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# Behavioral Response and Survival of Juvenile Coho Salmon Exposed to Pile Driving Sounds

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**Abstract**

Few experimental studies have been conducted to evaluate the effects of impact pile driving sound on juvenile salmon. We placed approximately 100 juvenile coho salmon (93-135 mm) in cages near (1.8-6.7 m) and distant (15 m) to the driven steel piles while exposing them to 1,627 strikes (14 piles) during a 4.3 hour period. Peak sound pressure levels ($SPL_{peak}$) reached 208 decibels (dB), root mean square pressure levels ($SPL_{rms}$) reached 194 dB, and sound exposure levels (SEL) reached 179 dB, leading to a cumulative SEL of approximately 207 dB during the 4.3 hour period. No juvenile salmon died in either of the test groups or control group (background sound levels) while holding the fish in cages for 10-19 days after the exposure. Behavioral responses of salmon to pile strikes were subtle. Startle responses of a small portion of total fish were observed in only 4 of 14 first strikes and they tended to occur when cages were close (1.8 m) to the piles and $SPL_{peak}$ (avg. 207 dB) and SEL (avg. 177 dB) were relatively high. Visual stimuli caused a greater startle response. An avoidance response was not apparent among fish for all but one pile and no fish exhibited a fright response. No gross external or internal injuries associated with pile driving sounds were observed. Underwater video revealed that the coho salmon readily consumed hatchery food on the first day of feeding (day 5) after exposure to pile driving sounds and most test salmon contained food when examined during necropsies 10 days after exposure. Although auditory system, cellular, and stress responses of coho salmon were not examined, our study suggests that coho salmon were not significantly affected by cumulative exposure to pile driving sounds produced during this investigation.

## Introduction

Concerns regarding the potential effects of anthropogenic sound on marine and aquatic animals have grown during the past decade or more. Anthropogenic sounds may affect animals by causing mortality, injury to internal organs, temporary or permanent loss of hearing, cellular damage, stress, and/or altered behavior leading to greater risk to predators or reduced feeding (Schwarz 1985, Pearson et al. 1992, McCauley et al. 2003, Smith et al. 2004, Popper et al. 2005, Wysocki et al. 2006). Although these effects have been documented in some animals, scientists recently concluded that existing studies are inadequate to determine minimum levels and durations of sound that adversely affect aquatic animals (NRC 2003, Popper 2003, Hastings and Popper 2005). Furthermore, the setting of criteria to protect animals from anthropogenic sound is complicated because species have evolved to use sound in various ways and may have different thresholds and tolerances to sound.

A frequent activity that produces high sound levels in nearshore marine and aquatic habitats is the installation of piles with an impact hammer to support docks, piers, and bridges. Sounds produced by pile driving differ from sounds produced by sonar, seismic air guns, and pure tones, and extrapolation of impacts may not be warranted (Popper 2006). Impact pile driving activities have received greater regulation by agencies in recent years because their sound may injure, kill, or alter the behavior of fishes, such as Pacific salmon (*Oncorhynchus* spp.), which are protected in some regions under the United States Endangered Species Act (Stadler 2003, NMFS 2007). Sound levels and frequencies produced by pile driving are complex and may vary with characteristics of pile (e.g., steel, wood, or concrete piles), pile-driving hammer, substrate, water depth, and other environmental conditions (Popper 2006). Effects of sound on fishes may vary with species, type of auditory system (e.g., generalist vs. specialist), body size, presence of swimbladder, and water depth (Hasting 2002, Hastings and Popper 2005). Smaller fishes tend to be affected more by sound than large fishes. Sound levels typically dissipate with distance from the source, but propagation of sound through substrate in shallow water may extend the range of high sound levels. Although information indicates pile driving sounds may impact fishes in a variety of ways, additional information is needed to quantify minimum levels and durations of sound that adversely affect the physiology and behavior of fishes.

Several scientists recently recommended interim threshold sound levels to protect fishes from pile driving sounds based on interpretation of available information (Popper et al. 2006). They suggested dual criteria thresholds for a single strike measured at a distance of 10 m from the pile: a sound exposure level (SEL) of 187 dB (re: 1 $\mu Pa^2 \bullet sec$) and a peak sound pressure level (SPL) of 208 dB (re: 1 µPa) in any single strike. This SPL is much higher (less conservative) than the peak SPL that the National Marine Fisheries Service (NMFS) initially identified as potentially causing physical damage to animals (180 dB re: 1 µPa; http://mapping.orr.noaa.gov/website/portal/pies/piledriving.html). NMFS reviewed Popper et al. (2006) and concluded that the proposed interim criteria were lacking because they did not incorporate 1) potential effects of sound on animal behavior, and 2) cumulative effects of multiple strikes from multiple piles on the survival, condition, and behavior fishes (Strach et al. 2006). As of July 2008, NMFS considers physical injury to begin when $SPL_{peak}$ reaches 206 dB (re: 1µPa) during a single strike and/or when the accumulated SEL from multiple strikes reaches 187 dB for large fishes (≥ 2 g) or 183 dB for small fishes (< 2 g; J. Stadler, NMFS, pers. comm.). Few data are available to evaluate adverse behavioral responses of fish to pile driving sounds (Feist 1992, Vagle 2003, Nedwell et al. 2006), therefore NMFS set the initial criterion at 150 $dB_{rms}$, a value that corresponds to $SPL_{peak}$ of 165 dB when driving piles with an impact hammer.

In this investigation, we examined short-term (hrs) and medium-term (10-19 days) effects of impact pile driving on caged yearling coho salmon (*O. kisutch*). Test fish were exposed to sound from two distances (2-7 m and 15 m) when installing 1 pile or 14 piles within a 4.3 hr period, then compared with fish held at a nearby control site. Sound characteristics in the fish cages were monitored so that effects on fish could be associated with sound characteristics of pile driving. The following null hypotheses were tested in relation to effects of impact pile driving sound:

1) coho salmon do not experience elevated mortality,

2) coho salmon do not develop gross external or internal injuries,

3) coho salmon do not alter their behavior (e.g., startle, freeze, or avoidance),

4) coho salmon resume feeding,

5) responses of coho salmon to sound are the same when near (< 5 m) or distant (15 m) from the pile driving operation, and

6) responses of coho salmon are the same when exposed to sound produced by the installation of 1 pile versus 14 piles.

## Methods

### Study Area

The study was conducted at Fishermen's Terminal located on the Lake Washington Ship Canal, Washington, from December 28, 2006 to January 17, 2007. Exposure of juvenile coho salmon to impact pile driving occurred on one day. Water depth was 4.3-5.2 m (14-17 ft), salinity was < 5 ppt (freshwater), and temperature was 6 °C. Lake elevation was constant and there were no currents. Surface substrate was soft mud overlying dense glacial soils. No large rocks or boulders were known to be present. Photographs of the study operation are shown in Appendix A.

### Pile Driving Operation

Fourteen hollow steel pipe piles (0.51 m [20 inch] diameter, 1.3 cm [0.5 inch] wall thickness) were installed within a 27.5 m x 6.1 m rectangular area in order to provide structural support for a fixed dock that may support vehicles. The fixed dock was located in the southwest corner of Fishermen's Terminal, approximately 1 m to 45 m from vertical sheet pile retaining walls (Fig. 1). The 17.7-18.3 m long (58-60 ft) piles were set in place prior to the experiment with a HPSI 300 vibratory hammer. Approximately 30.4 ± 8.2 seconds were required to vibrate each pile approximately 9.8-10.3 m into the substrate. No test fish were exposed to sound from operation of the vibratory hammer.

During the test period, the steel piles were “proofed” using a Delmag D30-23 open-end diesel impact hammer having a 6,615 lb ram weight and a variable ram stroke height. For this hammer type the approximate ram stroke height depends on the hammer fuel setting and the resistance of the soil to pile penetration. The approximate stroke height and the hammer blow rate (blows per minute) are known to be related to each other using an industry standard formula commonly referred to as the saximeter formula. Using the saximeter formula and data from the driving inspector’s log and our sound measurements we computed the approximate ram stroke height. A waiver was acquired from the Washington Department of Fish and Wildlife (WDFW) that allowed the experiment to be conducted without deployment of a bubble curtain so that fish would be exposed to maximum sound levels produced by the impact hammer.

<u>Juvenile Coho Salmon</u>

Approximately 700 juvenile coho salmon (fork length: 86-138 mm; weight: 7.6-29.8 g) were obtained from the WDFW Issaquah Hatchery on December 28, 2006. The fish were transferred to a 150 gallon (569 liter) tank that received 100% oxygen through a 30 cm air stone (2.5 liters per minute) and transported by truck approximately 35 km to the study site. Temperature in the tank reflected air temperature (6°C).

A total of 100 to 105 coho salmon were placed in each of six cages during the evening prior to the tests. Fish were dip-netted from the truck tank, placed in a 19 liter aerated container, and transported approximately 30 m and poured into the cages. The 1 m x 1 m x 1.5 m cages were constructed from 3 mm ace webbing supported by a PVC pipe frame. Large holes in the pipe allowed air to escape and water to enter the pipe. The cages were encased within two layers of wire mesh (2.5 cm and 5 cm) that protected the fish from potential attack by predators such as river otter (*Lontra canadensis*). The cages were suspended approximately 30 cm below the surface using eight floats attached to each cage. Caltrans (2004) reported that similar cages had no measurable effect on sound.

On the morning of the study (0700 h), four fish cages were towed slowly approximately 30 m by boat to the pile driving area and tied to a floating dock that could be moved to maintain distance between the test pile and fish cages. Two fish cages were maintained approximately 2-7 m from the pile and two fish cages were approximately 15 m from the pile. After exposing fish to noise produced by the first pile (97 strikes), one cage from each distance was towed by boat to the control site. The control site was approximately 370 m from the test area and a tongue of land and numerous deep-drafted boats intersected a direct line from the piles to the control fish cages (Fig. 1). Coho salmon in the two remaining test cages were exposed to sound produced by driving 14 piles during the one-day event. These two cages were towed to the control site upon completion of pile driving (1630 h). Prior to the tests, two cages containing 100 to 105 fish each were transported to a floating dock at the control site where sound measurements indicated noise from the impact hammer was minimal (see below). Fish in the control cages were towed by skiff the same distance as fish in test cages (~500 m).

Behavior of coho salmon before, during and after driving 14 piles was monitored with an underwater video camera (90° viewing angle) suspended in the middle of the cage that was closest to the active pile. The direction of the camera was remotely controlled so that fish in all areas of the cage could be observed on the monitor except for fish immediately below the camera. Behavior during the test period was observed during daylight, whereas behavior after pile driving was observed during both day and night. Viewing at night was facilitated by LED lights mounted on the underwater video camera. Both video and audio were recorded on digital tape for later viewing at the lab. Fish could not readily see the camera rotate 360° within the housing. Water clarity was sufficient to view the entire cage.

Salmon behaviors in response to pile driving were classified as avoidance, alarm, fright, or startle responses (Swarz and Greer 1984, Pearson et al. 1992). Avoidance behavior was identified when most test fish shifted position in the cage away from the sound source. Alarm behavior involved a change in directed (polarized) or undirected schooling behavior, body orientation, and/or vertical position of fish in the cage. Fright response was identified when fish "froze" in place in response to sound stimulus (Popper 2003). Startle behavior was identified as quick darting motion of fish in response to one or more strikes of the pile. We anticipated that responses to pile driving sound might be strongest during initial strikes followed by attenuation of behaviors as the fish acclimated to sound (Moore and Newman 1956). Quantification of behaviors and the percentage of individuals exhibiting the behaviors were made from recorded video tapes.

Cages were thoroughly examined for fish mortalities immediately after exposure to sound produced from hammering 1, 9 and 14 piles, then 4, 10, and 19 days after exposure to pile driving. Behavior of test and control fish was periodically observed throughout the 10 to 19 day holding period by suspending the underwater camera in the cages.

Coho salmon were not fed during the day prior to the study and for four days after exposure to the noise, a practice that is common in salmon culture to reduce stress when transporting fish. After five days, all test and control fish were fed daily with approximately four handfuls of hatchery pellets per cage. The percentage of test and control fish containing hatchery pellets was estimated during necropsies 10 days after exposure to pile driving sounds. Feeding behavior was documented with underwater video.

Non-histological necropsies were conducted on fish either 10 or 19 days after exposure to pile driving. This waiting period may have allowed low level hemorrhaging to heal and not be detected. All salmon exposed to hammering of 14 piles and 50 control fish were examined 10 days after exposure, and all remaining fish were examined 19 days after exposure. Approximately 50 fish were dip-netted from test and control groups and transported in aerated 19 liter containers to the on-site laboratory. Individual coho salmon were euthanized with MS-222 (Tricaine methane sulfonate), then immediately measured (fork length) and examined under a 10-30x dissecting scope for external injuries such as body bruise, snout bruise, erythema (redness) at the base of fins, eye hemorrhage, scale loss, and gill filament hemorrhage or discolor. Internal organs were examined after making an incision with surgical scissors from the anal vent to the isthmus and a transverse cut immediately posterior of the operculum to expose the heart within the pericardium. The lead investigator searched for internal injuries such as abnormal bleeding in the body cavity, ruptured (torn and deflated) swim bladder and pericardium, hemorrhaging of the heart, liver, and kidney. Presence or absence of hatchery food in the stomach was examined to determine whether test fish resumed feeding.

Sound Monitoring

Underwater sound levels were measured with Reson Type 4013 hydrophones placed in the center of the fish cages approximately 0.5 m below the surface. Signals from the pressure transducers (hydrophones) were recorded using a Dactron Photon 4-channel signal analyzer connected to a Fujitsu tablet computer. The sampling frequency on each channel was approximately 24 kHz (41.7 microseconds between samples). Digitized measurements were stored in a binary format native to the Dactron software and used for replay and data analysis. The overall sensitivity of the hydrophones and acquisition system were field-verified using a Gras type 42AC piston-phone calibrator on each channel.

A hydrophone was placed in the cage that was closest to the pile being driven (within 2-7 m) and in the cage located approximately 15 m from the pile. Background sound level measurements were recorded on several occasions. Prior to the start of driving on the final pile (No. 14) all three hydrophones were placed in a cage containing salmon at the control site.

Pile driving sounds are complex and a single metric is not known to best predict effects on fish. Therefore sounds were characterized using several metrics, as defined below. Most of these metrics were calculated for individual strikes, of which there were 1,627 strikes in this study. A subsample representing the strike having comparatively high peak sound level for each pile was selected for detailed analysis. The study focused on sound in the fish cage closest to the pile being driven because these fish were more likely to be affected by sound compared with fish in the distant cage. Sound in the distant cage was compared with that in the close cage during the same strike of three piles.

***Peak Sound Pressure Level***

Peak pressure is obtained from the maximum excursion (either positive or negative) from the ambient pressure. The "peak" pressure is the absolute value of the sound pressure excursion. Although pressure is measured in units such as Pascals or pounds per square inch (PSI), it is customarily expressed using the non-dimensional and logarithmic decibel scale and is called peak sound pressure level ($SPL_{peak}$). The formula for converting a measured peak pressure to $SPL_{peak}$ is given below:

$$SPL_{peak} = 20\log\left(\frac{p}{p_{ref}}\right)$$

where the absolute value of the measured peak in Pascals (Pa), p, is divided by a customary reference pressure. For water the customary reference pressure, $p_{ref}$, is 1 μPa. Thus, signals for which the peak pressure is 1000, 3163 and 10,000 Pa would have $SPL_{peak}$ values of 180, 190 and 200 dB, respectively. In other words, a 10 dB increase in sound pressure equates to a 3.16-fold increase in sound pressure.

***Sound Exposure Level***

Sound exposure is a measure of the sound energy in a single hammer blow. It is computed as the summation of the square of individual values multiplied by time between values:

$$\text{Sound Exposure} = \sum_{a}^{b} p^2 \Delta t$$

The summation begins at time "a" when the signal exceeds the background level and ends at time "b" when the signal returns to the background level. The length of time between "a" and "b" is generally close to 0.1 seconds and the time between successive hammer strikes is generally greater than 1 second. For this study Δt was 41.7 microseconds. Sound exposure is customarily expressed in dB (re: $1\mu Pa^2 \bullet sec$), and is called the Sound Exposure Level (SEL):

$$\text{SEL (dB)} = 10\log\left(\frac{\text{SEL}}{(p_{ref})^2 \bullet \text{sec}}\right)$$

***Root Mean Square Sound Pressure Level***

The Root Mean Square Sound Pressure Level, $SPL_{rms}$ is the square root of the mean of the squares of periodic pressure measurements over a specific period of time:

$$\text{RMS} = \sqrt{\frac{\sum_{t_{05}}^{t_{95}} p^2 \Delta t}{t_{95} - t_{05}}}$$

For this report we summed the squared pressure measurements over a time interval that began at $t_{05}$ and ended at $t_{95}$ when the sound energy (SEL) reached 5 and 95 percent of the total SEL, respectively. Such an interval is the customary interval in recent work (Hastings and Popper 2005); it is also customary to present the results in terms of dB (re: 1μPa):

$$SPL_{rms} \text{ (dB)} = 20\log\left(\frac{\text{RMS}}{p_{ref}}\right)$$

***Cumulative Sound Exposure Level***

The aforementioned measures of sound pressure involve a single strike of the pile. Characterization of cumulative sound from multiple strikes of a pile was based on the following formula (Strach et al. 2006):

Cumulative SEL = SEL dB + 10Log(Number of Strikes)

***Crest Factor***

The “crest factor”, CF, was calculated from the ratio of peak pressure to RMS pressure (Popper et al. 2006):

$$CF = \frac{\text{Peak Pressure (Pa)}}{\text{RMS (Pa)}}$$

***Sound Exposure Rise Time, Swing time and Swing Rate***

Some researchers have proposed that the length of time associated with the energy in a single strike, and the rate of change of pressure in a single strike may be relevant to the effect of that strike on fish (Hastings and Popper 2005, Popper et al. 2006). For this paper, we report the time required for sound exposure (in units of $Pa^2$•sec) to increase from 10 to 90 percent of its total value, and refer to that time as the Sound Exposure Rise Time ($SRT_{10\text{-}90}$). Also, to characterize the peak rate of change of sound pressure, we report a metric which we have called the Peak Swing Rate (PSR). The PSR value is peak sound pressure, in units of Pa not dB, divided by the Swing Time (ms), which is the time interval between the last occurrence of zero pressure before the peak pressure and the first occurrence of zero pressure after that peak. PSR is presented in units of MPa/sec.

**Results**

<u>Sound Characteristics</u>

Juvenile coho salmon were exposed up to 1,627 strikes while driving 14 piles during a 4.3 hour period (Table 1). Each pile was hammered approximately 2.6 minutes, on average. Approximately 54 strikes were required to drive the pile 1 m into the substrate (16.6 strikes per ft). Ram stroke height averaged 6.6 ± 0.2 ft.

In the cage closest to the pile, values of $SPL_{peak}$ ranged from 194 dB to 208 dB and averaged 204 dB while $SPL_{rms}$ ranged from 182 dB to 194 dB, averaging 189 dB (Table 1). The “crest factor”, which is the ratio of peak to rms pressure, averaged 5.6. The energy dose of each strike (SEL dB) ranged from 167 dB to 179 dB and averaged 175 dB. The cumulative energy dose (Cumulative SEL), experienced by fish exposed to the first pile (97 strikes) was 186 dB, whereas the cumulative energy dose experienced by fish exposed to all 1,627 strikes was approximately 207 dB. The Sound Exposure Rise $Time_{10\text{-}90}$, which is the time interval during which 80 percent of the strikes energy occurred, averaged 20.8 ms. Swing Time averaged 0.66 ms and Peak Swing Rate averaged 30 MPa/sec, ranging from 7 to 70 MPa/sec. The large difference in the PSR values for various strikes reflects the relatively large differences that exist in the temporal variation of pressure within individual strikes.

A plot of sound pressure (Pa) versus time produced by 13 pile strikes shows that sound pressure was highly variable within the first 20 ms, then stabilized as the pressure approached background levels (Fig. 2). Detailed waveform plots of three strikes shows that the sound pressure pattern varies from strike to strike (Fig. 3). However, $SPL_{peak}$, SEL, and $SPL_{rms}$ were positively correlated such that more than 86% of the variability in one metric could be predicted by variation in another metric (Fig. 4). Peak Swing rate was also correlated with $SPL_{peak}$, but this relationship was markedly improved after excluding values from the distant cage ($R^2 = 0.70$). Sound pressure variables ($SPL_{peak}$, SEL, and $SPL_{rms}$) were not correlated with either Swing Time or Sound Exposure Rise $Time_{10\text{-}90}$ ($P > 0.05$), except Sound Exposure Rise $Time_{10\text{-}90}$ was negatively correlated with $SPL_{rms}$ ($r = -0.53$, $P = 0.032$). The values of the various metrics discussed above and their correlations to each other were likely influenced by the complex field which included a sheetpile wall, the submerged portion of the work barge that supported the pile driving equipment, and the relatively short distance between the pile and the hydrophones. These field conditions are typical of most near shore pile driving, except that underwater sound measurements have generally been made at a distance of 10 m or more from the pile.

Salmonids appear to be most sensitive to sound frequencies near 100-200 Hz where they can detect $SPL_{rms}$ as low as 95-100 dB (Abbott 1973, Hawkins and Johnstone 1978, Popper 2003). In our study, most sound pressure energy occurred at lower frequencies but the level of energy oscillated as frequency increased (Fig. 5). For example, the highest average sound pressure was observed near 23 Hz (avg. 202 dB), then declined to 168-170 dB near 70- 164 Hz, then increased to 189-192 dB at 211-281 Hz, then declined to 167-174 dB at 328-422 Hz. Detailed sound pressures of three pile strikes across a range of frequencies are shown in Fig. 6.

Sound pressure levels recorded inside the cage located approximately 15 m from the pile were compared with levels recorded 1.8-3.0 m from the same pile (Piles 5, 6, and 12). On average, $SPL_{peak}$, $SPL_{rms}$, and SEL were 12.3 dB, 10.0 dB, and 8.8 dB less in the distant cages, respectively, after traveling approximately 13 m (Table 1). In absolute terms of pressure and energy (rather than dB) these values for $SPL_{peak}$ and SEL indicate a 76% decline in sound pressure and an 87% decline of sound energy between the close and distant cages. Sound Exposure Rise Time, $SRT_{10\text{-}90}$, was 38% greater in the distant cages, Peak Swing Rate was 68% less in the distant cages, and the Crest Factor declined 22%. These changes in $SRT_{10\text{-}90}$ , Peak Swing Rate, Crest Factor, and the narrow band frequency spectra for both cage locations, as presented in Appendix C, suggest that in the distant cages a slightly greater portion of the pressure fluctuation and energy was at low frequency.

Background underwater sound pressure levels were measured in the close fish cage during interruptions to driving and Fig. 7 presents results for an interruption that occurred during driving on Pile 13. Background levels were typically near 140 dB re: 1µPa, but peaks in the background sound pressure level approached 150 dB.

Sound pressure levels were also recorded in a control fish cage while driving Pile 14 with the impact hammer. Sound pressure levels in the control fish cage were typically near 155 dB (Fig. 7). Several very brief spikes approached 170 dB within a three second interval. There was no indication of periodic sound pressure changes that may have been caused by pile driving impacts which occurred at intervals of 1.3 seconds. Lack of detectable underwater pile driving sound at the control site indicates that the pile driving signal was lower than the background levels. The apparent weakness of the signal probably reflects distance (370 m), a tongue of land that separates the test site and control location, and deep-drafted boat hulls that lay between the two sites. Higher sound levels at the control site relative to background levels at the test site may reflect exposure to sounds produced in the ship canal (control site) versus the somewhat protected environment at Fishermen's Terminal (Fig. 1).

Coho Salmon Survival

No mortality of juvenile coho salmon was observed in response to exposure to impact hammer sound or to transport and holding conditions at the control site. All 421 coho salmon survived for at least 10-19 days after exposure to sound produced by hammering one pile (97 strikes) at distances of approximately 2.4 m and 15 m from the piles (Table 2). All 213 coho salmon survived for at least 10 days after exposure to sound produced by hammering 14 piles (1,627 strikes) at distances of 1.8-6.7 m and approximately 15 m from the piles. Fish exposed to 14 piles were removed for necropsy analyses 10 days after pile driving, whereas fish exposed to one pile were held for 19 days. All 207 coho held at the control site during and after the test period survived the entire study period (10-19 days).

External and Internal Injuries

All test and control fish appeared to be healthy during the test period and during the 10 to 19 day holding period, based on their swimming behavior and external appearance. Necropsies conducted on 200 salmon exposed to sound produced by hammering 14 piles revealed no external injuries that might have been caused by pile driving such as hemorrhaging eye, fin erythema, or discolored or hemorrhaged gill filaments (Table 3). Examination of 113 control fish did not reveal injuries that might reduce performance. Less than 10% of test and control fish exhibited external injuries that were likely related to transportation from the hatchery to the study site in a truck-mounted tank. Bruise snout (white color) was the most common injury (9% of fish). One percent or less of test fish had a damaged eye (opaque pupil) on one side of the head or slight scale loss (5% of body).

Examination of body cavity organs of test fish exposed to hammering of 14 piles and control fish did not reveal abnormalities or injuries (Table 3). No abnormal bleeding within the body cavity or behind the kidney membrane was observed. The swim bladder was inflated in all fish, indicating no rupture.

Coho Salmon Behavior

Behavioral responses of coho salmon in the cage held 2-7 m from impact hammer sound were subtle and not consistent for all 14 piles. Both test and control fish tended to be aggregated rather than dispersed during the tests and while being held at the control site for up to 19 days (see photographs in Appendix B). All fish tended to disperse and rise in the water column at night.

Coho salmon did not consistently exhibit a startle response during the first or subsequent hammer strikes of each pile. A brief startle response was observed during 4 of 14 first-strikes (29% of piles), and during 1 of 14 second-strikes (7%). Quiet time between driving of each pile ranged from two to 115 minutes, but quiet time was not related to startle response. Startle responses related to pile driving sound did not occur after the second strike, indicating some habituation to sound. Typically less than 10% of the fish exhibited the startle response. Startled fish darted only about 7 cm from their initial position while remaining within the aggregation of fish.

Three of the startle responses occurred when hammering the last three piles, indicating coho salmon did not habituate to driving of multiple piles over time. These startle responses occurred when the cage was very close to the pile (1.8 m) and SEL and peak SPL were somewhat high (up to 179 dB and 208 dB, respectively) compared with sound produced by previous piles (Table 1). Interestingly, another startle response occurred when the hammer tapped a pile with very little force and produced low sound after a few minutes of quiet.

On several occasions, coho salmon startled in response to visual stimuli caused by construction workers moving above the cage. Visual stimuli produced a stronger response in terms of distance moved and numbers of reacting fish.

Although the test fish were confined within a cage that limited their movement, they did not appear to avoid pile-driving sounds by moving to the opposite side of the cage. Fish tended to hover near the suspended camera in the middle of the cage. During installation of Pile 12, the fish moved to the side of the cage, then moved back to the middle after pile driving ceased. This behavior occurred when the cage was close to the pile (1.8 m) and sound level was relatively high (208 $SPL_{peak}$; 179 SEL).

Coho salmon did not exhibit an alarm or fright (freeze) response during pile driving. However, swimming depth of coho salmon slightly decreased during piles 2, 3, 7, and 12, then increased during piles 8, 9, and 10. Body orientation of coho salmon relative to the pile was mixed, indicating the fish were not polarized with their heads away from the sound source. Coho salmon typically moved slowly and randomly changed direction within the aggregation of fish. Body orientation of some fish, especially during the latter pile driving period, changed from horizontal to approximately 45° with the head elevated above the tail.

After transporting fish to the holding area, body orientation of both test and control fish became mostly horizontal only after the cages were exposed to the surface and fish apparently refilled their swim bladder. Throughout the holding period both test and control fish tended to remain aggregated during daylight near the lower portion of the cage then dispersed at night, indicating that the aggregation was not caused by pile driving but could have been related to the lack of cover within the cage. There was no unusual or erratic behavior in test fish and control fish during the holding period.

Coho Salmon Feeding

Underwater video revealed that both test and control salmon readily consumed hatchery pellets when tossed onto the surface of the cages during the first and subsequent feeding trials (5 to 19 days after exposure to sound). Swimming depth of coho tended to increase in response to the splashing of pellets on the surface. Both test and control fish darted away from the fish aggregation to consume pellets, then quickly returned to the group.

Examination of coho stomachs 10 days after exposure to pile driving indicated both test and control fish readily consumed food. Several hours after providing food to the caged fish, 61-71% of the test fish contained food and 44% of the control fish contained food. Many of the fish had distended stomachs.

**Discussion**

The key finding of this study was that external or internal injuries of juvenile coho salmon were not detected 10 days after exposure to sound produced by 1,627 strikes of an impact hammer on 20 inch steel piles during a 4.3 hour period. $SPL_{peak}$, $SPL_{rms}$, and SEL of strikes measured in the close fish cage averaged 204 dB, 189 dB, and 175 dB, leading to an approximate cumulative SEL of 207 dB. The lack of observed injuries was consistent with the healthy appearance and high feeding rates shown by the test fish (and control fish) for five to 19 days after exposure. We cannot exclude all potential injuries to the test fish because we did not examine potential injuries immediately after exposure or potential injuries to the auditory system, injuries that may have occurred at the cellular level, or stress caused by pile driving. Nor did we hold the fish beyond 19 days, or examine feeding rates immediately after exposure. However, swimming and feeding behavior of the coho salmon within the study period indicated that potential physical injury caused by exposure to sound, if any, was not life-threatening. External signs of stress, such as scale loss, excess mucus and fungus, were not apparent among test fish and control fish.

Behavioral changes of the juvenile coho in response to impact hammer strikes were subtle. A small portion of the fish aggregation exhibited a brief startle response during only 4 of the 14 piles. The average $SPL_{peak}$ of these strikes was 207 dB (192 dB $SPL_{rms}$) compared with 203 dB (188 dB $SPL_{rms}$) for piles where no startle response was detected, suggesting higher sound pressure may have initiated a startle response. Startle responses occurred in cages that were closer to the pile (1.8 m v. 4.6 m), indicating particle motion (Popper et al. 2003) might have influenced startle behavior. The startle response occurred only once after the first strike. The startle response caused by visual stimuli, such as a construction worker walking near the cage, was much greater in terms of both numbers of fish and distance traveled. Coho salmon did not exhibit a fright response to pile driving sound. Nor did they avoid sound by moving away from the pile, although the confinement in the cage might have inhibited a strong avoidance response. The lack of an avoidance response raises the question of whether juvenile salmon will swim away from injurious sound levels in the absence of visual stimuli. A startle response would not cause injury unless it increased vulnerability to predators, which often target darting prey (Ruggerone 1989), or if the startle resulted in reduced feeding.

The tendency for fish to gradually increase depth and change body orientation may have been caused by fish gradually expelling air from the swimbladder in response to impact hammer noise, although we did not observe expulsion of air from the fish. The submerged test cages did not allow salmon to access surface air where they might have gulped air to refill the swimbladder and regain body orientation and depth. Both test and control coho salmon formed aggregations during the day, possibly in response to the lack of cover in the cages, but fish dispersed at night.

Our investigation is consistent with findings provided in a limited number of studies, primarily gray literature, involving the effects of pile driving sound on salmonids. Caged juvenile Chinook salmon (*O. tshawytscha*) exposed to pile driving for 3-4 minutes (> 200 strikes 32 ft from pile), $SPL_{peak}$ up to 192 dB re 1µPa, and SEL up to 168 1µPa$^2$•sec did not experience elevated injuries or mortalities relative to control fish (Abbott et al. 2005). Caltrans (2004) exposed caged juvenile steelhead (*O. mykiss*) to multiple strikes for 1 to 20 minutes (23 to 314 m from pile) that produced $SPL_{peak}$ up to 210 dB and SEL up to 183 dB re: 1µPa$^2$•sec. These sound pressures, which tended to be higher than those in our study, produced erythema at the based of the pectoral fins and along the abdominal wall of the steelhead. Most barotrama occurred without use of a bubble curtain, which reduced $SPL_{peak}$ by approximately 5-20 dB and increased rise time. Statistical tests of steelhead mortality in relation to the use of a bubble curtain were inconclusive. Nedwell et al. (2003) reported that caged brown trout (*Salmo trutta*) exhibited no behavioral response and no gross injuries after being held in a cage approximately 400 m from pile driving sound, but $SPL_{peak}$ was low (134 dB). Several studies indicate that juvenile salmonids may startle in response to low frequency sound (Moore and Newman 1956, Knudsen et al. 1997, Popper and Carlson 1998), indicating that effects of sound on fish behavior is dependent on its characteristics. Popper et al. (2007) reported that rainbow trout exposed to low frequency sonar (SEL of 189 dB or maximum $SPL_{rms}$ of 193 dB) for 324-648 seconds experienced a temporary auditory threshold shift at 400 Hz, but no mortality and no morphological damage. However, the investigators cautioned that these findings may not be transferable to other anthropogenic sound sources such as pile driving.

Most previous sound studies involved salmon that were held in cages relatively far from the sound source and exposed to low sound levels compared with those in our investigation. Evidence from our study suggests that levels of pile driving sound up to approximately 208 dB (re: 1 $\mu Pa_{peak}$) or 179 dB re: 1µPa$^2$•sec had no apparent lasting effect on juvenile coho salmon (93-135 mm in length), even when exposed for numerous strikes leading to an approximate cumulative SEL of 207 dB re: 1µPa$^2$•sec, a value that is greater than the current NMFS criterion (187 dB 1 µPa$^2$•sec for large fishes). Additional tests are needed to define sound levels that begin to affect the behavior and physiology of juvenile salmon of various sizes, including tests with other salmon species. Based on our findings, a reasonable starting level ($SPL_{peak}$) would be approximately 202 dB when evaluating effects of impact pile driving. Salmon should be exposed to much higher sound levels in order to bracket levels that produce significant behavioral and physiological responses. Additionally, we note that metrics other than sound amplitude may affect salmon behavior, as indicated when tapping of the pile driving hammer caused a brief startle response in juvenile coho salmon. Thus, a variety of metrics should be reported when evaluating effects of sound on fishes.

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Combs). We appreciate constructive comments on manuscript by J. Stadler, D. Woodbury, S. O'Haleck, and M. Bhuthimethee.

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Table 1. Characteristics of impact pile driving at Fishermen's Terminal and associated sound pressure levels measured in the fish cage closest to the pile being driven and in the cage approximately 15 m from the pile.

| | | | | | | | Pile Driving Sound | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pile | Start Time (h) | Total Strikes | Ram stroke height (ft) | Strikes per pile-m | Impact Duration (min) | Distance to Pile (m) | $SPL_{peak}$ (dB) | $SPL_{rms}$ (dB) | SEL (dB) | Rise $Time_{10-90}$ (ms) | Swing Time (ms) | Peak Swing Rate (MPa/sec) | Crest Factor |
| Close Cage: | | | | | | | | | | | | | |
| 1 | 1003 | 97 | 6.8 | 45 | 2.2 | 2.4 | 194 | 182 | 167 | 21 | 0.50 | 9.6 | 4.0 |
| 2 | 1019 | 124 | 7.2 | 56 | 2.8 | 3.5 | 205 | 190 | 175 | 20 | 0.54 | 34.0 | 6.0 |
| 3 | 1033 | 124 | 6.8 | 56 | 2.8 | 5.0 | 204 | 191 | 174 | 12 | 0.50 | 31.0 | 4.2 |
| 4 | 1045 | 111 | 6.5 | 53 | 2.4 | 5.5 | 202 | 185 | 172 | 20 | 0.54 | 22.6 | 6.5 |
| 5 | 1057 | 145 | 6.8 | 68 | 3.2 | 3.0 | 208 | 194 | 177 | 11 | 0.38 | 70.3 | 5.2 |
| 6 | 1103 | 131 | 6.5 | 59 | 2.8 | 1.8 | 208 | 194 | 177 | 13 | 0.92 | 28.0 | 5.1 |
| 7 | 1116 | 113 | 6.5 | 53 | 2.5 | 6.7 | 203 | 188 | 173 | 22 | 0.71 | 20.7 | 6.1 |
| 8 | 1128 | 129 | 6.8 | 63 | 2.9 | 5.5 | 202 | 186 | 172 | 31 | 0.88 | 13.8 | 6.0 |
| 9 | 1132 | 132 | 6.5 | 62 | 2.9 | 4.0 | 206 | 188 | 174 | 30 | 0.38 | 51.7 | 7.9 |
| 10 | 1330 | 113 | 6.3 | 49 | 2.4 | 6.7 | 200 | 185 | 171 | 34 | 1.46 | 6.7 | 5.8 |
| 11 | 1338 | 107 | 6.8 | 52 | 2.3 | 4.0 | 205 | 190 | 174 | 16 | 0.58 | 29.8 | 5.7 |
| 12 | 1344 | 107 | 6.5 | 52 | 2.3 | 1.8 | 208 | 194 | 179 | 18 | 0.50 | 52.7 | 5.5 |
| 13 | 1356 | 98 | 6.5 | 48 | 2.1 | 1.8 | 204 | 189 | 176 | 22 | 0.71 | 21.4 | 5.1 |
| 14 | 1425 | 96 | 6.3 | 47 | 2.0 | 1.8 | NA | NA | NA | NA | NA | NA | NA |
| Mean | | 116.2 | 6.6 | 54.5 | 2.6 | 3.8 | 204.5 | 189.6 | 175.0 | 20.8 | 0.66 | 30.2 | 5.6 |
| SD | | 15.0 | 0.2 | 6.6 | 0.3 | 1.8 | 4.1 | 3.9 | 3.2 | 7.3 | 0.29 | 18.4 | 1.0 |
| | | | | | | | Cumulative SEL (db): | | 207.1 | | | | |
| Distant Cage: | | | | | | | | | | | | | |
| 5 | 1057 | 145 | 6.8 | 68 | 3.2 | 15.0 | 197 | 183 | 169 | 18 | 0.38 | 18.5 | 4.7 |
| 6 | 1103 | 131 | 6.5 | 59 | 2.8 | 15.0 | 196 | 185 | 170 | 14 | 0.29 | 21.7 | 3.4 |
| 12 | 1344 | 107 | 6.5 | 52 | 2.3 | 15.0 | 195 | 183 | 169 | 26 | 0.71 | 8.2 | 4.1 |
| Mean | | | | | | | 196.1 | 183.9 | 169.2 | 19.3 | 0.46 | 16.1 | 4.1 |
| SD | | | | | | | 0.8 | 1.2 | 0.4 | 6.1 | 0.22 | 7.1 | 0.6 |
| | | | | | | | Cumulative SEL (db): | | 201.3 | | | | |

Table 2. Survival of juvenile coho salmon after exposure to impact hammering of 1 pile (98 strikes), 14 piles (1,627 strikes during 4.3 hr period) at distances of 2-7 m and 15 m from the pile. Fish examined 10 to 19 days after exposure. Survival of control fish held at background sound levels is shown.

| Exposure: | 14 piles | 14 piles | 1 pile | 1 pile | Control |
|---|---|---|---|---|---|
| Distance from pile: | 2-7 m | 15 m | 3 m | 15 m | 370 m |
| Number examined | 107 | 106 | 103 | 105 | 207 |
| Days after test | 10 | 10 | 19 | 19 | 10-19 |
| Survival (%) | 100% | 100% | 100% | 100% | 100% |

Table 3. Necropsy and feeding results of juvenile coho salmon exposed to impact hammer sound produced by 14 piles (1,627 strikes during 4.3 hr period) compared with control fish exposed to background sound.

| Exposure: | 14 piles | 14 piles | Control |
|---|---|---|---|
| Distance from pile: | 3.8 m | 15 m | 370 m |
| Number examined | 100 | 100 | 113 |
| Days after test | 10 | 10 | 10 |
| Length (mm) | 114.3 ± 7.4 | 115.1 ± 7.7 | 115.1 ± 7.7 |
| Length range (mm) | 93-135 | 95-132 | 86-138 |
| Weight (g) | 17.4 ± 3.2 | 17.8 ± 3.4 | 17.8 ± 3.4 |
| Weight range (g) | 9.5-27.9 | 10.1-26.7 | 7.6-29.8 |
| Male (%) | 48% | 52% | 45% |
| Survival (%) | 100% | 100% | 100% |
| Number of Fish Exhibiting External Injuries | | | |
| Body bruise | 0 | 0 | 0 |
| Snout bruise | 10 | 12 | 5 |
| Fin erythema | 0 | 0 | 0 |
| Eye (white) | 1 | 0 | 1 |
| Scale loss | 2 @ 5% | 0 | 0 |
| Number of Fish Exhibiting Internal Injuries | | | |
| Excessive bleeding | 0 | 0 | 0 |
| Air bladder rupture | 0 | 0 | 0 |
| Heart hemorrhage | 0 | 0 | 0 |
| Liver hemorrhage | 0 | 0 | 0 |
| Kidney hemorrhage | 0 | 0 | 0 |
| Gill filament discoloration | 0 | 0 | 0 |
| Feeding (%) | 61% | 71% | 44% |

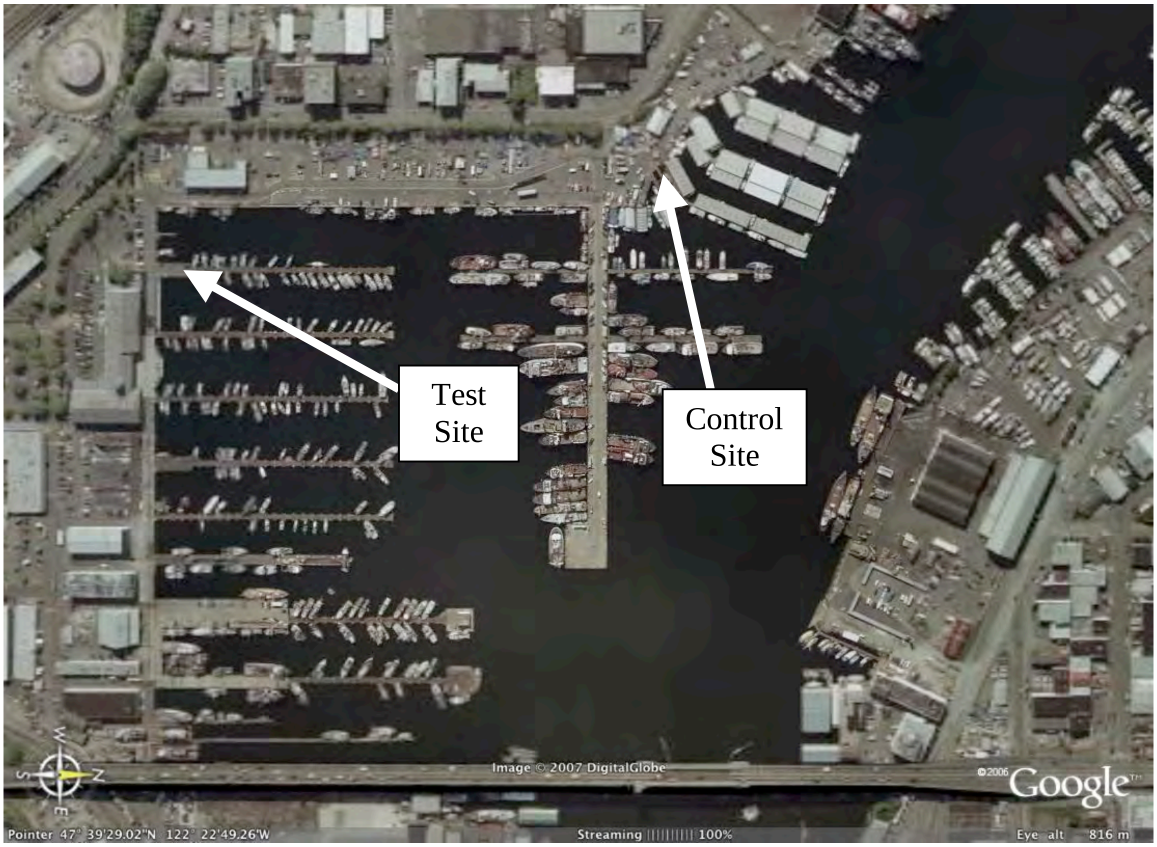



Fig. 1. Testing site at Fishermen's Terminal and location of the control site. Image was taken prior to the removal of the old docks.

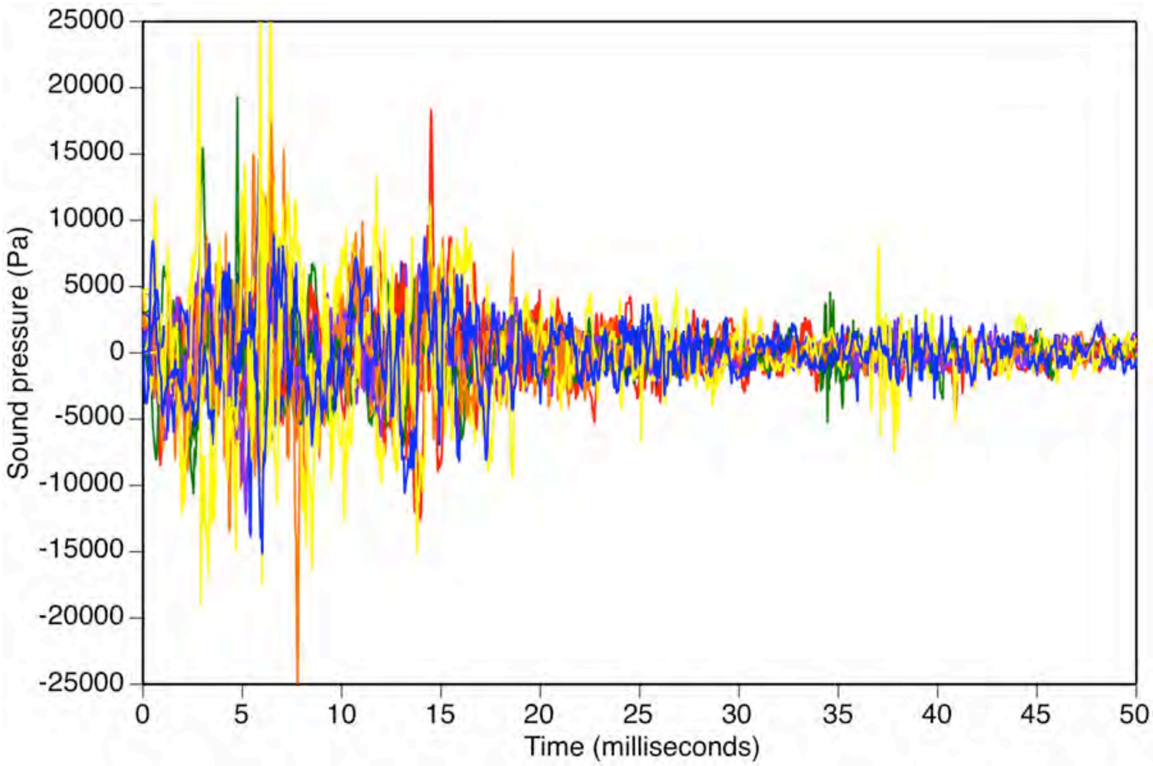



Fig. 2. Sound pressure levels in relation to time after the strike of 13 steel piles. The combined values of these strikes highlight the cumulative pattern of multiple strikes over time. Details of individual strikes are shown in Fig. 3. Values were measured in the cage closest to the pile.

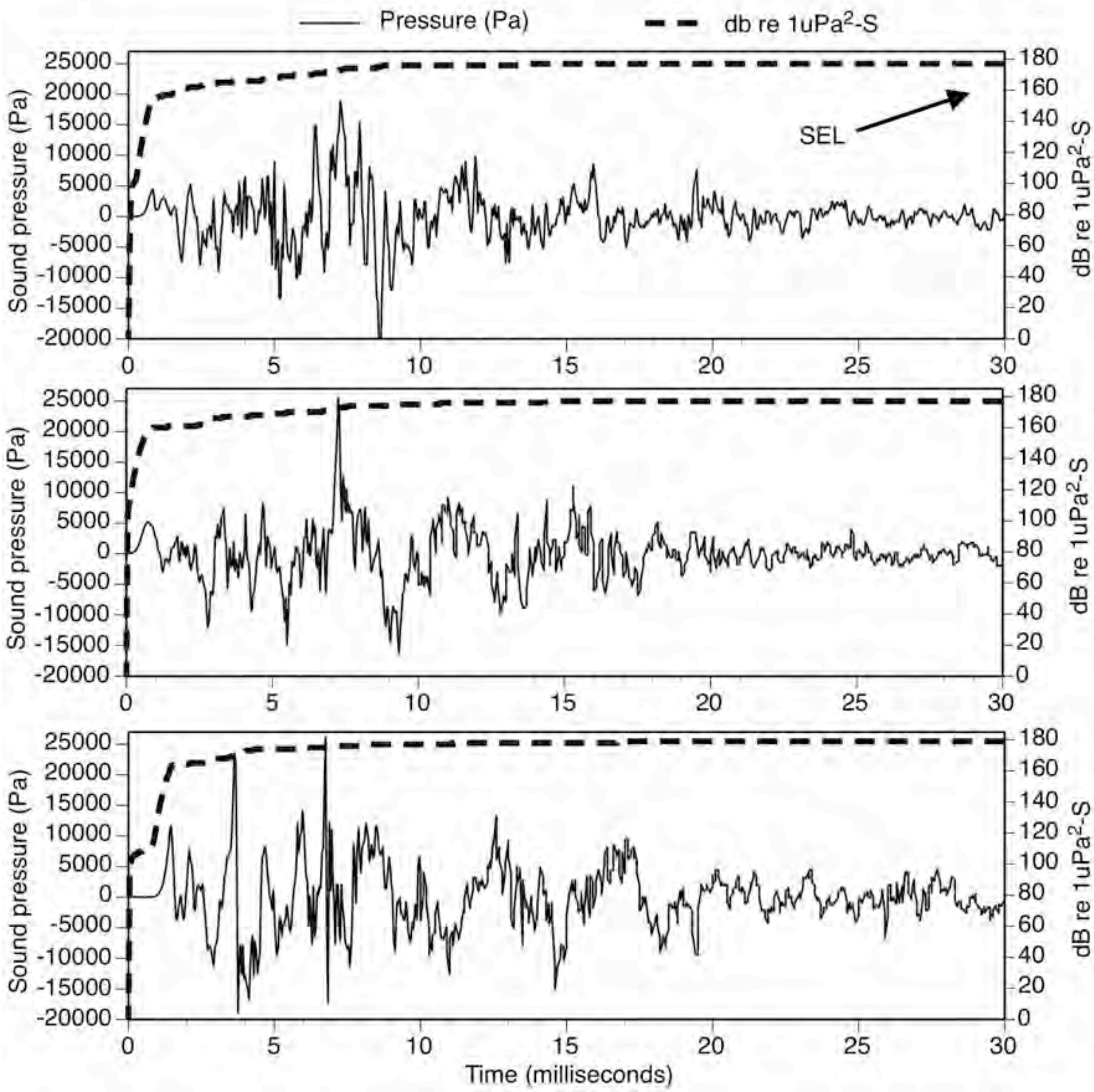



Fig. 3. Sound pressure levels in relation to time after the strike of three steel piles. Values were measured from piles 5, 6, and 12 in the cage closest to the pile.

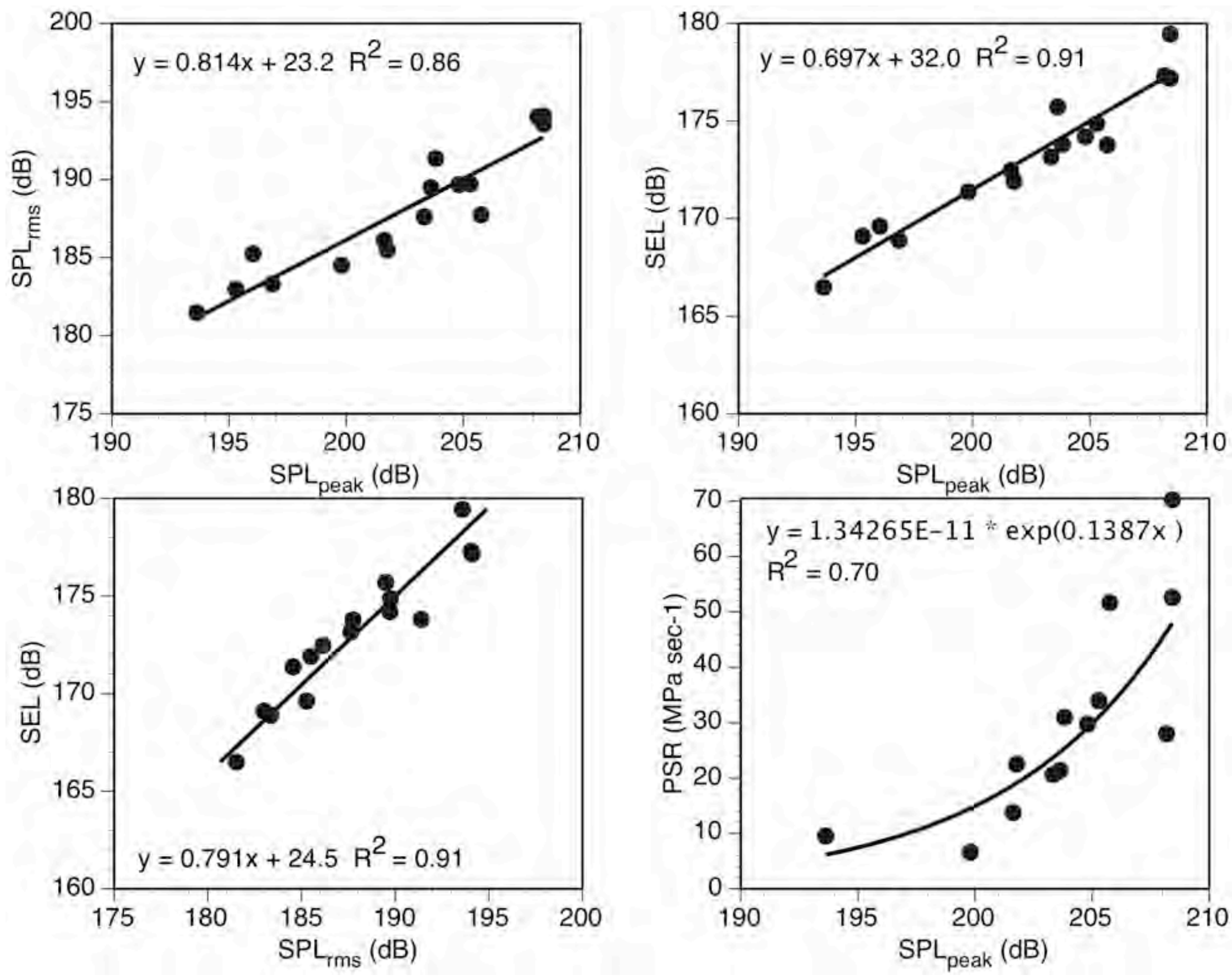



Fig. 4. Correlations between four measures of sound produced by impact pile driving in Fishermen's Terminal. Values from the distant cage were excluded from the Peak Swing Rate (PSR) relationship.

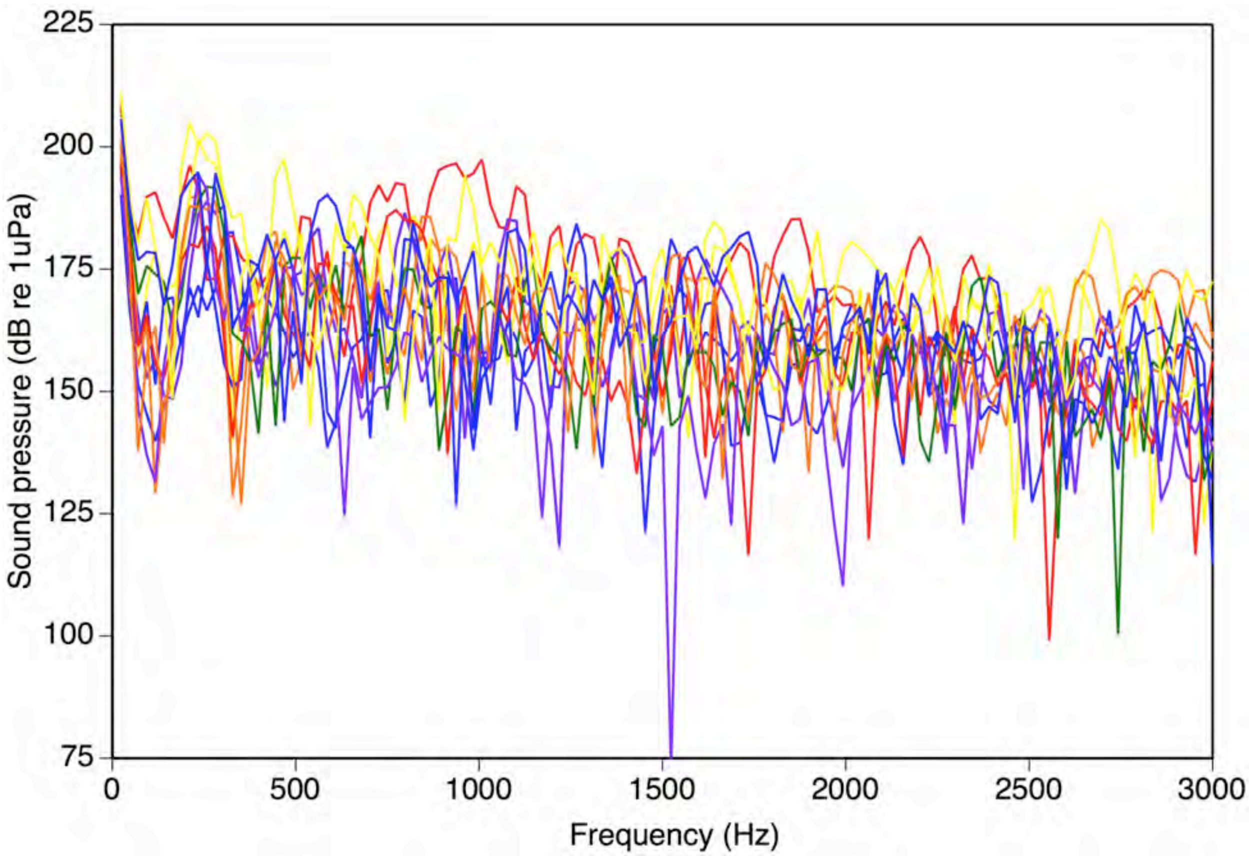



Fig. 5. Sound pressure level (dB re: 1μPa) in relation to sound frequency (Hz) produced during a single strike of each of 13 piles. Values were measured in the cage closest to the pile.

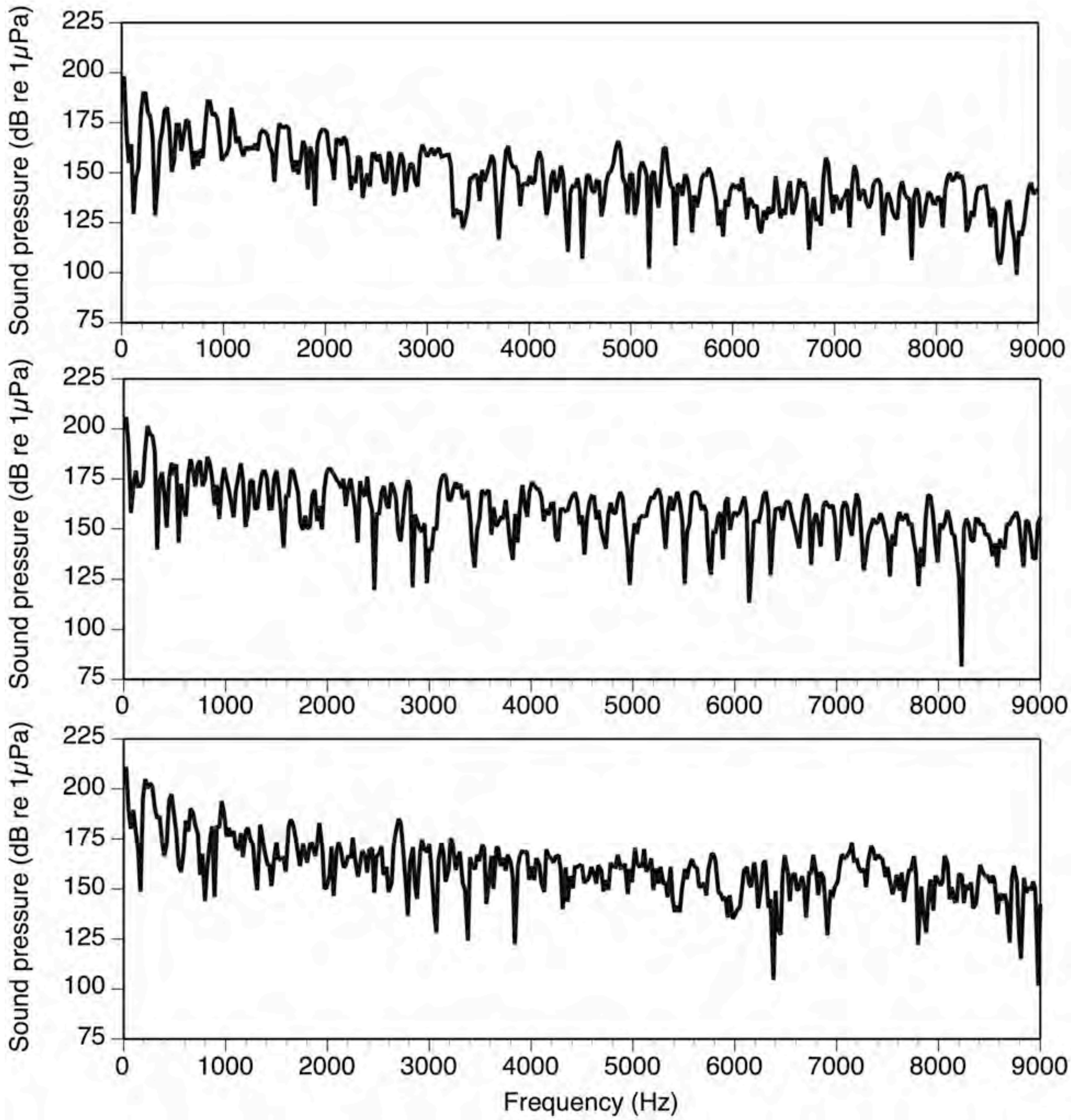
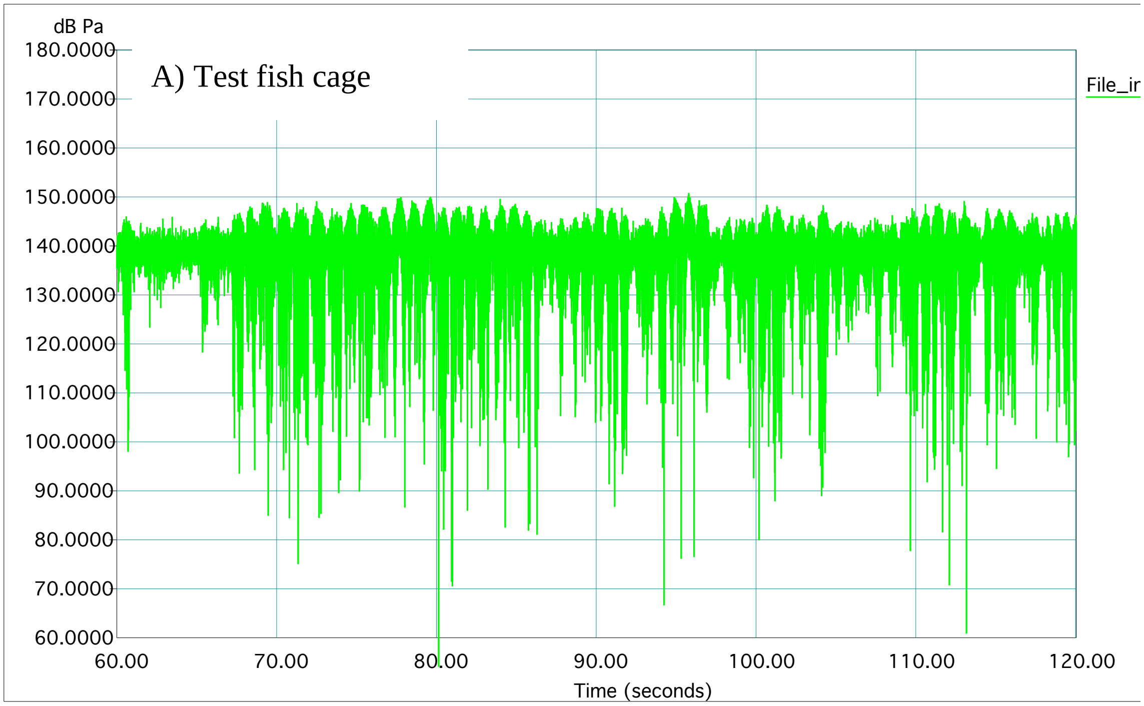



Fig. 6. Sound pressure level (dB re: 1μPa) in relation to sound frequency (Hz) produced during strikes of Piles 5, 6, and 12. Values were measured in the cage closest to the pile.



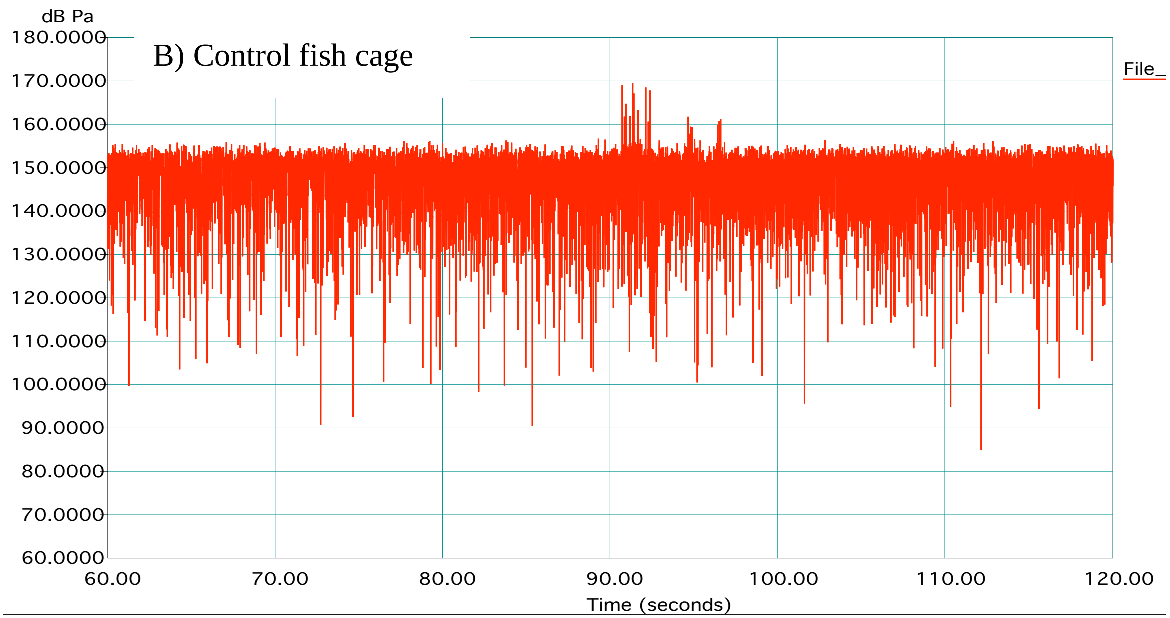




Fig. 7. Background sound pressure levels (dB) recorded in the fish cage closest to the working pile between pile driving events (A), and sound pressure levels recorded in control fish cage while driving Pile 14 (B).

# APPENDIX A:

## Study Photographs

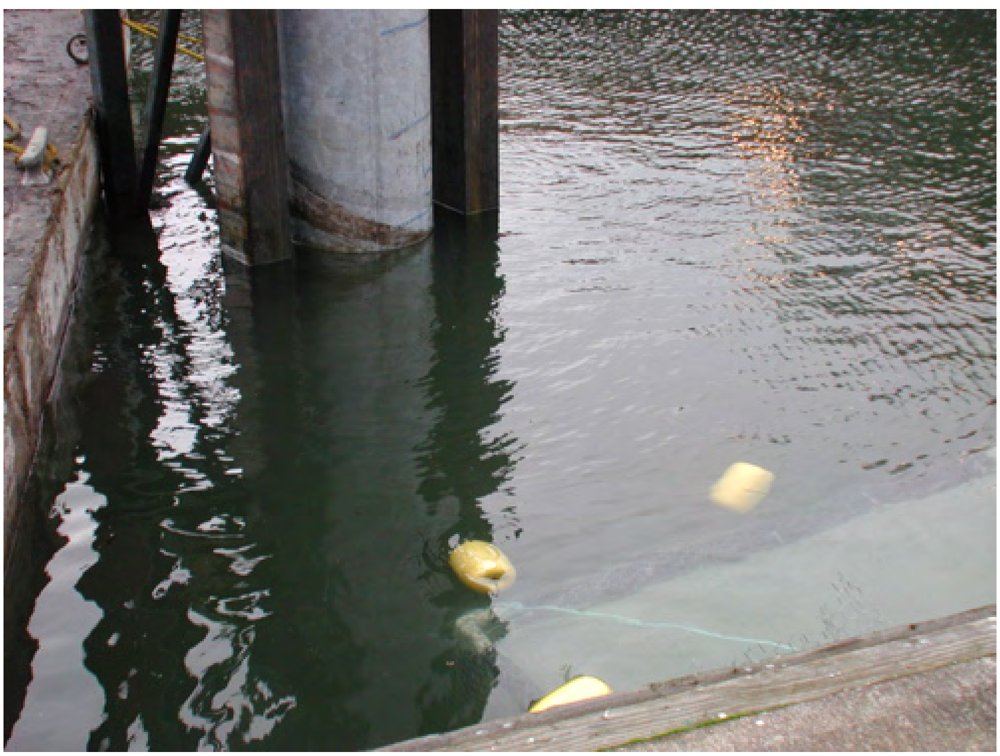
Fish transportation tank and oxygen bottle.


Setting up sound monitoring equipment.

Underwater video monitoring equipment.

Deploying hydrophone and camera in fish cage.

Impact hammer and crew.  Steel pile in foreground.



Salmon cage near pile to be hammered.

Salmon cage near pile to be hammered.

Towing fish cages from test area to control site.  Control fish were also towed.

Setting up fish cages at control site where all fish resided after exposure to pile driving.

Typical juvenile coho salmon during necropsy.

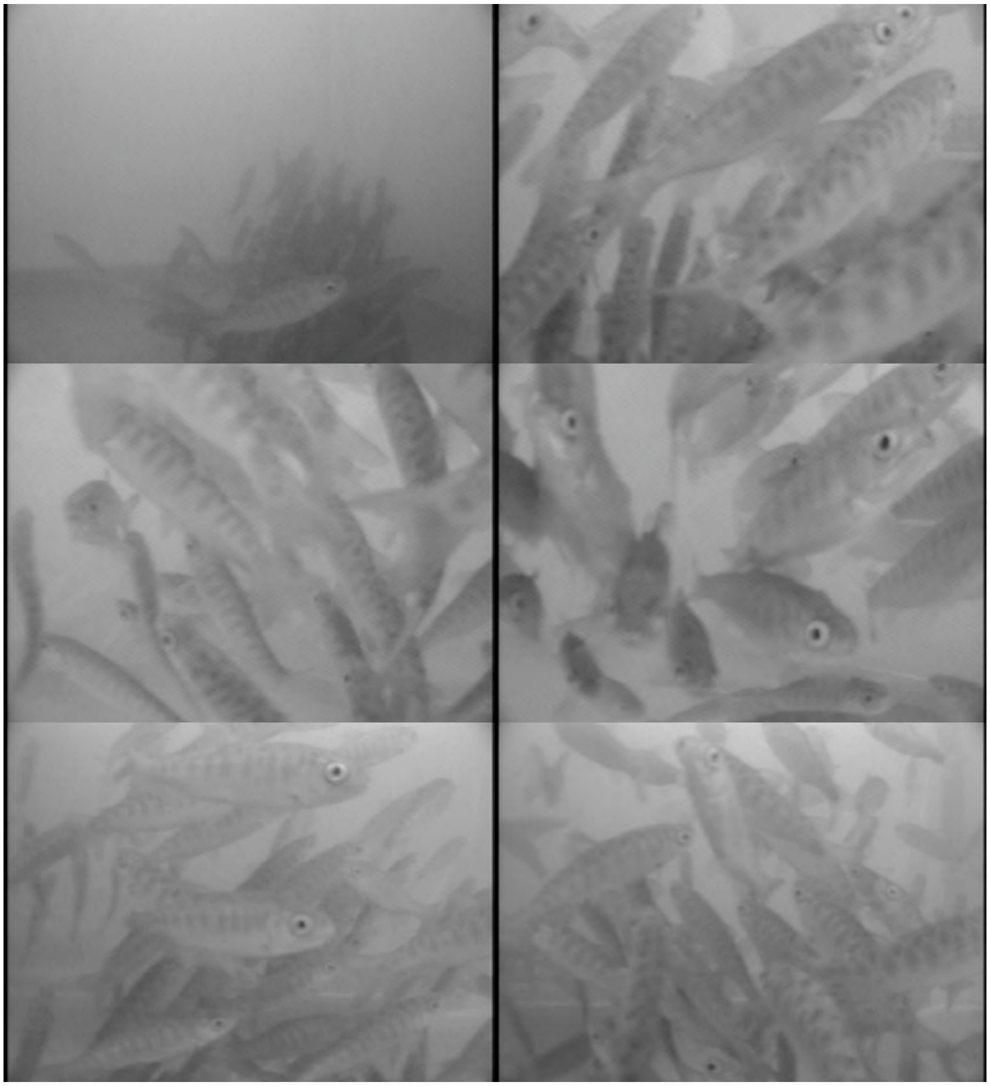
Examination of coho swimbladder.  Kidney is behind bladder.

Examination of coho swimbladder.  Kidney is behind bladder.

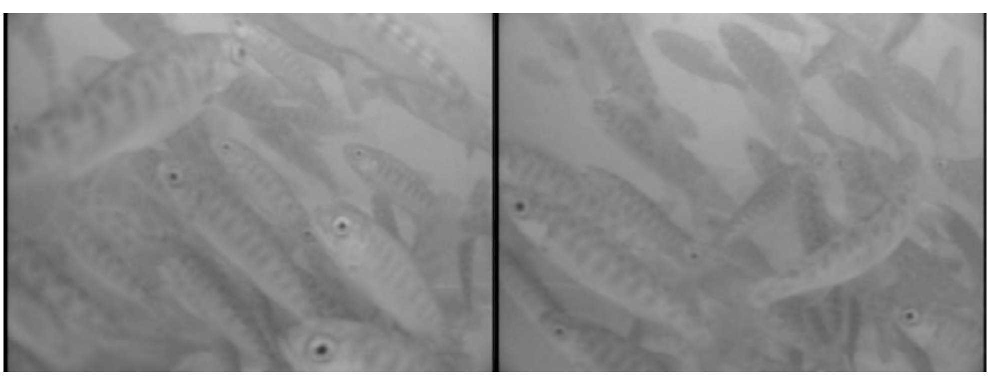
Examination of coho heart and liver.

APPENDIX B:

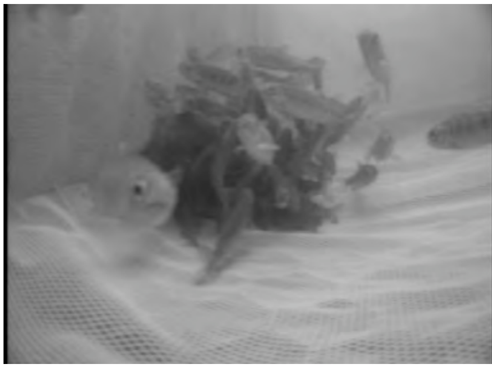
Photographs of test fish and control fish



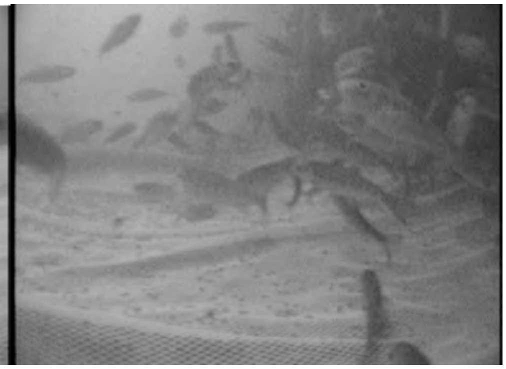
Photos of coho salmon in close cage during repetitive pile strikes.



Coho salmon 15 min after exposure to 1,627 pile strikes.



5 days after exposure to 14 piles.



Dusk: 6 days after exposure to 14 piles.

10 days after exposure to 14 piles.

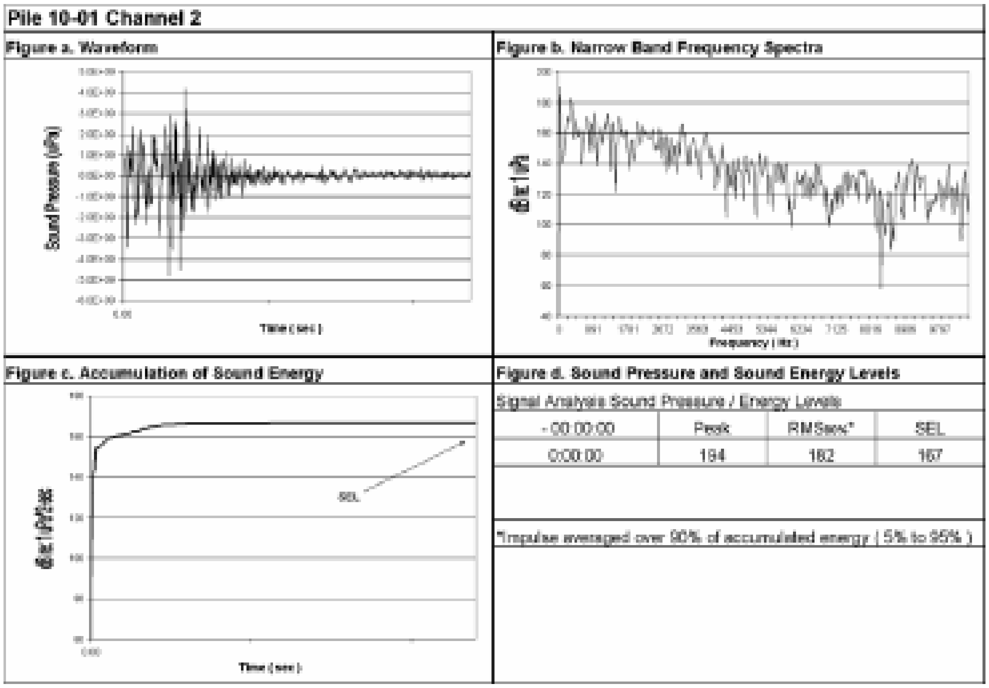
Night: 10 days after exposure to 14 piles.

Control fish aggregated during day.

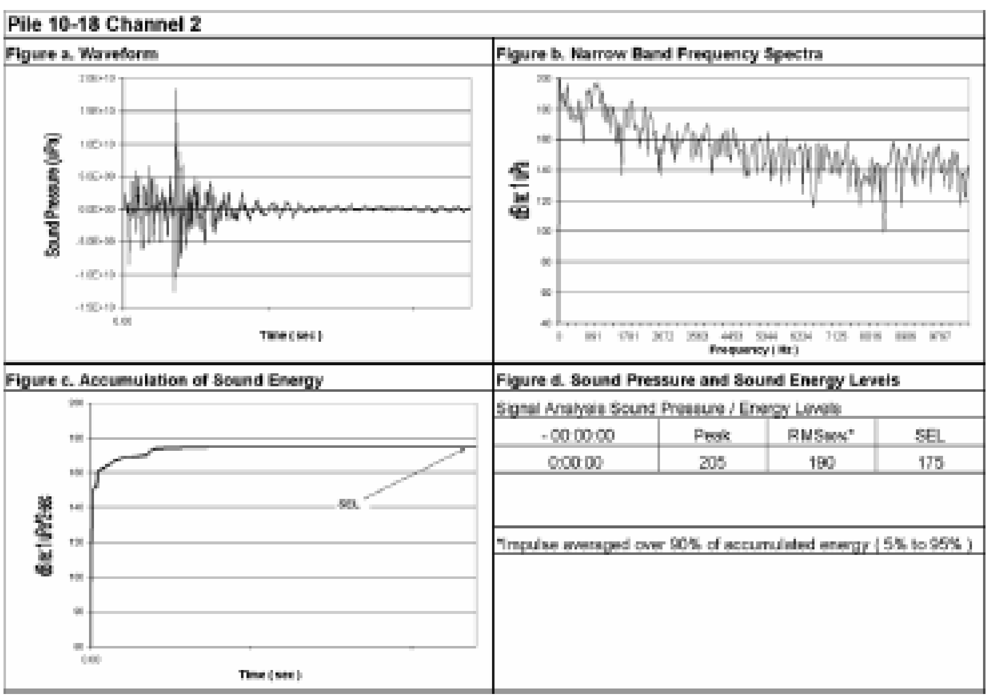
Control fish (& test fish) disperse at night.

APPENDIX C:

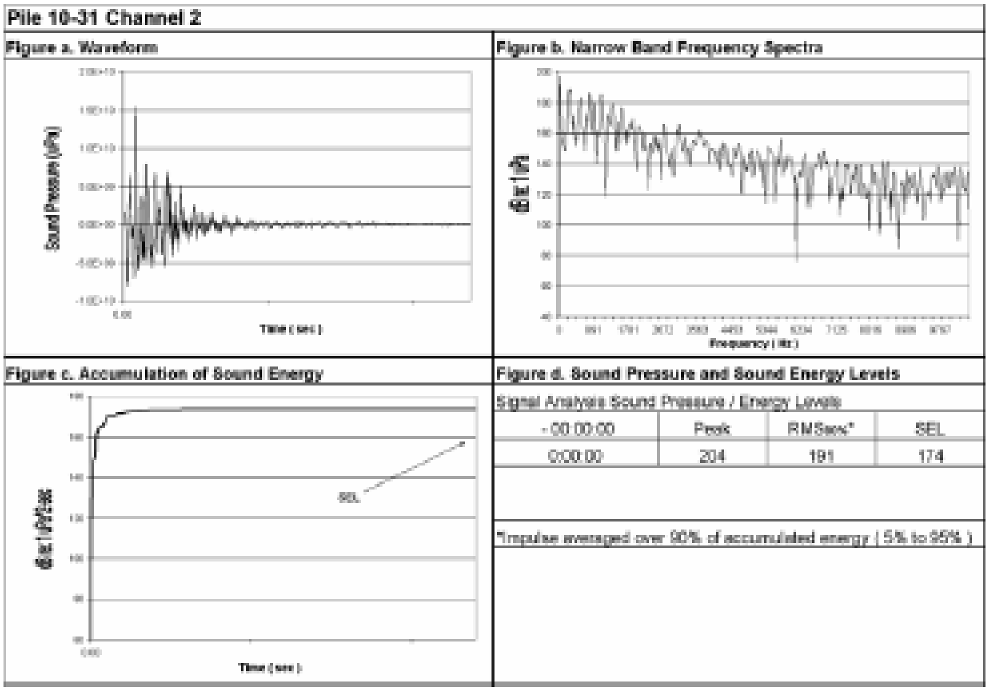
Sound measurements for a strike of each pile at Fishermen's Terminal, December 29, 2006.



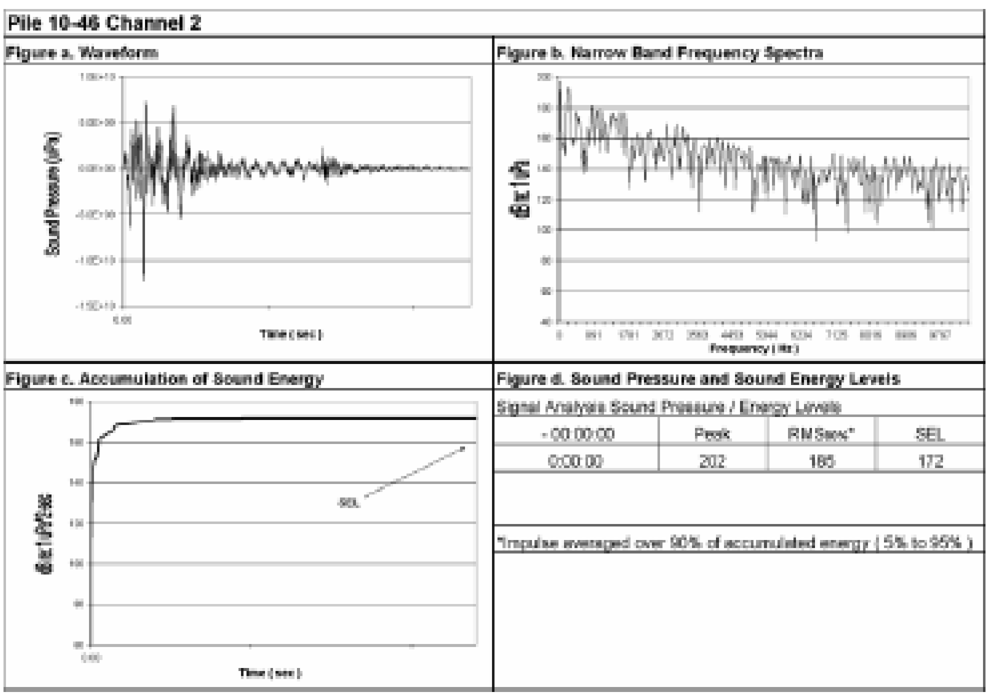

Pile 1.



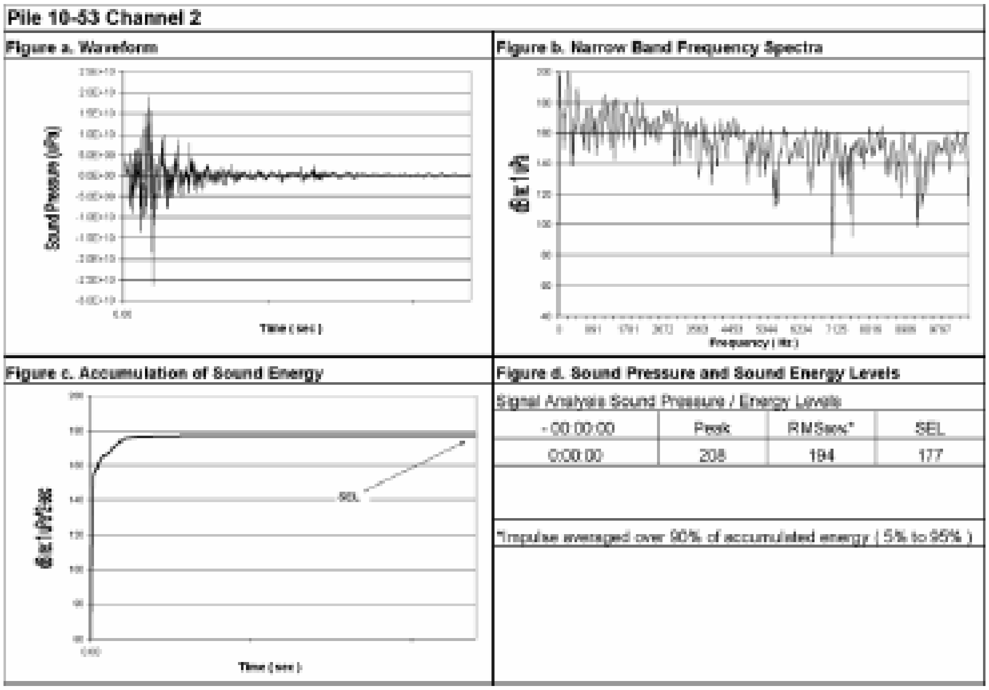

Pile 2.


Pile 10-31 Channel 2
Figure a. Waveform
Sound Pressure (µPa)
Time ( sec )
Figure b. Narrow Band Frequency Spectra
dB re 1 µPa
Frequency ( Hz )
Figure c. Accumulation of Sound Energy
dB re 1 µPa²-sec
SEL
Time ( sec )
Figure d. Sound Pressure and Sound Energy Levels
Signal Analysis Sound Pressure / Energy Levels
- 00:00:00
Peak
RMSavg*
SEL
0:00:00
204
191
174
*Impulse averaged over 90% of accumulated energy ( 5% to 95% )

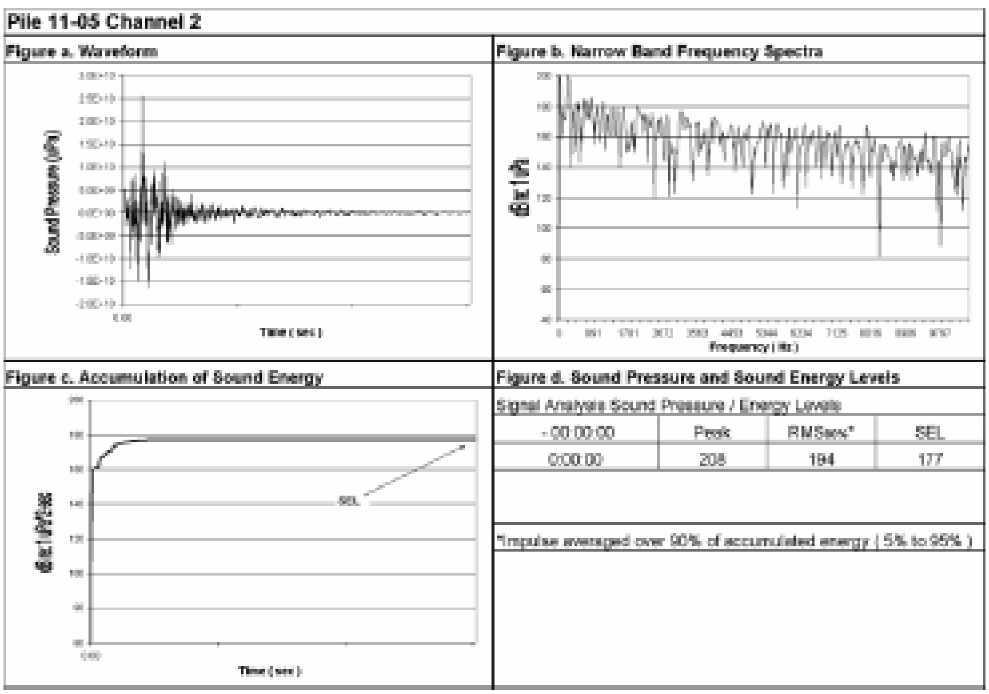
Pile 3.


Pile 10-46 Channel 2
Figure a. Waveform
Sound Pressure (µPa)
Time ( sec )
Figure b. Narrow Band Frequency Spectra
dB re 1 µPa
Frequency ( Hz )
Figure c. Accumulation of Sound Energy
dB re 1 µPa²-sec
SEL
Time ( sec )
Figure d. Sound Pressure and Sound Energy Levels
Signal Analysis Sound Pressure / Energy Levels
- 00:00:00
Peak
RMSavg*
SEL
0:00:00
202
185
172
*Impulse averaged over 90% of accumulated energy ( 5% to 95% )

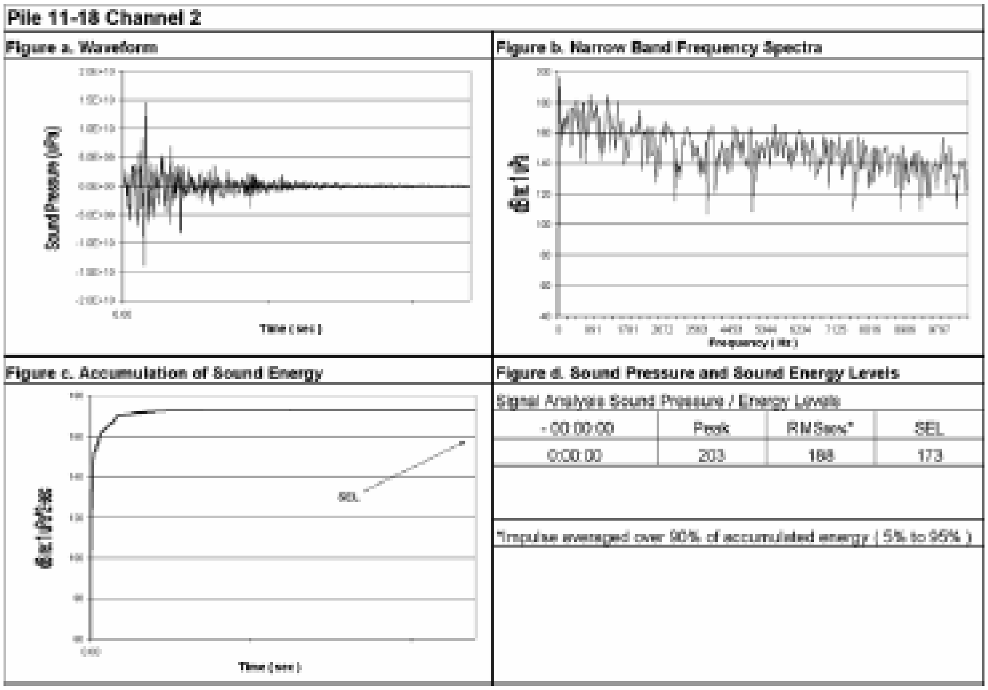
Pile 4.


Pile 10-53 Channel 2
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
- 00:00:00
Peak
RMS90%*
SEL
0:00:00
208
194
177
*Impulse averaged over 90% of accumulated energy ( 5% to 95% )
Sound Pressure (µPa)
Time ( sec )
Frequency ( Hz )
SEL

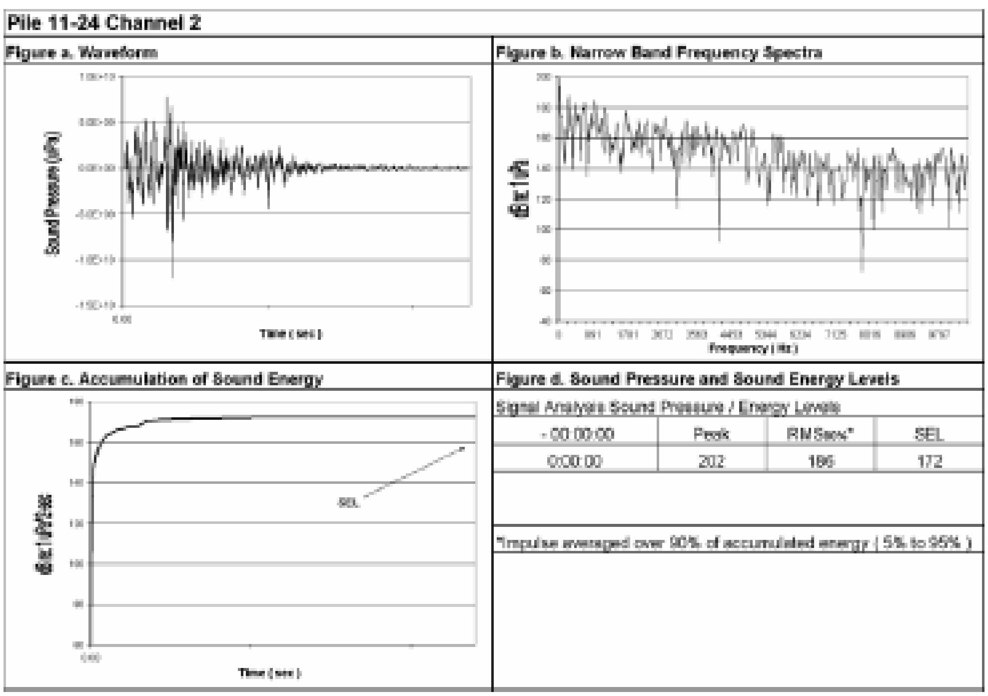
Pile 5.


Pile 11-05 Channel 2
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
- 00:00:00
Peak
RMS90%*
SEL
0:00:00
208
194
177
*Impulse averaged over 90% of accumulated energy ( 5% to 95% )
Sound Pressure (µPa)
Time ( sec )
Frequency ( Hz )
SEL

Pile 6.


Pile 11-18 Channel 2
Figure a. Waveform
Sound Pressure (uPa)
Time ( sec )
Figure b. Narrow Band Frequency Spectra
dB re 1 uPa
Frequency ( Hz )
Figure c. Accumulation of Sound Energy
Time ( sec )
SEL
Figure d. Sound Pressure and Sound Energy Levels
Signal Analysis Sound Pressure / Energy Levels
- 00:00:00 | Peak | RMSavg* | SEL
0:00:00 | 203 | 188 | 173
*Impulse averaged over 90% of accumulated energy ( 5% to 95% )

Pile 7.


Pile 11-24 Channel 2
Figure a. Waveform
Sound Pressure (uPa)
Time ( sec )
Figure b. Narrow Band Frequency Spectra
dB re 1 uPa
Frequency ( Hz )
Figure c. Accumulation of Sound Energy
Time ( sec )
SEL
Figure d. Sound Pressure and Sound Energy Levels
Signal Analysis Sound Pressure / Energy Levels
- 00:00:00 | Peak | RMSavg* | SEL
0:00:00 | 202 | 186 | 172
*Impulse averaged over 90% of accumulated energy ( 5% to 95% )

Pile 8.

**Pile 11-30 Channel 2**

**Figure a. Waveform**

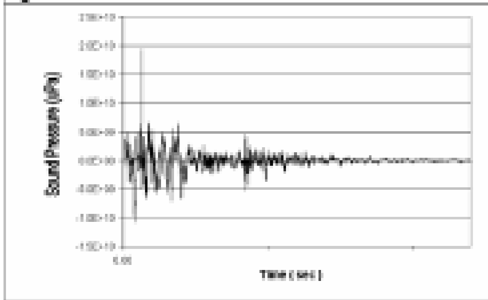



**Figure b. Narrow Band Frequency Spectra**

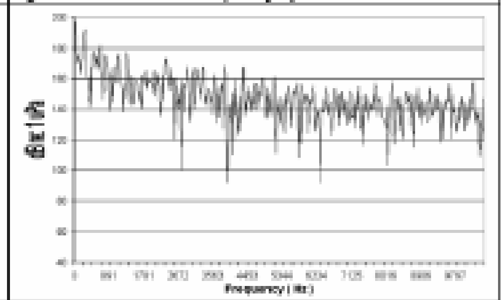



**Figure c. Accumulation of Sound Energy**

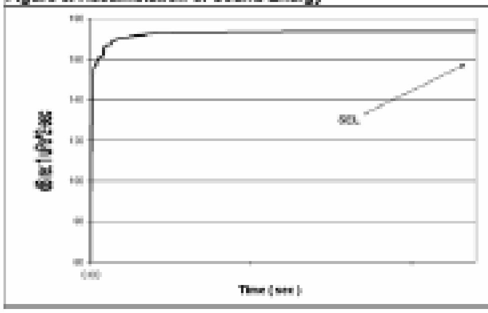



**Figure d. Sound Pressure and Sound Energy Levels**

Signal Analysis Sound Pressure / Energy Levels

| - 00:00:00 | Peak | RMSavg* | SEL |
|---|---|---|---|
| 0:00:00 | 206 | 188 | 174 |

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

Pile 9.

**Pile 13-30 Channel 2**

**Figure a. Waveform**

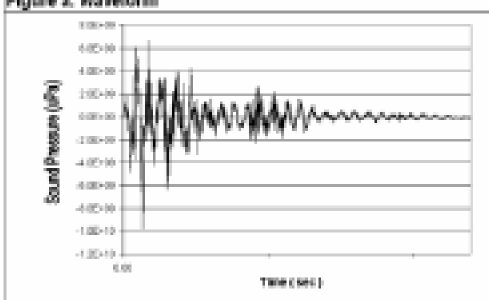



**Figure b. Narrow Band Frequency Spectra**

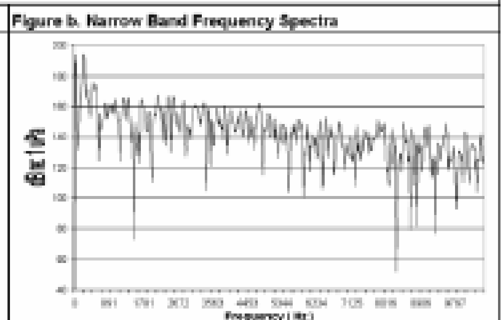



**Figure c. Accumulation of Sound Energy**

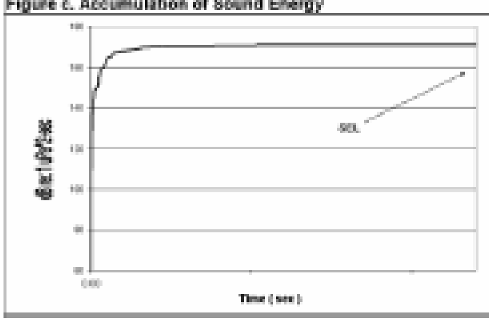



**Figure d. Sound Pressure and Sound Energy Levels**

Signal Analysis Sound Pressure / Energy Levels

| - 00:00:00 | Peak | RMSavg* | SEL |
|---|---|---|---|
| 0:00:00 | 200 | 185 | 171 |

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

Pile 10.

**Pile 13-38 Channel 2**

**Figure a. Waveform**

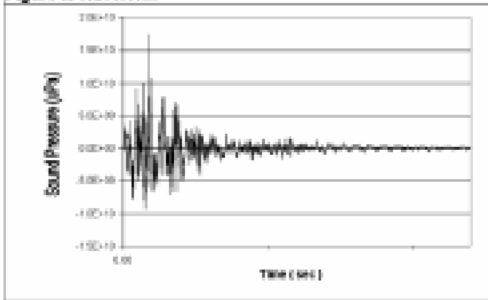



**Figure b. Narrow Band Frequency Spectra**

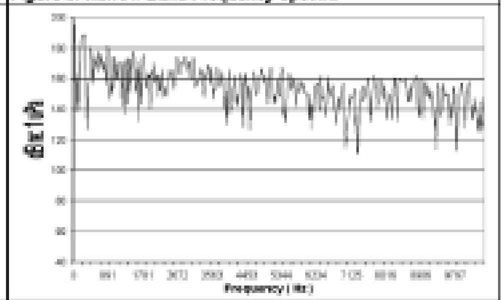



**Figure c. Accumulation of Sound Energy**

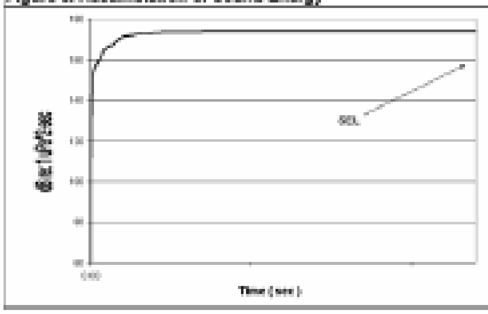



**Figure d. Sound Pressure and Sound Energy Levels**

Signal Analysis Sound Pressure / Energy Levels

| - 00:00:00 | Peak | RMSsec* | SEL |
|---|---|---|---|
| 0:00:00 | 205 | 190 | 174 |

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

Pile 11.

**Pile 13-46 Channel 2**

**Figure a. Waveform**

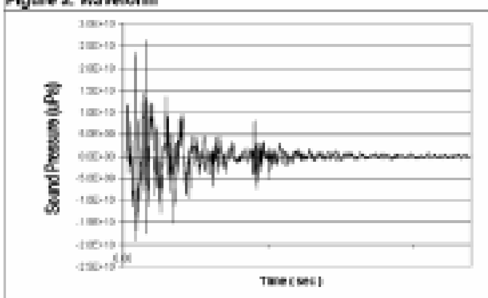



**Figure b. Narrow Band Frequency Spectra**

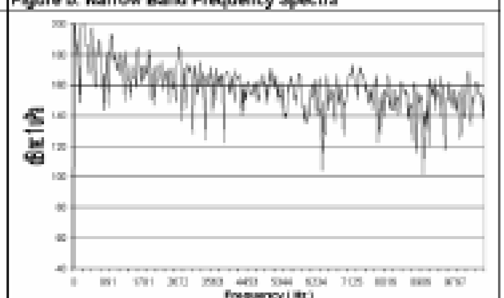



**Figure c. Accumulation of Sound Energy**

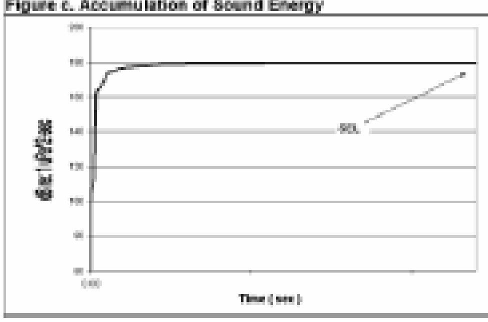



**Figure d. Sound Pressure and Sound Energy Levels**

Signal Analysis Sound Pressure / Energy Levels

| - 00:00:00 | Peak | RMSsec* | SEL |
|---|---|---|---|
| 0:00:00 | 208 | 194 | 179 |

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

Pile 12.

**Pile 13-57 Channel 2**

**Figure a. Waveform**

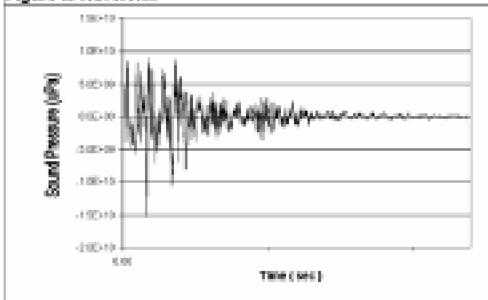



**Figure b. Narrow Band Frequency Spectra**

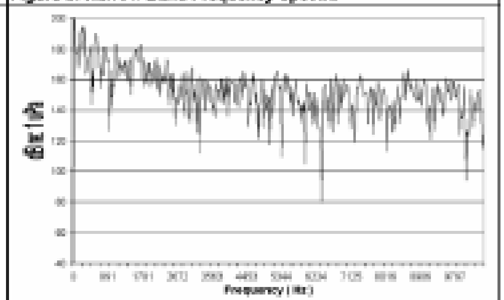



**Figure c. Accumulation of Sound Energy**

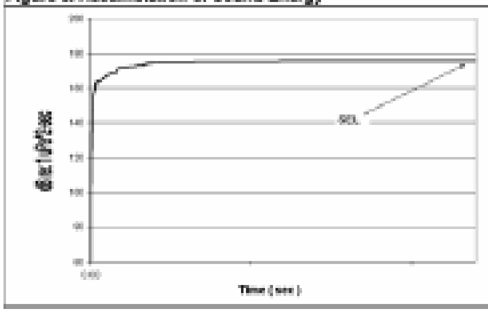



**Figure d. Sound Pressure and Sound Energy Levels**

Signal Analysis Sound Pressure / Energy Levels

| - 00:00:00 | Peak | RMS90%* | SEL |
|---|---|---|---|
| 0:00:00 | 204 | 189 | 176 |

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

Pile 13. (Equipment moved to control site for Pile 14).

**Pile 10-53 Channel 3**

**Figure a. Waveform**

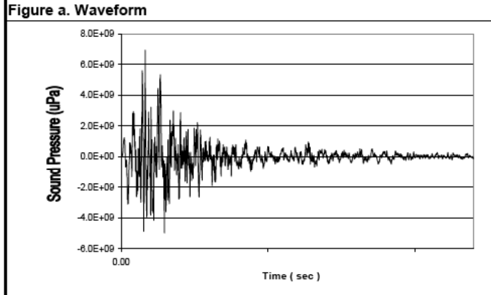



**Figure b. Narrow Band Frequency Spectra**

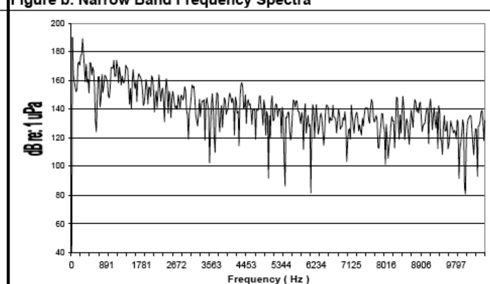



**Figure c. Accumulation of Sound Energy**

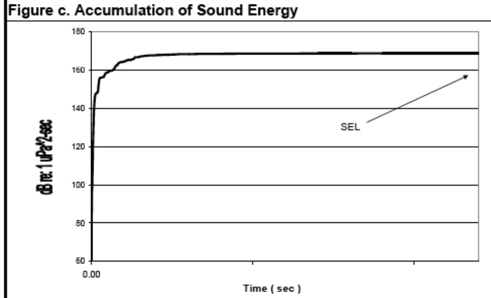



**Figure d. Sound Pressure and Sound Energy Levels**

Signal Analysis Sound Pressure / Energy Levels

| - 00:00:00 | Peak | RMS90%* | SEL |
|---|---|---|---|
| 0:00:00 | 197 | 183 | 169 |

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

Pile 5, 15 m away.

**Pile 11-05 Channel 3**

**Figure a. Waveform**

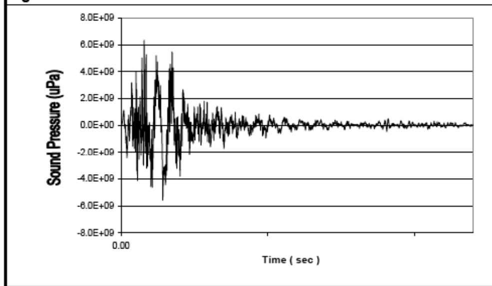



**Figure b. Narrow Band Frequency Spectra**

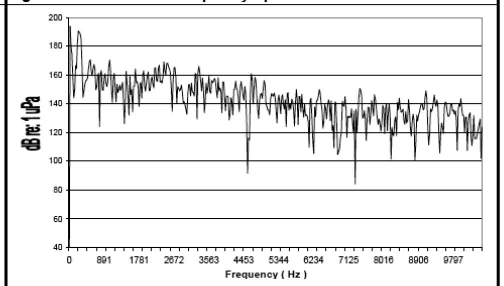



**Figure c. Accumulation of Sound Energy**

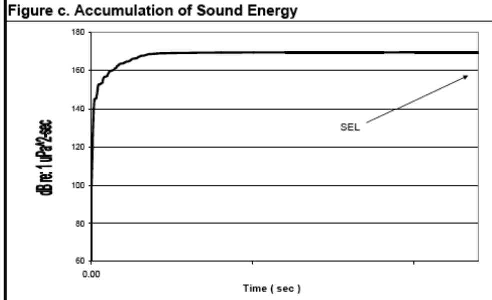



**Figure d. Sound Pressure and Sound Energy Levels**

Signal Analysis Sound Pressure / Energy Levels

| - 00:00:00 | Peak | RMS90%* | SEL |
|---|---|---|---|
| 0:00:00 | 196 | 185 | 170 |

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

Pile 6, 15 m away.

**Pile 13-46 Channel 3**

**Figure a. Waveform**

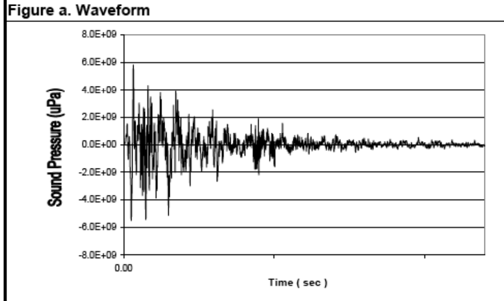



**Figure b. Narrow Band Frequency Spectra**

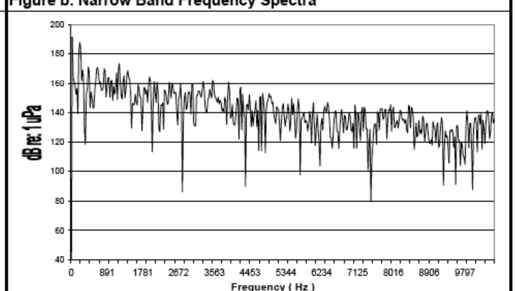



**Figure c. Accumulation of Sound Energy**

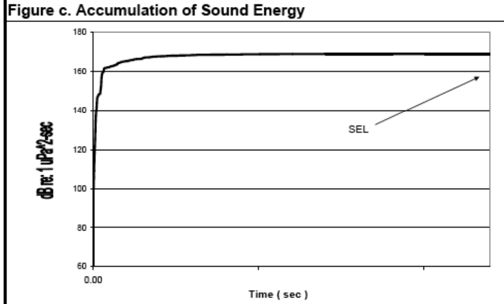



**Figure d. Sound Pressure and Sound Energy Levels**

Signal Analysis Sound Pressure / Energy Levels

| - 00:00:00 | Peak | RMS90%* | SEL |
|---|---|---|---|
| 0:00:00 | 195 | 183 | 169 |

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

Pile 12, 15 m away.