initial calibration of the system. The calibration level should be recorded on the real-time sound level meter and the data recorder. All settings should be noted in the logbook, and all instrumentation that is part of each system should be noted in the logbook.

Again, the instrumentation calibration should be verified in the field prior to conducting measurements. Ideally, this would be done at the location where the equipment is to be deployed, just prior to conducting measurements. Sometimes this is not possible if pile driving or other very noisy activities have already begun at the site. Under these conditions, the calibration must be conducted at a relatively quiet location prior to deploying the instrumentation at the job site. At the time of the field calibration, the instrumentation should be configured identically with the same components as during the pre-field calibration. This should be confirmed through notes in the logbook. Calibration levels should again be noted, as well as each of the instrumentation settings. The calibration signal should be listened to through headphones to confirm that there is no electrical noise.

II.3.3.2 Setup and Locations

Measurement locations must be determined in the field. As previously discussed, measurement distances and directions are normally specified in the orders from the resource agency and confirmed in the work plan. To determine the appropriate distance at a marine construction site, hand-held range finders, accurate to within +/- 1 meter at distances ranging from 10 to 1,000 meters, are typically used. Safe positions must be selected in consultation with the pile driving contractor. The instrumentation should be placed in waterproof field boxes to allow for the measurement of marine pile driving under wet or poor weather conditions. Measurements are normally made from the pile driving barge, from a boat attended by the noise analyst, or from instrumentation left unattended in a secured raft.

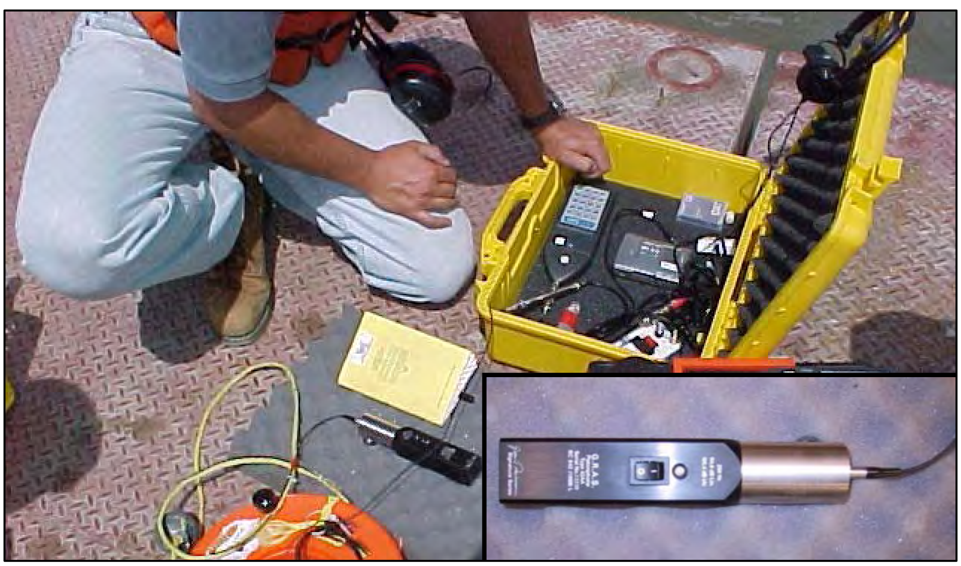

Figure II-6. Calibration in the Field

Once the locations have been identified and the instrumentation calibrated, the hydrophones are deployed to the specified depths. Measurement systems using at least two channels are recommended so that measurements may be made for two depths at each location with a single measurement system. The current of the water (or swiftly moving water in a river) can complicate the measurement location setup, as it will tend to move the hydrophones away from the desired depths and locations. The effects of the current on the hydrophone placement can be overcome variously by attaching the hydrophone to a line that contains a large weight, or by sinking an anchor and running the hydrophone line down the anchor line. Another problem related to water current, called "strumming" of the hydrophone line, occurs when the current induces a vibration in the hydrophone line that causes an audible noise in the system. This has been minimized by either attaching streamers to the hydrophone line or by taking the load off of the hydrophone line through secondary support. If there is a strong current, this should be noted in the logbook and accounted for as well as possible. Recorded signals should be monitored through headphones to confirm that systems are working properly and extraneous noise has been minimized. Current can produce considerable noise that could be mistaken as pile driving noise.

All instrumentation should be monitored periodically during the measurements to confirm that battery power has not been lost, storage media have not been filled up (tapes or digital media), and all cables and connectors are secured. Once the measurement session has concluded, instrumentation must be shut down and carefully stowed. All "live" data collected on data loggers should be downloaded from the instrumentation to a notebook computer. An appropriate file-saving protocol should be developed and followed so that there is no confusion later regarding the location or content of data files. All live data should be translated into file format suitable for storage in Excel, or whatever data management software is being utilized, then reviewed and annotated with information including date, location, and any special notes that may be applicable to the data set. If digital audio tape recordings have been made, the tapes should be properly labeled, including data, measurement location, and instrumentation system. If digital storage media have been used in the collection of data, these data should be treated like live data and transferred to a notebook computer. The flash card or other digital media should be labeled and safely stowed.

II.3.3.3 Safety

Safety for the noise analyst and instrumentation is a paramount consideration when conducting hydroacoustic measurements at a pile driving site. Use common sense. Wear all of the mandated safety gear, which normally includes hard hat, safety glasses, foam earplugs and ear muffs, an appropriate life jacket meeting the specifications for the jobsite, a whistle and safety light, long pants, and steel-toed boots. Pay attention to what is going on around you at all times, as very large pieces of equipment will be moved in proximity to the noise analyst and the measurement instrumentation. The construction contractor's onsite foreman should be made aware of your presence.

II.3.3.4 Field Logbooks

Good field notes are crucial. As previously noted, the calibration exercise must be documented for each measurement procedure. A small diagram of the instrumentation should be included in the logbook. After positioning the hydrophone, a sketch should be included in the logbook showing the relationship of the pile to the hydrophone and any other noteworthy obstructions (e.g., locations of barges, or proximity to a wharf). Sometimes an array of piles is in place and this should be noted, as well as the location of the pile being driven, because the existing piles can affect measured signals. The following should be noted at a minimum:

- All instrumentation settings,
- Date,
- Times pile driving begins and ends,
- Water depth,
- Hydrophone depth,

- Water conditions (e.g., surface waves and current),
- Distance to pile,
- Pile type and size,
- Soil composition,
- Pile driver size and type,
- Any out of normal conditions, and
- Observed peak and RMS-impulse levels.

II.4 Analysis of Data and Recorded Sounds

Data obtained following the procedures outlined in this manual include both live data obtained on the data logger (sound level meter) and recorded data used for subsequent detailed analysis. Procedures are described for managing both sets of data.

II.4.1 Real-Time (Live) Data

Live data should be analyzed first because it can be used as a guide in the field to confirm that data acquisition systems are working properly and can be checked against when analyzing the recorded signals. The live recorded data would include the peak and RMS sound pressure levels, measured in consecutive 1-second intervals at representative hydrophone positions. Levels observed at attended measurement locations are recorded in the logbooks at the beginning, during, and at the end of each pile driving event. Only a limited amount of data analysis is required for the live data. From this global data set, the important parameters are the absolute maximum peak and RMS pressures measured during each session, the range of peak and RMS pressures measured during each session, and typical maximum peak and RMS pressures (those that repeat themselves regularly during the measurement session).

Figure II-7 shows a typical chart of peak and RMS pressures measured over the course of a day of noise measurements at one location. Such a chart, when presented for each measurement location, provides a complete history of the overall sound pressures measured on a particular day of pile driving on a project site. Each measurement day could be made up of a number of pile driving events, which would each consist of numerous pile strikes.

Figure II-8 shows a typical chart of peak and RMS pressures measured over the course of a single pile driving event. Live data should not be presented until all of the systems have been post-calibrated and the data have been compared and contrasted. Then preliminary results can be reported to Department project staff. Data should be considered “preliminary” until all analyses are completed to confirm the quality and accuracy of the data.

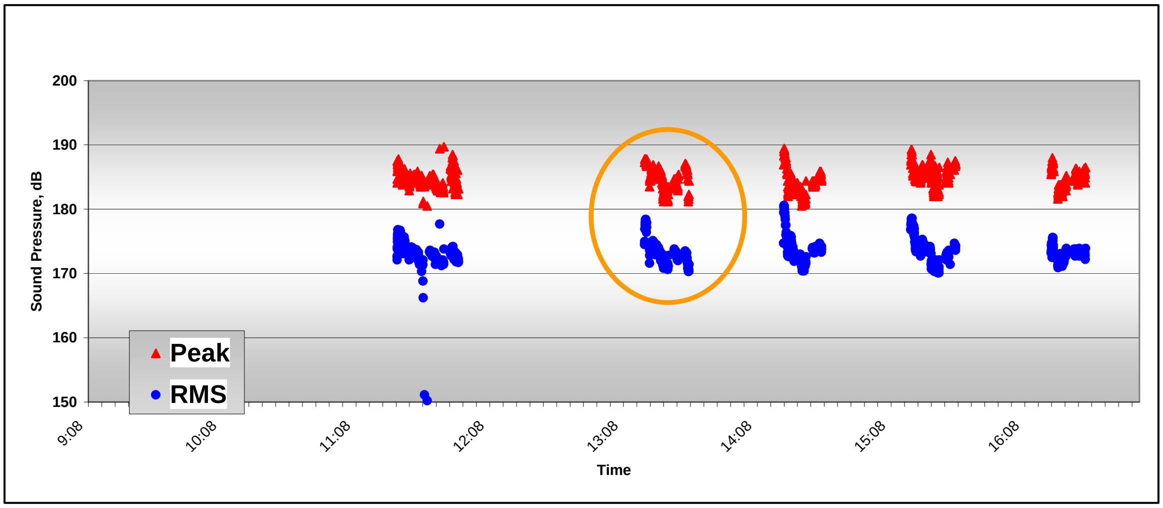

Figure II-7. Example of 1 Day of Pile Driving Data from a Sound Level Meter (Five Events)

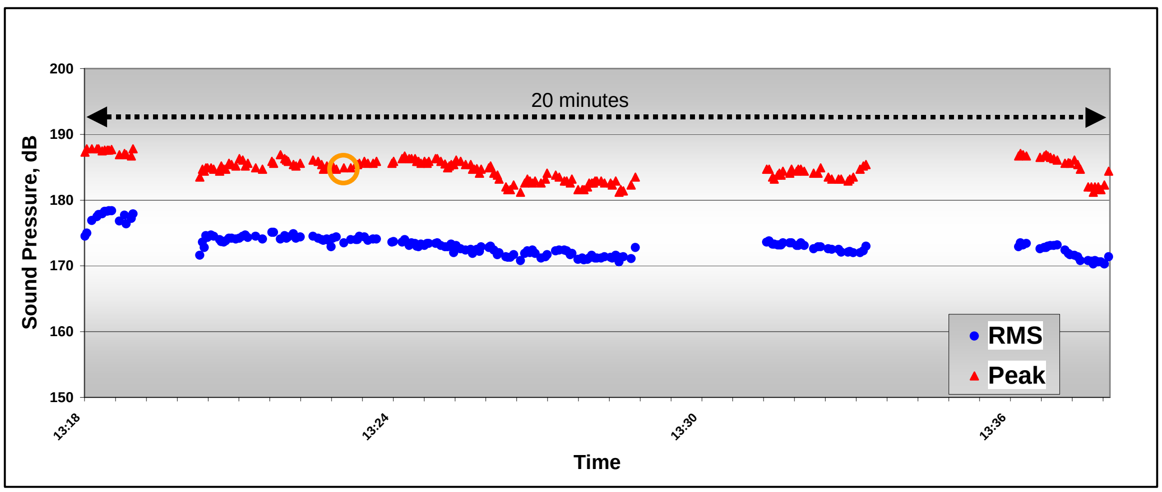

Figure II-8. Example of Peak and RMS Pressures for a Single Pile Driving Event

II.4.2 Recorded Data

The primary purpose for recording data and subsequent analysis is to obtain the characteristics of the pulses in the time and frequency domains. Figure II-9 shows a series of pile strikes in the time domain. The waveform for the pulse is a record of the variations in pressure over time during the individual pulse. Normally, it is necessary to analyze only pulses that are representative of typical maximum peak pressures. If a real-time frequency analyzer was used to analyze the pulses, then a narrow band frequency analysis of representative pulses would be completed first. The band width is typically set at 800 lines of resolution (6.25 Hz) over a frequency range of 0 to 5 KHz. This is accomplished by taking a Fast-Fourier Transform (FFT) of the representative pulses. The steps in this process are to: (1) identify and isolate the pressure time trace or waveform of interest; (2) perform the FFT to provide the frequency spectrum in the narrow bands; and (3) sum the results into 1/3 octave bands as necessary. The output from this analysis is a set of pressure data in increments of approximately 12 microseconds and a narrow band frequency analysis of the signal and constant bandwidth of 6.25 Hz. Figure II-10 shows a single pile strike that has been analyzed identifying the peak pressure; and Figure II-11 shows a typical four-panel display, which summarizes the data from each selected pile strike. The time history shown in the first panel of Figure II-11, also shown in Figure II-10, presents the variation in pressure over time from a single pulse. The pressure is shown in micro-Pascals, and the time shown is in hundredths of a second (Figure II-11a). Figure II-11b shows the frequency spectrum associated with this single pulse. Figure II-11c shows how acoustical energy accumulates over the duration of this individual pulse, resulting in the SEL. It can be seen that the time and the pulse when the peak pressure occurred corresponded to the most rapid rate of accumulation of energy. The energy is summed over the period when 90 percent of the energy occurred, leaving out the initial 5 percent and the final 5 percent. The resultant level is the sound exposure level in dB re: 1μPa^2 sec. Figure II-11d summarizes the calculated descriptors for the pulse, including the peak and $RMS_{90\%}$ sound pressure levels, the SEL, and typical peak and RMS_{35ms} sound pressure levels generated throughout the pile driving event.

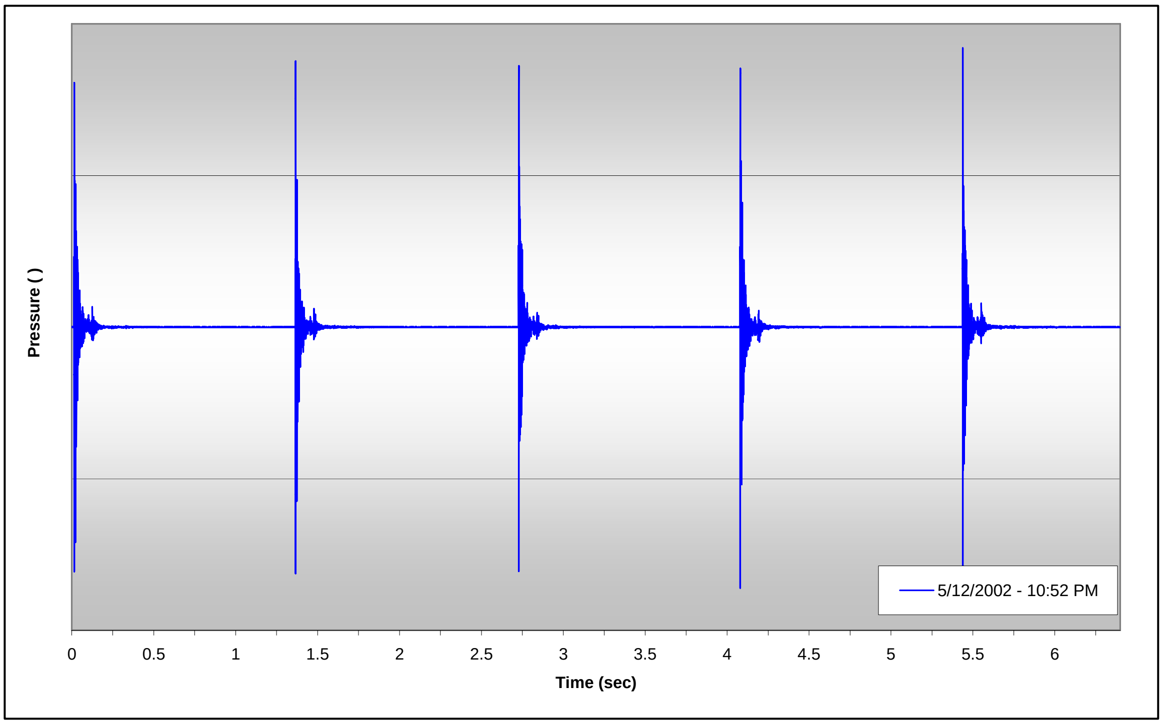

Figure II-9. Series of Pile Strikes in the Time Domain

The noise metrics used to assess the effects of pile driving sounds are still being reviewed. It is very important to record data and analyze data in a consistent manner so that data sets can be compared to one another. It is important that data can be re-analyzed in the future as the regulatory criteria are formalized. A consistent approach to data analysis and data management is necessary in order to provide a consistent and uniform basis for categorizing and predicting noise levels from pile driving projects for use in the environmental and regulatory review processes.

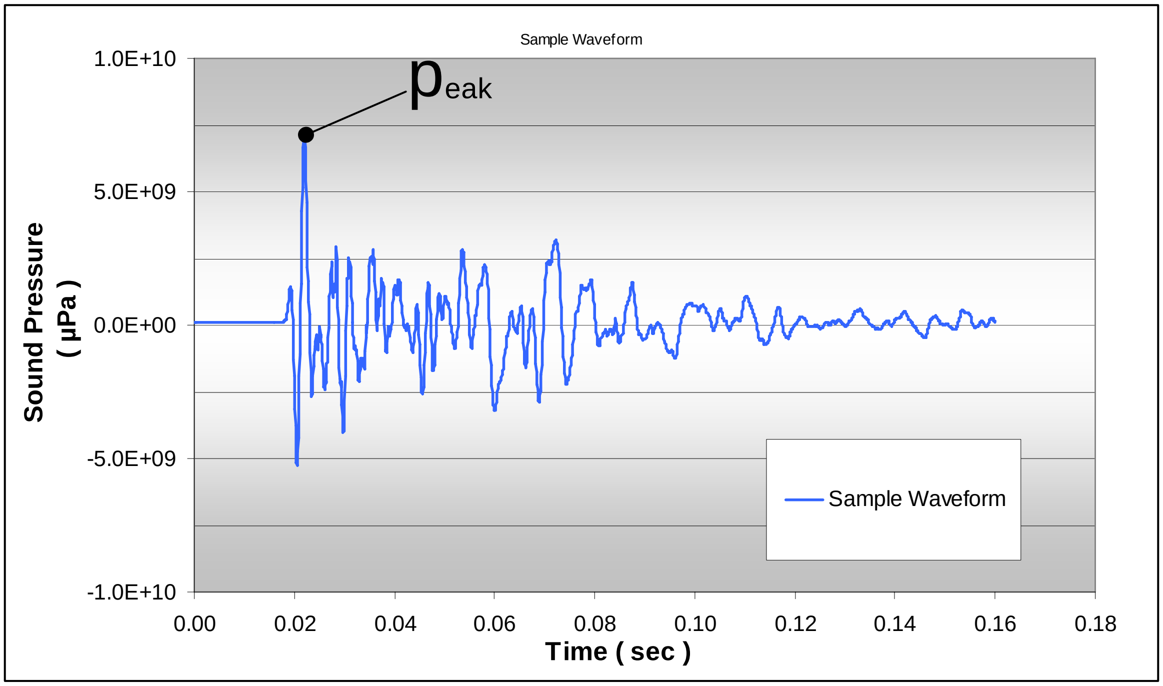

Figure II-10. Peak Sound Pressure of a Sample Pile Driving Pulse

II.5 Quality Control

To ensure quality control of all data from field measurements, measurement systems must be properly calibrated and operating correctly, all equipment settings and field observations must be documented, and work must be made by or under the supervision of a noise analyst that is qualified and trained to conduct these types of measurements.

II.5.1 Measurement Systems

The measurement systems should be calibrated prior to use in the field with a proper calibrator, such as a pistonphone and hydrophone coupler. The pistonphone, when used with the hydrophone coupler, produces a continuous tone at a specified frequency and known amplitude. The sound level meters are calibrated to this level prior to use in the field. The calibration tone is then measured by the sound level meter and is recorded onto the beginning of the digital audiotapes and digital recorders that are used in the field. Both measurement systems are thereby separately calibrated with the same calibrator. The system calibration should be checked at the end of the measurement event both by measuring the calibration tone with the sound level meter and recording the post-measurement calibration tone onto the recording system. Calibration utilizing an acoustical calibrator calibrates the entire system, including all cables and connectors. The pistonphone calibrator should be certified at an independent facility by a certified metrologist. The measurement systems proposed in this manual allow for a direct reading of sound pressures in the field and the subsequent detailed analysis of the pile driving pulses. While the systems use the same input hydrophone, they are otherwise completely separate and can be used to check each other to confirm that measured and analyzed levels are correct.

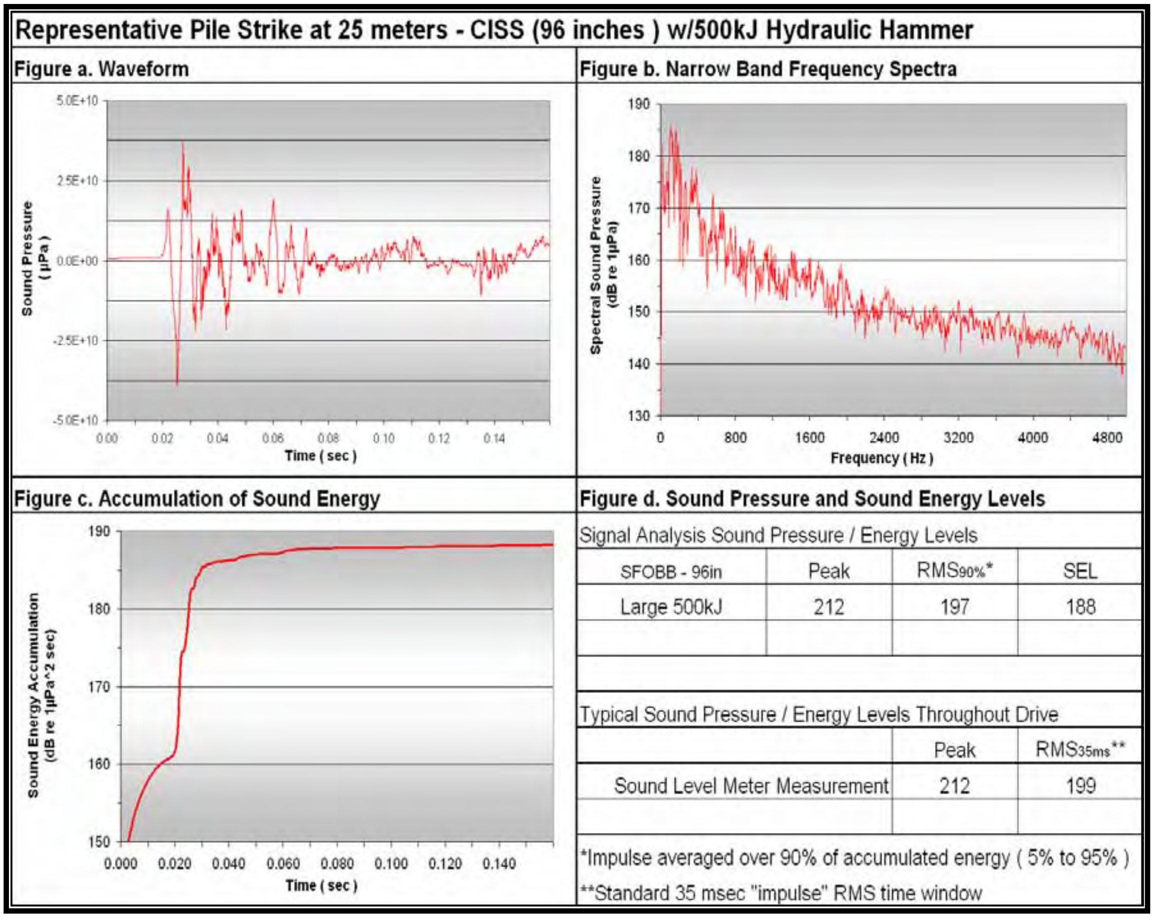

Figure II-11a–d. Example Four-Panel Display

II.5.2 Field Logbooks

Field logbooks are used to note all equipment settings and field conditions. Notebook entries should be copied after each measurement day and filed for safekeeping. Digital audiotapes or other storage media should be labeled and stored for subsequent analysis.

II.5.3 Supervision

All work should be done by or under the direct supervision of a person with demonstrated qualifications and experience.

II.6 Reporting

Data reporting normally occurs at the end of a series of events of pre-established benchmarks during a construction project. Interim data reports typically include discussion of all of the relevant information for each pile drive that had been noted in the logbooks and described in the field logbooks section of this report. A chart similar to Figure II-11, which shows a four-panel display used to summarize data from each pile driving event, should be created and presented for each hydrophone during each pile driving event. The real-time data that was displayed in Figure II-7 also should be summarized for each measurement location for each day of monitoring. Any unusual events that affected the measured data should be noted in summary paragraphs describing the reported data. Verbal reports should be made only if proper protocols have been established for the project.

At the conclusion of a project, a final report is prepared. The final report includes an introduction describing the project; a methodology section that describes measurement positions, measurement equipment, underwater sound descriptors, and the methods used to manage measurement data; a complete report of measured data; a report of the performance of attenuation systems, if applicable; and an analysis of the data with respect to orders from regulatory agencies.

Appendix III Fish Habitat Types and Distribution

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List of Acronyms

CESA	California Endangered Species Act
Delta	Sacramento/San Joaquin River Delta
DFG	California Department of Fish and Game
DPS	distinct population segments
EEZ	exclusive economic zone
EFH	essential fish habitat
ESA	federal Endangered Species Act
ESU	evolutionarily significant unit
HSP	habitat suitability probability
NOAA Fisheries	National Oceanic and Atmospheric Administration National Marine Fisheries Service
PC	present in coastal waters
PN	present in nearshore
PO	present offshore only
USFWS	U.S. Fish and Wildlife Service

Appendix III Fish Habitat Types and Distribution

III.1 Introduction

This appendix provides information on fish distribution and habitat types throughout California. The information is intended to give Caltrans staff a broad of perspective of the diversity of fish and fish habitat that may be encountered on projects throughout the state. However, the information will need to be supplemented for specific project locations through querying the CalFish database, reviewing basin-specific publications, and contacting local California Department of Fish and Game (DFG), National Oceanic and Atmospheric Administration National Marine Fisheries Service (NOAA Fisheries), U.S. Fish and Wildlife Service (USFWS), and other fisheries biologists familiar with the aquatic habitats in the project location.

This appendix includes the following sections:

- Location – Describes the 10 major watersheds in California and the 12 Caltrans districts.
- Species Occurrence – Reviews the status, habitats, and hearing capabilities of fish commonly found in California. It also reviews unique populations of fish found in isolated environments.
- Habitat – Three aquatic environments are discussed in detail: (1) aquatic environments occurring within areas of tidal influence, including marine nearshore areas and estuaries; (2) rivers and streams outside the influence of marine tidal habitats; and (3) lakes and isolated ponds.

III.2 Location

The State of California Department of Natural Resources identifies 10 major watersheds throughout the state (Figure III-1). The major coastal watersheds include the North Coast, San Francisco Bay, Central Coast, and South Coast. Inland watersheds include the North Lahontan, Sacramento River, San Joaquin River, Tulare Lake, South Lahontan, and Colorado River. Within these major watersheds, a variety of habitats occur (see Section III-4).

Figure III-1 shows the major watersheds that occur in California. Figure III-2 shows the 12 Caltrans districts. Table III-1 shows the relationship of the major watershed areas identified in Figure III-1 to the 12 Caltrans districts shown in Figure III-2.

Figure III-1. Major California Watersheds

Figure III-2. Caltrans Districts

Table III-1. Relationship of California Watershed Regions to Caltrans Districts

Watershed Region	Caltrans District
North Coast	1, 2, 4, and a small portion of 3
North Lahontan	2, 3, 9, and 10
Sacramento River	1, 2, 3, 4, and 10
San Francisco Bay	4 and a small portion of 1
Central Coast	5, 7, and a small portion of 4 and 6
San Joaquin River	3, 4, 6, 10, and a small portion of 5
Tulare Lake	6 and a small portion of 5
South Coast	7, 8, 11, 12, and a small portion of 5 and 6
South Lahontan	6, 7, 8, and 9
Colorado River	8 and 11

III.2.1 North Coast

The North Coast region includes all streams in California draining to the Pacific Ocean north of San Francisco Bay. North Coast streams pass through or drain from the California coastal mountains. These streams are typically relatively high-gradient steams with small estuaries. Watersheds are often rugged, with steep valley sides. Valleys are often heavily forested, especially in the upper elevations. All North Coast watersheds have been affected by various human actions. The North Coast Regional Water Control Board summarizes information on conditions and management actions along the North Coast. The North Coast Watershed Assessment Program web site (available at http://coastalwatersheds.ca.gov/Watersheds/tabid/55/Northcoast/tabid/56/Default.aspx) links to additional aquatic habitat and species information for North Coast streams.

III.2.1.1 Major River Systems

North Coast major river systems include the following:

- Winchuck River,
- Smith River,
- Klamath River,
- Trinity River,
- Redwood Creek,
- Mad River,
- Eel River,
- Mattole River,
- Ten Mile River,
- Pudding Creek,
- Gualala River, and
- Russian River.

III.2.1.2 Caltrans Districts

Portions of Caltrans Districts 1 and 2 and District 4 to the San Francisco Bay are in the North Coast watershed (Figure III-2). A small portion of Caltrans District 3 in Glenn County is also within the North Coast watershed.

III.2.1.3 Key Fish Species

Along the North Coast, fish species that are most likely to be of concern to pile driving activities are coho and Chinook salmon and steelhead trout. NOAA Fisheries separates populations of salmon into evolutionarily significant units (ESUs) or distinct population segments (DPSs) based on life history characteristics, genetic distinctness, and location—among other factors. Several salmon ESUs and steelhead DPSs are found in the North Coast region. The Southern Oregon/Northern California coho, California Coastal Chinook, Central California Coast steelhead, and Northern California steelhead populations are all found in the North Coast region and are listed as Threatened under the federal Endangered Species Act (ESA). Central California coho are listed as Endangered under the ESA and are present in streams of the North Coast. Southern Oregon/Northern California Chinook, Upper Klamath Chinook, and Klamath Mountains Province steelhead also inhabit the North Coast region but are not listed under the ESA or California Endangered Species Act (CESA). Salmon and steelhead are anadromous, spawning in freshwater and moving to the ocean to grow and mature. Salmon and steelhead trout may be present in North Coast streams and rivers year-round. Other protected fish species associated with habitats in North Coast streams and estuaries are listed in Table III-2 (at the end of this section) (also see Section III.4).

III.2.2 San Francisco Bay

The San Francisco Bay region consists of the San Francisco Bay and tributaries, the Sacramento/San Joaquin River Delta (Delta), and coastal streams southward to Pescadero Creek (inclusive). The San Francisco Bay is the largest estuary on the west coast. It is highly modified by extensive urbanization, diking and drainage of wetlands, and diversion of significant inflow from the Sacramento and San Joaquin Rivers. Despite extensive environmental degradation, the San Francisco Bay and Delta provide important habitat for protected estuarine resident species (such as the delta smelt) and protected anadromous species (such as Chinook salmon, steelhead trout, and Sacramento splittail). The California Bay-Delta Authority administers many activities in the San Francisco Bay region related to fish and their habitats, and may be contacted for more information specific to this area.

III.2.2.1 Major Tributaries

Major tributaries that provide the San Francisco Bay with freshwater input include the following:

- Sacramento River, and
- San Joaquin River.

However, these rivers are not within the San Francisco Bay watershed. Only coastal streams and streams that directly discharge to the Bay are considered to be within the San Francisco Bay watershed. Tributaries in the San Francisco Bay watershed that occur within the coverage area include the following:

- Lagunitas Creek,
- Petaluma River,
- Napa River, and
- Guadalupe River.

III.2.2.2 Caltrans Districts

A portion of Caltrans District 4 and a small portion of District 1 in Lake County are within the San Francisco Bay watershed (Figure III-2).

III.2.2.3 Key Fish Species

Typical fish species in the San Francisco Bay and Delta areas are listed in Table III-2 (at the end of this section) (also see Section III.4). Protections granted to a number of fish species potentially can affect the planning and design processes of projects that involve pile driving activities in the San Francisco Bay watershed. Resident fish of concern in the estuary include Delta smelt and the tidewater goby. Delta smelt (federally and state-listed as Threatened) and the tidewater goby (federally listed as Endangered and a State Species of Special Concern) occupy shallow-water habitats and wetlands in San Francisco Bay and parts of the Delta. Anadromous salmonids federally listed as Threatened in the region include Central Valley steelhead, Sacramento winter-run Chinook, and Central Valley spring-run Chinook. Central California coho are federally listed as Endangered in the region. Anadromous salmonids migrate through the Bay and Delta during both their out-migration to the ocean, and during their upstream migration to spawn in the Sacramento and San Joaquin River systems and tributaries of the Bay. The Delta is designated as critical habitat for steelhead.

Southern DPS green sturgeon (a species federally listed as Threatened) are also considered to be present year-round in San Francisco Bay and the Delta, and those areas are part of the critical habitat that has been proposed for designation for the species.

III.2.3 Sacramento River

The Sacramento River occupies the north lobe of the California Central Valley. The mainstem of the Sacramento River is of relatively low gradient and is fed by a number of higher gradient tributaries. Most river flow originates as snowmelt from Mt. Shasta and a number of streams draining the California Cascades. The California Coastal Mountains block much of the incoming moisture from the Pacific Ocean. As a result, the environment of the Central Valley is arid, except at higher elevations of the Cascades.

The Sacramento River system has been heavily modified by human actions related to agriculture, forestry, and urbanization. Agriculture is the dominant activity across the wide valley floor. Water diversions for irrigation occur throughout the mainstem and tributaries. Most tributaries are dammed to provide electricity, flood control, and irrigation.

III.2.3.1 Major Tributaries

Major tributaries in the Sacramento River watershed include the following:

- Sacramento River,
- Lake Shasta,
- Cow Creek,
- Bear Creek,
- Battle Creek,
- Mill Creek,
- Deer Creek,
- Big Chico Creek,
- Feather River,
- Yuba River,
- American River, and
- Pit River.

III.2.3.2 Caltrans Districts

Portions of Caltrans Districts 1, 2, 3, 4, and 10 are within the Sacramento River watershed (Figure III-2).

III.2.3.3 Key Fish Species

Fish species likely to be encountered in the Sacramento River system are listed in Table III-2 (at the end of this section) (also see Section III.4). The status and restoration of salmon are major concerns in the Sacramento River system. Programs to restore and protect the populations of Sacramento River winter-run Chinook, Central Valley spring-run Chinook, and California Central Valley steelhead—all listed as Threatened under the ESA—are prominent in this region. Central Valley fall-run and late-fall-run

Chinook also are present in the region; they are a federal candidate for listing under the ESA and a State Species of Special Concern. Although Chinook are anadromous and migratory, certain life stages occur in the Sacramento River year-round.

Green sturgeon (a species federally listed as Threatened) also are considered to be present year-round in the Sacramento River system, and the river and several tributaries (e.g., the Feather River system) are part of the critical habitat that has been proposed for designation for the species.

III.2.4 San Joaquin River

The San Joaquin River drains the smaller, southern lobe of the Central Valley. It originates high on the western slopes of the Sierra Nevada in Kings Canyon National Park near Mount Goddard and is the second largest river drainage in the state (only the Sacramento River is larger). The San Joaquin River's tributaries include the Stanislaus River, Tuolumne River, Merced River, Calaveras River, and Mokelumne River. These tributary rivers are perhaps the most heavily dammed and diverted rivers in the world. The Cosumnes River is the only major river on the western slope of the Sierra Nevada that is not dammed. The San Joaquin River flows west to the trough of the Central Valley, where it is joined by the Sacramento River and then flows into the Sacramento/San Joaquin River Delta before entering San Francisco Bay.

III.2.4.1 Major Tributaries

Major tributaries in the San Joaquin River system include the following:

- San Joaquin River,
- Calaveras River,
- Stanislaus River,
- Tuolumne River,
- Merced River,
- Cosumnes River, and
- Mokelumne River.

III.2.4.2 Caltrans Districts

Portions of Caltrans Districts 3, 4, 6, and 10 and a small portion of District 5 in San Benito County are within the San Joaquin River region (Figure III-2).

III.2.4.3 Key Fish Species

Fish species likely to be encountered in the San Joaquin River system are listed in Table III-2 (at the end of this section) (also see Section III.4). Fall-run Chinook salmon, steelhead trout, striped bass, American shad, and white sturgeon are anadromous species found in the system. Spring-run Chinook salmon were extirpated with completion of Friant Dam in 1946.

Steelhead/rainbow trout in the San Joaquin River are of the Central Valley steelhead DPS and are of concern because they are federally listed as Threatened under the ESA. Critical habitat has been designated for this species in all accessible reaches and tributaries of the river. Most Central Valley steelhead rear in freshwater for 2 years before migrating to the ocean, and rainbow trout reside in freshwater their entire lives. Therefore, steelhead/rainbow trout occur in the San Joaquin system year-round, with peak adult migration occurring in December, spawning from December to April, and peak out-migrations occurring through May.

Central Valley fall- and late-fall-run Chinook also are found in the San Joaquin River watershed; they are a federal candidate for listing under the ESA and a State Species of Special Concern.

III.2.5 Central Coast

The Central Coast region encompasses coastal California south of the Pescadero Creek Lagoon in San Mateo County to the Carpenteria salt marsh in Santa Barbara County. This region's environment consists of areas of coniferous/redwood forests of the Big Sur region in Monterey County and the semi-arid to arid regions of San Luis Obispo, San Benito, Santa Cruz, and Santa Barbara Counties.

III.2.5.1 Major River Systems

Major river systems in the Central Coast watershed include the following:

- Salinas River,
- Big Sur River,
- Little Sur River,
- Carmel River,
- Estrella River,
- Pajaro River,
- Santa Maria River, and
- Santa Ynez River.

III.2.5.2 Caltrans Districts

Portions of Caltrans Districts 5 and 7, and small portions of Districts 4 and 6 are within the Central Coast region (Figure III-2).

III.2.5.3 Key Fish Species

Activities in tidal areas of the Central Coast have the potential to affect the federally Endangered tidewater goby. This species occurs in isolated populations throughout coastal California in bays, estuaries, lagoons, and coastal wetland habitat that contain low salinities. No critical habitat has been designated on the Central Coast for the tidewater goby at this time; however, critical habitat does exist in the South Coast region.

The Central Coast also harbors protected species of salmon. Federally Endangered Central California Coast coho salmon occur in the San Lorenzo River, and three populations of federally listed steelhead (Central California Coast, South Central California Coast, and Southern California DPSs) occur in the region. Contact NOAA Fisheries for details on species occurrence and designated critical habitat.

Other protected fish species present within the Central Coast region are listed in Table III-2 (at the end of this section) (also see Section III.4).

III.2.6 South Coast

In general, streams and rivers of the South Coast region originate in the mountains of the four Southern California National Forests (Los Padres, Angeles, San Bernardino, and Cleveland), drain into the valleys, and meet the sandy beaches of the southern coastline. The aquatic and terrestrial environment of the South Coast has been substantially impacted by human development. Large rivers have been channelized, dammed, and dewatered. Perennial tributaries exist in higher elevations, but large rivers are generally disconnected to the ocean due to water going subsurface in some reaches. Most rivers and streams are connected only during winters of high rainfall and during El Niño events that occur every 3 to 4 years.

South Coastal wetlands, lagoons, salt marshes, and estuaries are known to harbor at least 60 species of fish (California Wetland Recovery Project 2001) and are extremely important elements of South Coast fish habitat. Most of the South Coast wetland and lagoon habitats have been destroyed or altered by human activities. Only 30 percent of wetland/lagoon habitats remain in southern California (Southern California Coastal Wetland Inventory 1998).

III.2.6.1 Major River Systems and Associated Lagoons

Major river systems and associated lagoons in the South Coast watershed include the following:

- Ventura River,
- Santa Clara River,
- Santa Ana River,
- San Gabriel River,
- Malibu Creek,
- Calleguas Creek/Mugu Lagoon, and
- San Mateo Creek.

III.2.6.2 Caltrans Districts

All of Caltrans District 12 and portions of Caltrans Districts 7, 8, and 11 are within the South Coast region (Figure III-2). Small portions of Caltrans District 5 in Santa Barbara County and District 6 in Kern County are also within the South Coast watershed.

III.2.6.3 Key Fish Species

Some typical fish species found in Southern California rivers and estuaries are listed in Table III-2 (at the end of this section) (also see Section III.4). Species with special protections in this region include Southern California steelhead/rainbow trout, unarmoured three-spine stickleback, and tidewater goby.

III.2.7 North Lahontan

The eastern California region of North Lahontan consists of 6,122 square miles of portions of Modoc, Lasssen, Sierra, Nevada, Placer, El Dorado, Alpine, Tuolumne, and Mono Counties. The northern part of this region is primarily arid high desert with relatively flat valleys. The central and southern portions of this region are comprised of the eastern slopes of the Sierra Nevada and include the California portion of the Lake Tahoe Basin. The major rivers in the region drain east into Nevada.

III.2.7.1 Major River Systems and Lakes

Major river systems and lakes in the North Lahontan region include the following:

- Lake Tahoe,
- Truckee River,
- Carson River, and
- Walker River.

III.2.7.2 Caltrans Districts

Portions of Caltrans Districts 2, 3, 9, and 10 are within the North Lahontan region (Figure III-2).

III.2.7.3 Key Fish Species

Lake trout, rainbow trout, brown trout, brook trout, and Kokanee are common salmonid species found in Lake Tahoe. A number of warmwater fish species have been illegally introduced to Lake Tahoe, including largemouth and smallmouth bass, crappie, and sunfish. While these fish typically are associated with warmwater environments, their populations are able to grow and spread within the Tahoe Basin. Only six native species remain in the lake: mountain whitefish, Lahontan redside shiner, Lahontan speckled dace, tui chub, Tahoe sucker, and Paiute sculpin. The Lahontan cutthroat is a native of the Truckee, Walker, and Carson drainages; is federally listed as Threatened; and is now extinct in Lake Tahoe. The federally Threatened Paiute cutthroat trout is located in the Carson River above Llewellyn Falls.

III.2.8 South Lahontan

The South Lahontan region includes Mono Lake, Owens Valley, Panamint Valley, Death Valley, and the Amargosa River Valley. The Mojave Desert occupies the southern half of the region. The South Lahontan region has fewer permanent rivers and streams due to the dryer hydrology of the east side of the Sierra Nevada. The largest river in this region is the Owens River, which flows from north to south over the length of the Owens Valley.

III.2.8.1 Major River Systems and Lakes

Major river systems and lakes in the South Lahontan region include the following:

- Owens River,
- Mono Lake,
- Amargosa River, and
- Mojave River.

III.2.8.2 Caltrans Districts

Portions of Caltrans Districts 6, 7, 8, and 9 are within the South Lahontan region (Figure III-2).

III.2.8.3 Key Fish Species

The Owens sucker, Owens pupfish, Owens tui chub, and Owens speckled dace are all native to the Owens River and are restricted to habitats in this system. The Owens tui chub and Owens pupfish are listed under both the CESA and ESA. Critical habitat has been designated for these species in the Owens River. The Owens sucker and speckled dace are both Species of Special Concern in California. The Mohave tui chub (federally and state-listed as Endangered) occurs in the region at four sites: Soda Springs, DFG's Camp Cady Wildlife Area, China Lake Naval Air Weapons Center, and the Barstow Desert Information Center. The Amargosa speckled dace is restricted to the Amargosa River and is a State Species of Special Concern. The Arroyo chub has been found in the Mojave system and is a State Species of Special Concern. Common non-native species in the region include largemouth bass, smallmouth bass, channel catfish, and bluegill.

III.2.9 Tulare Lake

The Tulare Lake watershed comprises the drainage area of the San Joaquin Valley south of the San Joaquin River. Tulare Lake is an intermittent lake in the Central Valley. At one time, the Kings, Kaweah, and Kern Rivers flowed into the lake; but their waters have been diverted for irrigation. In dry seasons, Tulare Lake is almost without water. The Tulare Lake watershed is essentially closed because surface water drains north into the San Joaquin River only in years of extreme rainfall. The major rivers in the region, the Kings, Kaweah, Tule, and Kern, begin in the Sierras and generally flow east to west into the San Joaquin Valley.

III.2.9.1 Major River Systems

As noted above, the major river systems in the Tulare Lake watershed include the following:

- Kaweah River,
- Tule River,
- Kern River, and
- Kings River.

III.2.9.2 Caltrans District

A portion of Caltrans District 6 and a small portion of District 5 (mainly in San Benito County) are within the Tulare Lake region (Figure III-2).

III.2.9.3 Key Fish Species

The Little Kern golden trout is found in the Tulare Lake region and is federally listed as Threatened. Critical habitat for Little Kern golden trout consists of the entire Little Kern River basin upstream from the barrier falls, 1 mile below the mouth of Trout Meadows Creek. Critical habitat for this species occurs within the Sequoia National Park and the Sequoia National Forest, in Tulare County. Other native species of concern in the region include the Kern brook lamprey, Kern River rainbow trout, and hardhead.

III.2.10 Colorado River

The Colorado River region covers approximately 20,000 square miles in the southeastern portion of California. It includes all of Imperial County and portions of San Bernardino, Riverside, and San Diego Counties. It is bound on the east by the Colorado River; on the south by the Republic of Mexico; on the west by the Laguna, San Jacinto, and San Bernardino Mountains; and on the north by the New York, Providence, Granite, Old Dad, Bristol, Rodman, and Ord Mountain Ranges.

III.2.10.1 Major Rivers and Lakes

Major rivers and lakes in the Colorado River region include the following:

- Colorado River, and
- Salton Sea.

III.2.10.2 Caltrans Districts

Portions of Caltrans Districts 8 and 11 are within the Colorado River region (Figure III-2).

III.2.10.3 Key Fish Species

The boneytail chub, Colorado pikeminnow, razorback sucker, and desert pupfish are all listed as Endangered under both the CESA and ESA in the Colorado River region. Critical habitat also has been designated for these species in the region.

III.3 Species Occurrence

This section reviews the status, habitats, and hearing capabilities of fish commonly found in California; it also reviews unique populations of fish found in isolated environments.

III.3.1 Fish of California

Table III-2 (at the end of this section) summarizes species that may be encountered in the coastal and Central Valley regions of California and includes information on life histories, hearing categories, habitat, and distribution by watershed[1]. Species are listed in order of the extent of protections granted to them.

III.3.2 Fish in Restricted Habitats

Many species or subspecies of fish are adapted to particular unique environments or are geographically restricted to particular drainages. Geographically restricted habitats are common in the arid and desert environments of the east (North Lahontan, South Lahontan, Tulare Lake, and Colorado River regions). These restricted environments often are degraded or lost due to human encroachment or natural causes;

[1] The following table is not a complete list of all fish that occur in California but a partial list intended only to aid the biologist in considering a wide range of species.

therefore, fish that depend on these environments tend to have special protections through the State and federal governments. Table III-3 (at the end of this section) lists protected fish species (in alphabetical order) found in restricted environments in California.

III.3.3 Essential Fish Habitat

Table III-4 (at the end of this section) summarizes the geographical regions and marine habitat for groundfish, coastal pelagic, and salmonid species protected under the Magnuson-Stevens Fisheries Conservation and Management Act. The areas in which these species are located may be more restrictive than areas designated as essential fish habitat (EFH) for the species complex to which they belong. Fish are listed in alphabetical order within the respective species complex.

Designated groundfish EFH is found along the entire California coastline. In the *Pacific Coast Groundfish EFH Final Environmental Impact Statement* authored by NOAA Fisheries[1] (2005), "groundfish EFH" is defined as all waters and substrates in depths less than or equal to 3,500 meters, including areas associated with seamounts in depths greater than 3,500 meters, to the upriver extent of saltwater intrusion. "Saltwater intrusion" is defined as areas where ocean salt levels are less than 0.5 parts per thousand during average annual low flow. Groundfish occurrence by species was estimated for Table III-4 by evaluating habitat suitability probability (HSP) maps prepared by the Pacific Fisheries Management Council as Appendix B, Part 4, to the *Pacific Coast Groundfish Fisheries Management Plan*[2] (2005). All areas in which the HSP is greater than zero for each EFH groundfish species fall within the designated EFH area.

The HSP maps were evaluated for each groundfish species. Species shown utilizing nearshore habitat along a significant portion of a watershed's coastline, sometimes including embayments, estuaries and river systems, for at least one life history stage were designated as present in nearshore (PN). These species can also utilize offshore habitat extensively or exclusively at some stage in their development. Species commonly present in or near coastal shelf waters according to the HSP maps and occasionally found in the nearshore of a watershed were designated as present in coastal waters (PC). Species that were not shown on the HSP maps to utilize nearshore habitat at any point during their life history in the watershed in question were designated as present offshore only (PO) if distributed in deeper waters parallel to the coastline.

Information regarding EFH for Pacific Coast salmonids and coastal pelagic species was obtained from their respective Fisheries Management Plans[3]. Salmon EFH is found in nearshore and tidal marine waters out to the limit of the exclusive economic zone (EEZ), offshore of California, north of Point Conception. In freshwater, salmon EFH is defined as all currently viable waters and most historically accessible habitat within designated hydrologic units. Species occurrence in marine or freshwater habitats is presented by watershed in Table III-4. EFH for coastal pelagic species in California is defined as all marine and estuarine waters along the shoreline to the limits of the EEZ and above the thermocline where sea surface temperatures fall between 10° and 26°C. This means that the northern limit varies seasonally while the southern limit is consistently set at the California-Mexico border.

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[1] Available online at http://www.nwr.noaa.gov/Groundfish-Halibut/Groundfish-Fishery-Management/NEPA-Documents/EFH-Final-EIS.cfm.

[2] Available online at http://www.pcouncil.org/groundfish/gffmp/gfa19.html.

[3] Available online at http://www.pcouncil.org/salmon/salfmp.html and http://www.pcouncil.org/cps/cpsfmp.html, respectively.

Table III-2. Protected Fish Species That May Be Encountered in Coastal and Central Valley Regions in California

Name	Life History	Perception of Sound	Habitat			Status by Region and District[a]					
			Tidally Influenced/ Marine	Rivers and Streams	Lakes	North Coast (1, 2, 3, and 4)	Sacramento River (1, 2, 3, 4, and 10)	San Joaquin River (3, 4, 5, 6 and 10)	San Francisco Bay (1 and 4)	Central Coast (4, 5, 6, and 7)	South Coast (5, 6, 7, 8, 11, and 12)
Steelhead/rainbow trout (*O. mykiss*)	Anadromous and resident	Generalist	X	x	x	FT CH SSC	FT CH	FT CH	FT CH	FE FT CH SSC	FE CH SSC
Chinook salmon	Anadromous	Generalist	X	x	x	FT CH EFH	FT FE CH EFH SE ST SSC	EFH SCC	FE FT CH EFH SE ST SSC		
Coho salmon	Anadromous	Generalist	X	x	x	FE FT CH EFH SE ST SCC			FE CH EFH SE	FE CH EFH SE	
Tidewater goby	Estuarine	Generalist	X			FE SSC			FE SSC	FE SSC	FE CH SSC
Delta smelt	Estuarine	Generalist	X				FT ST		FT ST		
Green sturgeon	Anadromous		X	x		FT SSC PCH	FT SSC PCH		FT SSC PCH	FT SSC PCH	
California roach (includes all sub-species)	Freshwater			x	x	SSC	SSC	SSC	SCC	SSC	

Table III-2. (continued)

Name	Life History	Perception of Sound	Habitat: Tidally Influenced/ Marine	Habitat: Rivers and Streams	Habitat: Lakes	Status by Region and District[a]: North Coast (1, 2, 3, and 4)	Sacramento River (1, 2, 3, 4, and 10)	San Joaquin River (3, 4, 5, 6 and 10)	San Francisco Bay (1 and 4)	Central Coast (4, 5, 6, and 7)	South Coast (5, 6, 7, 8, 11, and 12)
Hardhead	Freshwater			x		SSC	SSC	SSC	SSC		
Eulachon	Anadromous	Specialist	X	x		SSC			SSC	SSC	
Sacramento splittail	Anadromous	Generalist	X	x			SSC	SSC	SSC		
Arroyo chub	Freshwater									SSC	SSC
Longfin smelt	Estuarine	Generalist	X			SSC			SSC		
River lamprey	Anadromous		X	x		SSC			SSC		
Chum salmon	Anadromous	Generalist	X	x		SSC					
Coastal cutthroat trout	Anadromous and resident	Generalist	x	x		SSC					

[a]

CH = Species for which critical habitat has been federally designated.

EFH = Species for which essential fish habitat has been designated.

FE = Federally Endangered species.

FT = Federally Threatened species.

FP = Federally Proposed species.

PCH = Species for which critical habitat has been proposed for federal designation.

SE = State Endangered species.

SSC = State Species of Special Concern.

ST = State Threatened species.

Table III-3. Fish Species Found in Restricted Environments in California

Name	River System	North Coast (1, 2, 3, and 4)	Sacramento River (1, 2, 3, 4, and 10)	San Joaquin River (3, 4, 5, 6, and 10)	North Lahontan (2, 3, 9, and 10)	South Lahontan (6, 7, 8, and 9)	Tulare Lake (5 and 6)	Colorado River (8 and 11)	South Coast (5, 6, 7, 8, 11, and 12)
Amargosa pupfish	Amargosa River					SSC			
Amargosa speckled dace	Amargosa River					SSC			
Bigeye marbled sculpin	Pit River		SSC						
Blue chub	Klamath River	SSC							
Bonytail chub	Colorado River							FE, CH, SE	
Clear Lake hitch	Sacramento/Clear Lake and tributaries		SSC						
Colorado pikeminnow	Colorado River							FE, CH, SE	
Cottonball marsh pupfish	Amargosa River/ Death Valley					ST			
Cowhead Lake tui chub	Cowhead Lake Slough				SSC				
Desert pupfish	Lower Colorado River, Salton Sea							FE, CH, SE	
Eagle Lake rainbow trout	Eagle Lake				SSC				
Eagle Lake tui chub	Eagle Lake				SSC				
Goose Lake lamprey	Goose Lake/ Lassen Creek		SSC						
Goose Lake redband trout	Goose Lake and tributaries		SSC						

Table III-3. (continued)

Name	River System	North Coast (1, 2, 3, and 4)	Sacramento River (1, 2, 3, 4, and 10)	San Joaquin River (3, 4, 5, 6, and 10)	North Lahontan (2, 3, 9, and 10)	South Lahontan (6, 7, 8, and 9)	Tulare Lake (5 and 6)	Colorado River (8 and 11)	South Coast (5, 6, 7, 8, 11, and 12)
Goose Lake sucker	Goose Lake and tributaries		SSC						
Goose Lake tui chub	Goose Lake and tributaries		SSC						
Kern Brook Lamprey	Merced, Kaweah, Kings and San Joaquin Rivers			SCC			SCC		
Kern River Rainbow Trout	Kern River						SCC		
Klamath largescale sucker	Klamath River	SSC							
Klamath River lamprey	Klamath River/ Upper Klamath Lake	SSC							
Little Kern golden trout	Kern River (Tulare County)						FT, CH		
Lahontan cutthroat trout	Lakes and streams of northeastern California				FT				
Lahontan Lake tui chub	Lake Tahoe				SCC				
Lost River sucker	Klamath reservoirs, Lost River	FE, SE							
McCloud River red-band trout	McCloud River		SSC						
Modoc sucker	Pit River (Modoc and Lassen Counties)		FE, CH, SE						
Mojave tui chub	Mojave River					FE, SE			

Table III-3. (continued)

Name	River System	North Coast (1, 2, 3, and 4)	Sacramento River (1, 2, 3, 4, and 10)	San Joaquin River (3, 4, 5, 6, and 10)	North Lahontan (2, 3, 9, and 10)	South Lahontan (6, 7, 8, and 9)	Tulare Lake (5 and 6)	Colorado River (8 and 11)	South Coast (5, 6, 7, 8, 11, and 12)
Mountain sucker	Lahontan Drainage, North Fork Feather, Truckee, Walker, and Carson Rivers		SCC		SCC				
Owens pupfish	Spring ponds, wetlands in Owens Valley					FE, SE			
Owens speckled dace	Owens Valley					SCC			
Owens sucker	Owens River, June Lake, Santa Clara River, Piru Creek and Reservoir					SCC			SCC
Owens tui chub	Owens River					FE, CH, SE			
Piute cutthroat trout	Carson River above Llewellyn Falls				FT				
Razorback sucker	Colorado River, Senator Wash Reservoir (Imperial County)							FE, CH, SE	
Reticulated sculpin	Rogue River	SSC							
Rough sculpin	Pit River		ST						
Russian River tule perch	Russian River	SSC							
Sacramento perch	Clear Lake and local reservoirs		SSC						
Salt Creek pupfish	Salt Creek					SSC			

Table III-3. (continued)

Name	River System	North Coast (1, 2, 3, and 4)	Sacramento River (1, 2, 3, 4, and 10)	San Joaquin River (3, 4, 5, 6, and 10)	North Lahontan (2, 3, 9, and 10)	South Lahontan (6, 7, 8, and 9)	Tulare Lake (5 and 6)	Colorado River (8 and 11)	South Coast (5, 6, 7, 8, 11, and 12)
Santa Ana speckled dace	Santa Ana and San Gabriel Rivers								SSC
Santa Ana sucker	Los Angeles, San Gabriel, and Santa Ana Rivers								FT, CH, SCC
Saratoga Springs pupfish	Saratoga Springs					SSC			
Shortnose sucker	Klamath, Lost River	FE, SE							
Shay Creek threespine stickleback	Baldwin Lake, Shay Creek, Sugarloaf Meadows								SSC
Shoshone pupfish	Shoshone Spring					SSC			
Unarmored threespine stickleback	Streams of the South Coast								FE, SE
Volcano Creek golden trout	Golden trout Creek, South Fork Kern River, Cottonwood Lakes						SSC		
Note: For an explanation of status definitions, please refer to footnote “a” in Table III-2.									

Table III-4. Presence of Species Protected under Essential Fish Habitat in California Coastal Waters

Name	Range in California Coastal Waters	North Coast (1, 2, 3, and 4)	San Francisco Bay (1 and 4)	Central Coast (4, 5, 6, and 7)	South Coast (5, 6, 7, 8, 11, and 12)	San Joaquin River (3, 4, 5, 6, and 10)	Sacramento River (1, 2, 3, 4, and 10)
Pacific Coast Groundfish[a]							
Flatfishes							
Arrowtooth flounder	From Oregon south to Santa Barbara	PN	PN	PN			
Butter sole	From Oregon south to Ventura	PN	PN	PN			
Curlfin sole	All of California	PN	PN	PN	PN		
Dover sole	All of California	PN	PN	PC	PC		
English sole	All of California	PN	PN	PN	PN		
Flathead sole	From Oregon south to Monterey Bay	PN	PN				
Pacific sanddab	All of California	PN	PN	PN	PN		
Petrale sole	All of California	PN	PN	PN	PN		
Rex sole	All of California	PN	PN	PN	PN		
Rock sole	All of California	PN	PN	PN	PN		
Sand sole	From Oregon south to Redondo Beach	PN	PN	PN	PN		
Starry flounder	From Oregon south to Avila Beach	PN	PN	PN	PN		

Table III-4. (continued)

Name	Range in California Coastal Waters	North Coast (1, 2, 3, and 4)	San Francisco Bay (1 and 4)	Central Coast (4, 5, 6, and 7)	South Coast (5, 6, 7, 8, 11, and 12)	San Joaquin River (3, 4, 5, 6, and 10)	Sacramento River (1, 2, 3, 4, and 10)
Rockfishes							
Nearshore Rockfish Complex							
Black rockfish	From Oregon south to Hunington Beach	PN	PN	PN	PN		
Black-and-Yellow Rockfish	All of California	PN	PN	PN	PN		
Blue rockfish	All of California	PN	PN	PN	PN		
Brown rockfish	All of California	PN	PN	PN	PN		
Calico rockfish	From San Francisco south to Mexico		PN	PN	PN		
China rockfish	From Oregon south to Redondo Beach	PN	PN	PN	PN		
Copper rockfish	All of California	PN	PN	PN	PN		
Gopher rockfish	All of California	PN	PN	PN	PN		
Grass rockfish	All of California	PN	PN	PN	PN		
Kelp rockfish	From Albion, California to Mexico	PN	PN	PN	PN		
Olive rockfish	All of California	PN	PN	PN	PN		
Quillback rockfish	From Oregon south to the northern Channel Islands	PN	PN	PN	PN		
California scorpionfish	From Monterey Bay south to Mexico		PC	PN	PN		
Treefish	From San Francisco south to Mexico		PN	PN	PN		

Table III-4. (continued)

Name	Range in California Coastal Waters	North Coast (1, 2, 3, and 4)	San Francisco Bay (1 and 4)	Central Coast (4, 5, 6, and 7)	South Coast (5, 6, 7, 8, 11, and 12)	San Joaquin River (3, 4, 5, 6, and 10)	Sacramento River (1, 2, 3, 4, and 10)
Shelf Rockfish Complex							
Bocaccio	All of California	PN	PN	PN	PN		
Bronzespotted rockfish	From Eureka, California south to Mexico			PO	PO		
Canary rockfish	All of California	PN	PN	PN	PN		
Chilipepper	All of California	PN	PN	PN	PN		
Cowcod	All of California	PC	PC	PC	PC		
Flag rockfish	All of California	PN	PN	PN	PC		
Greenblotched rockfish	From Punta Delgada, California to Mexico	PO	PO	PC	PO		
Greenspotted rockfish	All of California	PN	PN	PN	PN		
Greenstriped rockfish	All of California	PC	PC	PC	PC		
Honeycomb rockfish	From Point Pinos, Monterey County, California to Mexico			PC	PC		
Mexican rockfish	From Point Sur, California to Mexico			PC	PC		
Pink rockfish	All of California	PC	PO	PC	PO		
Redstripe rockfish	All of California	PN	PN	PN	PN		
Rosethorn rockfish	All of California	PC	PO	PC	PC		
Rosy rockfish	All of California	PN	PN	PN	PN		
Shortbelly rockfish	All of California	PC	PC	PC	PC		
Silvergray rockfish	From Oregon south to Santa Barbara Island	PO					

Table III-4. (continued)

Name	Range in California Coastal Waters	North Coast (1, 2, 3, and 4)	San Francisco Bay (1 and 4)	Central Coast (4, 5, 6, and 7)	South Coast (5, 6, 7, 8, 11, and 12)	San Joaquin River (3, 4, 5, 6, and 10)	Sacramento River (1, 2, 3, 4, and 10)
Shelf Rockfish Complex (continued)							
Speckled rockfish	All of California	PN	PN	PN	PN		
Squarespot rockfish	All of California	PN	PN	PN	PN		
Starry rockfish	From San Francisco south to Mexico		PC	PN	PC		
Stripetail rockfish	All of California	PN	PN	PN	PN		
Tiger rockfish	From Oregon south to Tanner and Cortes Banks	PN	PN	PN	PN		
Vermilion rockfish	All of California	PN	PN	PN	PN		
Widow rockfish	All of California	PN	PN	PN	PN		
Yelloweye rockfish	All of California	PN	PC	PN	PC		
Yellowtail rockfish	From Oregon south to La Jolla	PN	PN	PN	PN		
Slope Rockfish Complex							
Aurora rockfish	All of California	PC	PO	PC	PC		
Bank rockfish	All of California	PC	PC	PC	PC		
Blackgill rockfish	All of California	PC	PO	PC	PO		
Darkblotched rockfish	From Oregon south to Santa Catalina Island	PC	PC	PC	PC		
Pacific ocean perch	From Oregon south to La Jolla	PN	PN	PN	PN		
Redbanded rockfish	From Oregon south to San Diego	PC	PO	PC	PO		

Table III-4. (continued)

Name	Range in California Coastal Waters	North Coast (1, 2, 3, and 4)	San Francisco Bay (1 and 4)	Central Coast (4, 5, 6, and 7)	South Coast (5, 6, 7, 8, 11, and 12)	San Joaquin River (3, 4, 5, 6, and 10)	Sacramento River (1, 2, 3, 4, and 10)
Slope Rockfish Complex (continued)							
Rougheye rockfish	From Oregon south to San Diego	PN	PN	PN	PN		
Sharpchin rockfish	From Oregon south to San Clemente Island	PN	PC	PC	PC		
Shortraker rockfish	From Oregon south to Point Conception	PC	PO	PC			
Splitnose rockfish	All of California	PN	PN	PN	PN		
Yellowmouth rockfish	From Oregon south to Point Arena	PO					
Thornyheads							
Longspine thornyhead	All of California	PO	PO	PO	PO		
Shortspine thornyhead	All of California	PN	PN	PN	PC		
Roundfish							
Lingcod	All of California	PN	PN	PN	PN		
Cabezon	All of California	PN	PN	PN	PN		
Kelp greenling	From Oregon south to La Jolla	PN	PN	PN	PN		
Pacific cod	From Oregon south to Santa Monica	PN	PN	PN	PN		
Pacific hake (pacific whiting)	All of California	PN	PN	PN	PN		
Pacific flatnose (finescale codling)	All of California	PO	PO	PO	PO		

Table III-4. (continued)

Name	Range in California Coastal Waters	North Coast (1, 2, 3, and 4)	San Francisco Bay (1 and 4)	Central Coast (4, 5, 6, and 7)	South Coast (5, 6, 7, 8, 11, and 12)	San Joaquin River (3, 4, 5, 6, and 10)	Sacramento River (1, 2, 3, 4, and 10)
Roundfish (continued)							
Pacific grenadier	All of California	PN	PN	PN	PN		
Sablefish	All of California	PN	PN	PN	PN		
Sharks, Skates, and Chimaeras							
Leopard shark	All of California	PN	PN	PN	PN		
Soupfin shark	All of California	PN	PN	PN	PN		
Spiny dogfish	All of California	PN	PN	PN	PN		
Big skate	All of California	PN	PN	PN	PN		
California skate	All of California	PN	PN	PN	PN		
Longnose skate	All of California	PN	PN	PN	PN		
Spotted ratfish	All of California	PN	PN	PN	PN		
Pacific Salmon[b]							
Pacific salmon essential fish habitat		Marine, freshwater	Marine, freshwater	Marine, freshwater		Freshwater	Freshwater
Chinook salmon		Marine, freshwater	Marine, freshwater	Marine	Marine	Freshwater	Freshwater
Coho salmon		Marine, freshwater	Marine, freshwater	Marine, freshwater			

Table III-4. (continued)

Name		Range in California Coastal Waters	North Coast (1, 2, 3, and 4)	San Francisco Bay (1 and 4)	Central Coast (4, 5, 6, and 7)	South Coast (5, 6, 7, 8, 11, and 12)	San Joaquin River (3, 4, 5, 6, and 10)
Coastal Pelagic Species[c]							
Northern anchovy	All of California (seasonally following waters warmer than 10°C)	Estuarine, nearshore	Estuarine, nearshore	Estuarine, nearshore	Estuarine, nearshore		
Pacific sardine	All of California (seasonally following waters warmer than 10°C)	Estuarine, nearshore	Estuarine, nearshore	Estuarine, nearshore	Estuarine, nearshore		
Pacific (chub) mackerel	All of California (seasonally following waters warmer than 10°C)	Estuarine, nearshore	Estuarine, nearshore	Estuarine, nearshore	Estuarine, nearshore		
Jack mackerel	All of California (seasonally following waters warmer than 10°C)	Estuarine, nearshore	Estuarine, nearshore	Estuarine, nearshore	Estuarine, nearshore		
Market squid	All of California (probably seasonally following waters warmer than 10°C)	Rarely found in estuaries, bays or near river mouths	Rarely found in estuaries, bays or near river mouths	Rarely found in estuaries, bays or near river mouths	Rarely found in estuaries, bays or near river mouths		

PN = Present in nearshore PC = Present in coastal waters PO = Present offshore only

[a] Information obtained from Coastal Groundfish Fisheries Management Plan, Appendices B4 and I and from the California Department of Fish and Game website, http://www.dfg.ca.gov/marine/groundfish_fedlist.asp.

[b] Information obtained from Pacific Coast Salmon Fisheries Management Plan, Amendment 14, Appendix A.

[c] Information obtained from Coastal Pelagic Fisheries Management Plan, Appendix D.

III.4 Habitat

Typical aquatic habitat types in which Caltrans may conduct pile driving projects are divided into three categories: (1) aquatic areas occurring within areas of tidal influence, including marine nearshore areas and estuaries; (2) rivers and streams outside the influence of marine tidal habitats; and (3) lakes and isolated ponds. The boundary between tidally influenced areas and lower portions of streams and rivers is not rigid but is generally evident from the types of conditions found in these areas. Lakes may be man made (reservoirs) or natural, and may or may not be connected to large riverine systems.

III.4.1 Estuarine Areas under Tidal Influence

Estuarine areas under tidal influence include tidal flats, lagoons, vegetated marshes, wetlands, sloughs, and lower river-reaches.

Estuaries are places where freshwater streams and rivers meet the marine environment; they may be highly influenced by tides. During the outgoing tide, lagoons may be drained, mud flats may be exposed, flow may be reversed in sloughs, and the extent of saltwater in lower river systems recedes. Incoming tides may send ocean waters across tidal flats, fill lagoons, and extend saltwater some distance upstream of lower river reaches.

Tidally influenced areas provide important habitat for a number of fish species. Some species occur in brackish estuarine waters throughout their lives; others are dependent on estuaries only for reproduction, migration, or feeding. Anadromous species such as salmon, sturgeon, and lamprey also use estuaries to acclimate before entering the ocean or freshwater.

III.4.1.1 Key Habitats in Tidally Influenced Environments

Key habitats in tidally influenced environments of California include lower river reaches, sloughs, vegetated marsh wetlands, tidal flats, and lagoons. These key habitats are discussed briefly in this section.

Lower River Reaches

Tidal zones of rivers are unique environments due to the daily fluctuation of flow and mixing of saltwater and freshwater.

Tidally influenced riverine habitats are typically low-gradient, low-velocity areas with brackish water created from tidal influx (Figure III-3). Substrates usually consist of fine-grained mud and sand. River reaches influenced by tides can comprise a complex of main and secondary channels with associated sloughs and tidally inundated wetlands.

Estuarine river reaches are where adult and juvenile anadromous fish make their transitions to and from freshwater and saltwater life history stages.

III.4.1.2 Representative Fish Species in Tidally Influenced Habitats

Fish communities in tidal areas include a mix of marine, estuarine, and anadromous freshwater species. Species like starry flounder and herring move in and out of estuarine areas to feed or reproduce. Other species, such as tidewater gobies or Delta smelt, are residents within tidal habitats. Salmon, sturgeon, and other anadromous species move between freshwater and marine areas. For anadromous species, estuaries are transitional environments that are used during adult and juvenile migrations. Table III-2 lists common species likely to be encountered in different habitat types, including tidally influenced and marine areas (also see Section III.4).

Figure III-3. Tidally Influenced Riverine Habitat – Sacramento River at Rio Vista

Sloughs

Sloughs are tidally flushed channels typical of estuarine delta areas (Figure III-4). Sloughs are often, although not necessarily, connected to the river channel. They have little or no gradient, and flow is controlled significantly by tidal flow. Flow direction in sloughs often reverses with the direction of tides. Consequently, water velocities can be near zero during slack tide and then can be pronounced during ebb and flood tides. Substrates in sloughs usually consist of mud and silt.

Figure III-4. Tidal Slough – Watsonville Slough

Vegetated Marsh

Vegetated marshes are typical of estuarine areas on the north coast. Marshes include both emergent and submerged vegetation (Figure III-5). Eelgrass beds occur in deeper water and provide important habitat for a variety of fish species. The invasive grass *Spartina* also occurs in vegetated tidal marshes along the North Coast.

Figure III-5. Vegetated Wetland/Marsh – Fish Slough near Bishop, California

Tidal Flats

Tidal flats are very low-gradient mud and sand banks exposed by tidal fluctuations (Figure III-6). They create important habitat for many fishes, including shiner perch, surf smelt, and eulachon.

Figure III-6. Tidal Flats – San Felipe, Baja California

Lagoons

Lagoons are estuarine habitats typical of Southern California. Lagoons in Southern California are located at the lower end of stream confluences with the Pacific Ocean (Figure III-7). Many Southern California lagoons are disconnected from the stream and the ocean during much of the year. A sand berm is often built between the lagoon and the ocean by deposited sediments. Stream reconnection may occur only after several days of heavy rainfall due to an increase in the connected stream's water quantity, groundwater recharge, and water velocity. The stream's water velocity and quantity then will allow the sand berm to breach, connecting the stream, lagoon, and the marine nearshore. Extreme high tides may occasionally overtop the sand berm that keeps the outlet closed and recharge the lagoon with fresh saltwater. Southern California lagoons tend to have extremely high salinities and temperatures, and extremely poor water quality due to pollution and stagnant water. Some species that may be found in Southern California lagoons are included in Table III-2 (also see Section III.4). Other species found in these environments include topsmelt, California killifish, mosquitofish, and arrow gobies.

Figure III-7. Lagoon – Ventura River Lagoon

III.4.2 Rivers and Streams

Above areas influenced by tides, are large mainstem river reaches, primary tributaries, and headwater streams. In rivers and streams, native fish communities are primarily anadromous and resident salmonids, suckers, lamprey, and various minnow and sculpin species.

III.4.2.1 Key Riverine Habitats

Main River Channels

Large mainstem rivers, such as the Sacramento and San Joaquin Rivers, represent distinct habitats. In their natural condition, these main rivers also would contain secondary channels, sloughs, and wetlands. In most cases, however, large rivers in California have been diked and channelized to allow development on adjacent floodplains. As a result, most large rivers are characterized by a single large channel (Figure III-8). In upper watershed areas, the main channel may consist of rapids and pools; however, lower sections are generally simpler and consist of long stretches of relatively flat, deep water.

Figure III-8. Main River Habitat – Sacramento River at Knights Landing

Floodplains

Floodplains are the areas adjacent to a stream or river channel that are seasonally inundated by floods (Figure III-9). There is often a gradation of habitats—from the permanently wetted channel, to secondary channels that flow during high-flow periods, to wetlands and ponds that are inundated only during floods. Floodplains provide important habitat for wildlife and fish. In the Sacramento River, for example, the Yolo Bypass and intact floodplains in the Cosumnes River provide important habitat for juvenile Chinook salmon and spawning habitat for splittail and other native fish species. Floodplain habitats in California have been reduced by channelization and diking of stream banks.

Figure III-9. Floodplain of the Sacramento River

Tributaries (Riffles and Pools)

Tributary streams of higher elevations drain smaller sub-watersheds and feed main river channels. These tributary streams contain rapid and riffle, and pool habitat. Rapids and riffles are characterized by surface turbulence and white water, reflecting relatively shallow water over underlying boulders or cobble (Figure III-10). In large rivers, these can be dramatic rapids formed by boulders and bedrock; in smaller streams, they are often riffles flowing over small cobble. Riffles are primary spawning areas for salmon and steelhead as well as resident trout. Coho often spawn in riffles in smaller tributaries such as those entering the rivers along the North Coast. Steelhead are the most athletic salmonid and often spawn in small, higher gradient tributaries. Larger Chinook, especially fall Chinook, use larger cobble riffles and rapids found in large rivers, such as those found in the Sacramento River.

Figure III-10. Riffle Habitat in a Small Stream

Tributary pools are flat-water areas of relatively deeper water scoured out by flow. Pools form in conjunction with riffles, and an alteration of pools and riffles usually occurs along a stream (Figure III-11). Water velocities are reduced in pools, causing deposition of finer suspended sediment. In small streams, pools provide key feeding and rearing habitat for juvenile coho and trout. Deep pools provide resting areas for adult salmon, especially spring-run Chinook and steelhead/rainbow trout that must survive over the summer. Pools and riffles often form because of large wood in the stream channel—downed trees, limbs, and root wads. The lack of these materials often leads to reduction in the frequency of pools and riffles and the loss of key habitat for many fish species.

Figure III-11. Riffle-Pool Sequence in a Small Stream

III.4.2.2 Representative Fish Species in Riverine Habitats

Freshwater riverine habitats above tidal influence support a number of important and rare fish species (Tables III-2 and III-3). Widely recognized species such as salmon, steelhead, and sturgeon are anadromous. These species use freshwater environments for spawning and juvenile rearing, and then migrate to the estuaries and ocean to grow and mature. Life stages of anadromous salmon and steelhead are likely to be found in virtually any stream or river with free access to the ocean. Because of habitat loss and other factors, many salmon populations are listed under the CESA and ESA.

III.4.3 Lakes

Lakes are characterized by deep water and little or no discernible current. They include natural lakes and ponds, as well as artificial lakes or reservoirs. Reservoirs are common features in California river systems because most rivers contain one or more dams. Although some seasonal variation occurs, natural lakes usually have relatively stable water levels. In contrast, reservoirs can be quite dynamic; and water levels can vary widely seasonally, as well as daily. Reservoirs can be drawn down to provide flood storage, irrigation, groundwater recharge, or energy and later can be refilled during the rainy season.

III.4.3.1 Key Habitats in Lakes

Overall, habitats in lakes are generally simpler than those defined in streams and estuaries. A unique feature of lakes and many reservoirs is that they thermally stratify (Figure III-12). As surface water warms, it becomes less dense and "floats" on top of a cooler and denser layer. The demarcation between these layers (the thermocline) can be abrupt and is often used to define two general lake habitats: a surface layer (usually 10–15 feet deep) and a deep layer. The surface layer consists of a shallow fringe area that follows the shoreline and an open water area that sits atop the deep, cooler water.

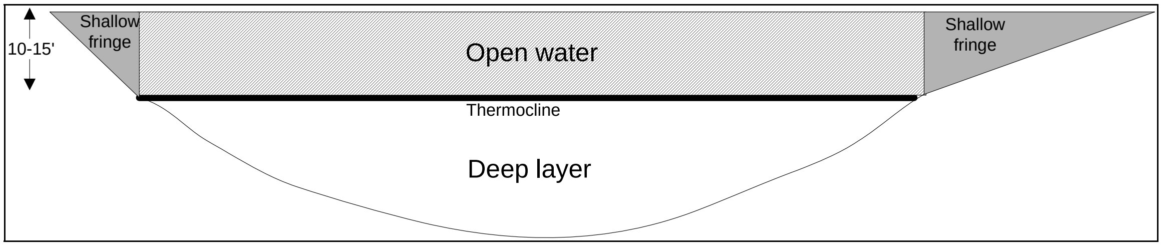

Figure III-12. Cross Section III of a Thermally Stratified Lake Showing General Habitat Types

The shallow fringe has structure provided by downed trees, aquatic plants, and bottom topography. Many juvenile fish take refuge around this structure while other species use the shallow areas for spawning. The open water above the thermocline is where aquatic algae and zooplankton are found and where many fish feed. The deeper layer provides a cooler refuge area. However, the thermocline can isolate the deeper layer; in some lakes, oxygen levels below the thermocline become low enough to exclude most fish species.

Ponds

In addition to lakes and reservoirs, California has numerous small ponds, particularly in the more eastern arid regions. These ponds can contain rare fish species that are often listed under the CESA and ESA. Table III-3 lists these rare fish species found in ponds, as well as fish species found in isolated lakes and headwater tributaries.

III.4.3.2 Representative Fish Species in Lakes

Lakes display a wide variety of environments and consequently a diverse array of fish species. Many California lakes support large numbers of non-native species, such as large mouth bass, crappie, and sunfish. Other lakes support unique sub-species of fish such those listed in Table III-3. Table III-2 (also see Section III.4) provides some guidance as to which species are common in California lakes. Take note, however, that many dams block passage of anadromous fish, and that each reservoir or lake must be reviewed independently for fish occurrence.

III.5 References

California Wetland Recovery Project. 2001. Available online at: http://www.scwrp.org/regional_strategy.htm.

Southern California Coastal Wetland Inventory. 1998. Available online at: http://ceres.ca.gov/wetlands/geo_info/so_cal.html.

Appendix IV Agreement in Principal for Interim Criteria for Injury to Fish from Pile Driving Activities

NOAA's Fisheries Northwest and Southwest Regions | *U.S. Fish and Wildlife Service Regions 1 & 8* | *California/Washington/ Oregon Departments of Transportation* | *California Department of Fish and Game* | *U.S. Federal Highway Administration*

MEMORANDUM

June 12, 2008

From: Fisheries Hydroacoustic Working Group

Subject: Agreement in Principle for Interim Criteria for Injury to Fish from Pile Driving Activities

To: Applicable Agency Staff

The signatory agencies, identified below, have agreed in principle to use the attached Interim Criteria for Injury to Fish from Pile Driving Activities. The agreement was concluded at a meeting in Vancouver, Washington on June 10-11, 2008 with key technical and policy staff from the Federal Highway Administration, NOAA Fisheries, U.S. Fish and Wildlife Service, the Departments of Transportation from California, Oregon, and Washington; and national experts on sound propagation activities that affect fish and wildlife species of concern. The agreed upon criteria identify sound pressure levels of 206 dB peak and 187 dB accumulated sound exposure level(SEL) for all listed fish except those that are less than 2 grams. In that case, the criteria for the accumulated SEL will be 183 dB.

These criteria will apply to all new projects beginning no later than 60 days from the date of this memorandum. During the interim 60 day period, the Transportation Agencies will work with the Services to identify projects currently in the consultation process and reach agreement on which criteria will be used to assess project effects.

The agencies agree to review the science periodically and revise the threshold and cumulative levels as needed to reflect current information. Behavioral impacts to fish and impacts to marine mammals are not addressed in this agreement. Sub-injurious effects will continue to be discussed in future meetings.

The respective agencies also agree to develop appropriate training for staff on these revised criteria, as well as a process to review and possibly refine the criteria, when appropriate.

For questions or concerns about the revised criteria, we recommend staff contact their agency environmental coordinator or agency expert on pile driving issues.

Federal Highway Administration*

*FHWA supports the use of these interim criteria in the states signing this agreement in principle. FHWA leaves the schedule for implementation to the discretion of the state DOTs in cooperation with their respective FHWA Division Offices and the Services.

NOAA Fisheries – NWR

NOAA Fisheries – SWR

US Fish and Wildlife Service Region 1

US Fish and Wildlife Service Region 8

California Department of Transportation

California Department of Fish and Game

Oregon Department of Transportation

Washington State Department of Transportation

Washington State Department of Transportation

FHWG Agreement in Principle
Technical/Policy Meeting Vancouver, WA
June, 11 2008

Interim Criteria for Injury	Agreement in Principle
Peak	206 dB (for all size of fish)
Cumulative SEL	187 dB - for fish size of two grams or greater. 183 dB - for fish size of less than two grams.*

**see Table—to be developed*

Glossary

acoustical pulse – Integral over time of the initial positive acoustic pressure pulse. This metric has been used by researchers to evaluate the effects of blast signals on fish where the signal is typically characterized by a single positive peak pressure pulse.

acoustic energy flux –The work done per unit area and per unit time by a sound wave on the medium as it propagates. The units of acoustic energy flux are joules per square meter per second (J/m^2-s) or watts per square meter (W/m^2). The acoustic energy flux is also called acoustic intensity.

acoustic particle velocity – The time rate of change of the displacement of fluid particles created by the forces exerted on the fluid by acoustic pressure in the presence of a sound wave. The units of velocity are meters per second (m/s).

air bubble curtain – A device that infuses the area surrounding a pile with air bubbles, creating a bubble screen that reduces peak underwater sound pressure levels.

ambient sound – Normal background noise in the environment that has no distinguishable sources.

ambient sound level – The background sound level, which is a composite of sound from all sources near and far. The normal or existing level of environmental sound at a given location. Distribution of sound pressure versus frequency for a waveform, dimension in root mean square pressure, and defined frequency bandwidth.

amplitude – The maximum deviation between the sound pressure and the ambient pressure.

bandwidth – The range of frequencies over which a sound is produced or received.

characteristic impedance (ρc) – The product of the density (ρ) and speed of sound (c) of a material. The difference in the characteristic impedance values in air vs. water causes a sound transmission loss between air and water of about 30 dB.

cofferdam – A temporary structure used to isolate an area generally submerged underwater from the water column.

critical habitat – Some listed fish populations also have legally protected habitat designated for the species. The federal Endangered Species Act requires designation of critical habitat for listed populations. Critical habitat refers to areas that are considered necessary for the survival and recovery of a species federally listed as threatened or endangered.

cumulative sound exposure level ($SEL_{cumulative}$) – In an evaluation of pile driving impacts on fish, it may be necessary to estimate the cumulative SEL associated with a series of pile strike events. $SEL_{cumulative}$ can be estimated from the single-strike SEL and the number of strikes that likely would be required to place the pile at its final depth by using the following equation:

$$SEL_{cumulative} = SEL_{single\ strike} + 10 \log (\#\ of\ pile\ strikes)$$

cushion block – A block of material placed atop a piling during pile driving to minimize the noise generated during pile driving. Materials typically used for cushion blocks include wood blocks, nylon blocks, and micarta blocks.

dead blow – An ineffective hammer strike on the pile when the pile is advancing through soft soil.

decibel (dB) – A customary scale most commonly used for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. A unit describing the amplitude of sound, equal to 20 times the logarithm to the base 10 of the ratio of the pressure of the sound measured to the reference pressure. The reference pressure for water is 1 micro-Pascal (µPa), and for air is 20 micro-Pascals (the threshold of healthy human audibility).

effective pressure – A measure of the square root of mean square (RMS) pressure. For pulses, the average of the squared pressures over the time that comprises that portion of the wave form containing 90 percent of the sound energy of the impulse. This measure historically has been used to calculate the RMS pressure for marine mammals.

essential fish habitat (EFH) – Habitat protected under the Magnuson-Stevens Fishery Conservation and Management Act and designated as those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity.

evolutionarily significant unit (ESU) – A Pacific salmon population or group of populations that is substantially reproductively isolated from other conspecific populations and that represents an important component of the evolutionary legacy of the species.

frequency – The number of complete pressure fluctuations per second above and below atmospheric pressure. Normal human hearing is between 20 and 20,000 hertz (Hz). Infrasonic sounds are below 20 Hz and ultrasonic sounds are above 20,000 Hz. Measured in cycles per second (hertz [Hz]).

frequency spectrum – The distribution of frequencies from low to high that comprise a sound. Frequency spectra are important because the frequency content of the sound may affect the way the fish responds to the sound (in terms of physical injury as well as hearing loss). From an engineering perspective, the frequency spectrum is important because it affects the expected sound propagation and the performance of a sound attenuation (i.e., reduction) system, both being frequency dependent.

hearing generalists – Fish that sense sound directly through their inner ear. Other fish use their inner ear but also sense additional energy from the swim bladder.

hearing specialists – Fish that have evolved any one of a number of different mechanisms to couple the swim bladder (or other gas-filled structure) to the ear. The swim bladder is stimulated by the pressure of sound waves and serves as a transducer that re-radiates energy in the form of particle motion that is detected by the inner ear. This increases hearing sensitivity compared to hearing generalists and therefore makes them more susceptible to loud noises.

hertz (Hz) – The units of frequency where 1 hertz equals 1 cycle per second.

impulse level – Integral over time of the initial positive acoustic pressure pulse. A graphical plot illustrating the time history of positive and negative sound pressure of individual pile strikes shown as a plot of µPa versus time. Measured in Pascals milliseconds (Pa msec).

intensity (I) –The product of sound pressure and acoustic particle velocity divided by the acoustic impedance of the medium; also referred to as the acoustic energy flux density.

isolation casing – A hollow casing slightly larger in diameter than the piling to be driven that is inserted into the water column and bottom substrate. The casing is then dewatered, and the piling is driven within the dewatered isolation casing. Isolation casings are similar to cofferdams in that they isolate the work area from the water column; however, because isolation casings have a smaller footprint, they cannot be used to isolate large areas. In addition, because the air space is smaller between the pile and the casing, isolation casings do not have as great of an attenuation value as cofferdams.

lateral line – A series of sensors along the body and head of fish that detects water motion.

otolith – A dense calcareous structure found in the otolithic end organs (i.e., the saccule, lagena, and utricle) of the ears of fishes. Otolithic organs overlie a tissue layer containing numerous sensory hair cells. Because the body of a fish contains mostly water, and otoliths are stiffer and denser than the rest of the body, sound will penetrate the otoliths more slowly than the rest of the fish. The

peak sound pressure level (L_{PEAK}) – The largest absolute value of the instantaneous sound pressure. This pressure is expressed as a decibel (referenced to a pressure of 1 micro-Pascal [µPa] for water and 20 µPa for air) or in units of pressure, such as µPa or PSI.

permanent threshold shift (PTS) – A permanent loss of hearing caused by some kind of acoustic or drug trauma that is generally accompanied by death of the sensory hair cells of the ear.

physoclists – Fishes in which the swim bladder is not connected to the esophagus. Gas is added to the swim bladder using a highly specialized gas-secreting system called the *rete mirabile* that lies in the wall of the swim bladder and extracts gas from the blood using a counter-current system, like that of a kidney, to remove wastes from the blood.

physostomes – Fish species in which the swim bladder is connected to the esophagus by a thin tube. Air to fill the swim bladder is swallowed by the fish and is directed to the swim bladder. Air removal from the swim bladder is by expulsion through this tube to the esophagus.

plane wave – A constant-frequency wave with wavefronts that are infinite parallel planes of constant amplitude normal to the velocity vector of the wave.

project action area – The area experiencing direct and indirect project-related effects.

resonance frequency – The frequency at which a system or structure will have maximum motion when excited by sound or an oscillatory force.

rise time – The time interval a signal takes to rise from 10 to 90 percent of its highest peak value (ANSI S12.7). Measured in milliseconds (msec).

root mean square (RMS) sound pressure level –Decibel measure of the square root of mean square (RMS) pressure. For impulses, the average of the squared pressures over the time that comprise that portion of the waveform containing 90 percent of the sound energy of the impulse.

sound – small disturbances in a fluid from ambient conditions through which energy is transferred away from a source by progressive fluctuations of pressure (or sound waves).

sound exposure – The integral over all time of the square of the sound pressure of a transient waveform.

sound exposure level (SEL) –The time integral of frequency-weighted squared instantaneous sound pressures. Proportionally equivalent to the time integral of the pressure squared and can be described in terms of μPa^2 sec over the duration of the impulse. Measured in dB re: 1 μPa^2 sec. In this guidance manual, sound energy associated with a pile driving pulse, or series of pulses, is characterized by the SEL. SEL is the constant sound level in one second, which has the same amount of acoustic energy as the original time-varying sound (i.e., the total energy of an event). SEL is calculated by summing the cumulative pressure squared over the time of the event.

sound pressure level (SPL) – An expression of the sound pressure using the decibel (dB) scale and the standard reference pressures of 1 micro-Pascal (μPa) for water and biological tissues, and 20 μPa for air and other gases. Sound pressure is the sound force per unit area, usually expressed in micro-Pascals (or micro-Newtons per square meter), where 1 Pascal is the pressure resulting from a force of 1 Newton exerted over an area of 1 square meter. The SPL is expressed in decibels as 20 times the logarithm to the base 10 of the ratio between the pressure exerted by the sound to a reference sound pressure (e.g., 20 micro-Pascals). SPL is the quantity that is directly measured by a sound level meter. Measured in decibels (dB).

speed of sound (c) –The rate at which sound propagates through a medium. The speed of sound in sea water at a standard temperature of 21 ºC is equal to 4.4 times the speed of sound in air at standard temperature and pressure.

swim bladder – A gas filled chamber found in the abdominal cavity of many species of bony fishes but not in cartilaginous fishes. The swim bladder serves in buoyancy control and may serve as a radiating device for sound production.

teleost fishes – Fishes that maintain their buoyancy by inflating and deflating their swim bladder with air.

temporary threshold shift (TTS) – A temporary loss of hearing as a result of exposure to sound over time. The level and duration of exposure that cause auditory tissue damage and TTS varies widely and can be affected by factors such as repetition rate of the sound, pressure level, frequency, duration, size and life history stage of the organism, and many other factors. Both peak sound pressure level and sound exposure level can affect hearing through auditory tissue damage or TSS. TSS will occur at lower levels than auditory tissue damage.

threshold – The lowest signal level an animal will detect in some statistically predetermined percent of presentation of a signal. Auditory thresholds are the lowest sound levels detected by an animal at the 50-percent level.

waveform – A graph obtained by plotting the instantaneous values of a periodic quantity against time.

wave length (λ) – The length of one full cycle (i.e., the distance between peaks) of a periodic quantity. The wave length is equal to the speed of sound divided by the frequency (i.e., peaks per second expressed as Hertz [Hz]).