Hydroacoustic Impacts on Fish from Pile Installation

DETAILS

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HYDROACOUSTIC IMPACTS ON FISH FROM PILE INSTALLATION

Bridges, ferry terminals, and other structures commonly have driven-pile foundations, and pile driving can cause effects on fish ranging from altered behavior, hearing loss, and tissue injuries to immediate mortality. The objective of NCHRP Project 25-28 was to develop guidelines for the prediction and mitigation of the negative impacts on fish from underwater sound pressure during pile and casing installation and removal. The research was conducted by a team comprised of researchers from the University of Maryland and Battelle–Pacific Northwest Division. The Principal Investigators were Michele B. Halvorsen, Thomas J. Carlson, and Arthur N. Popper, assisted by Brandon M. Casper and Christa M. Woodley.

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SUMMARY

Introduction and Background

As more pile driving activity occurs, there is an increased concern about its potential effects on fishes and other aquatic organisms. The possibility of effects on fishes rises as more offshore wind farms are installed around the United States and other nations in addition to the ongoing infrastructure and industrial maintenance and development activities, such as those performed by transportation agencies throughout the United States. Effects on fishes potentially associated with pile driving include damage to body tissues that could result in death, as well as impacts on behavior that could cause fishes to leave sites of biological importance (e.g., feeding, spawning).

The goal of this study was to provide quantitative data that may be used to define criterion levels for tissue damage onset and then use these criteria in design of future pile driving projects with options for protection of animals. Regulations for pile driving on the U.S. west coast currently utilize a dual interim criteria approach for onset of physiological effects. These criteria include a cumulative sound exposure level (SEL_{cum}) of 187 dB re 1 μPa^2·s for fishes more than 2 grams and 183 dB re 1 μPa^2·s for fishes less than 2 grams, and a single-strike peak level (SPL_{peak}) of 206 dB re 1 μPa for all sizes of fishes (Stadler and Woodbury, 2009). If either the SEL_{cum} or SPL_{peak} are exceeded, mitigation protocols should be applied.

Field research on effects of pile driving is difficult to execute, and researchers have not had control over the pile driving exposures (frequency of strikes, intensity, duration, and other parameters) nor, in many cases, the physiological state of test fishes during exposure. Thus, it was critical in this study to design an experiment in which researchers had control of all experimental parameters in order to investigate which variables play a role in tissue damage caused by barotrauma. Barotrauma occurs when there is a rapid change in pressure that directly affects the body gases. Free gas in the swim bladder, blood, and tissue of fishes along with gas in solution in blood and other fluids can respectively experience a change in volume and state (e.g. expansion and contraction and/or bubble formation and

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absorption) during rapid pressure changes, which can lead to tissue damage, organ failure, and changes in behavior.

Experimental Approach

To examine the effects of pile driving on fishes, a High Intensity Controlled Impedance Fluid-filled wave Tube (HICI-FT) was developed that enabled replication of aquatic far-field, plane-wave acoustic conditions in the laboratory. The HICI-FT is constructed of a thick stainless steel tube that has a moving coil shaker at either end of the tube for sound stimulation. The HICI-FT system enabled presentation of pile driving sounds in the laboratory and provided control of the parameters that affect pile driving signals. Juvenile Chinook salmon (*Oncorhynchus tshawytscha*), a federally protected species that is of great concern around pile driving activities on the U.S. west coast, were exposed to pile driving signals that had been recorded in the field during actual pile driving installations.

One objective of the project was to prove a correlation between the SEL_{cum} with the response level of barotrauma injury. Another objective was to test the validity of the "equal energy" hypothesis that has been implicitly accepted for management of activities that generate impulsive sounds. The equal energy hypothesis states that *the relevant metric for risk of injury to fish is the* SEL_{cum} *while other metrics are not relevant [e.g., single-strike SEL* (SEL_{ss}) *and/or the number of strikes]*. In other words, the equal energy hypothesis predicts that no matter how a damaging SEL_{cum} is reached (e.g., a few strikes or many strikes), the effects on fishes would be the same. To test this hypothesis, experiments paired sound exposures such that there were two treatments with the same SEL_{cum}, while the SEL_{ss} and number of strikes changed.

Findings

Examination of barotrauma injuries showed that not all injuries had the same physiological significance for the fish following exposure. Table S-1 displays a rank, weight, and categorization for each injury based on physiological effect. These data were used in the computation of a response weighted index (RWI). Injuries were categorized as *Mild, Moderate,* or *Mortal.*

The distributions of results from experimental treatments of 1,920 and 960 pile driving strikes showed a statistically significant correlation between RWI and SEL_{cum}. Additional statistical analysis showed that as SEL_{cum} increased, there was an increase in RWI values. The increase in RWI was the result of the number of injuries each exposed fish experienced as well as the physiological significance of those injuries.

Results also showed that fish exposed to 960 strikes had a significantly higher RWI value ($p = 0.0145$) than fish exposed to 1,920 strikes at the same value of SEL_{cum}. In other words, for the same values of SEL_{cum}, higher levels of SEL_{ss} resulted in increases in the number and severity of injuries observed. These injury trends, when quantified using our assessment model, resulted in significantly higher RWI values for 960 vs. 1,920 strikes. This result is understandable if the energy in a strike and the accumulated number of strikes are viewed as factors in producing the RWI.

Conclusions

The findings of this study demonstrate that the equal energy hypothesis does not apply to effects of pile driving, thereby showing that a single metric of total energy, SEL_{cum}, is not sufficient to determine criteria. Other metrics are necessary and should be taken into consideration. Those metrics include, but are not necessarily limited to, SEL_{cum}, SEL_{ss}, and total number of strikes.

Interpreting the contour plot (Figure S-1) for application, an RWI of 1 would be a single *Mild* injury, and an RWI of 2 would be any two *Mild* injuries (see Table S-1 for injury descriptions). An RWI of 1 or 2 can only be achieved by 1 or 2 *Mild* injuries. Because it is clear that there are no life-threatening effects from these *Mild* injuries, an RWI of 2 is an acceptable level of effect and one that is sub-onset of injury.

In contrast, an RWI of 3 could be any three *Mild* injuries or a single *Moderate* injury. The RWI contours in Figure S-1 along with Table S-1 would first be used to determine an acceptable level of injury; i.e., an RWI of 2. Second, the SEL_{cum} contours and x axis would then be used to determine which SEL_{ss} and SEL_{cum}, in combination with number of strikes, define the acceptable limits for exposure.

Table S-1 Observed barotrauma injuries by mathematical weight, category, injury, physiological rank, and brief biological significance statement.

Wt	Trauma Category	Injury Description	Physiol. Rank	Biological Significance of Injury
5	*Mortal*	Dead within 1 hr	1	Dead
5	*Mortal*	Pericardial (heart) hemorrhage	2	Discrete organ, main body blood pump, bleeding from heart; decreased blood pressure
5	*Mortal*	Hepatic (liver) hemorrhage	3	Discrete organ; bleeding from liver; decreased blood pressure
5	*Mortal*	Renal (kidney) hemorrhage	4	Non-discrete spongy organ, held in place with membrane, bleeding; decreased blood pressure
5	*Mortal*	Ruptured swim bladder	5	Lost ability to maintain buoyancy, sank to bottom; may affect hearing
3	*Moderate*	Intestinal hemorrhage	6	Blood filling the abdominal cavity; decreasing blood pressure
3	*Moderate*	Burst capillaries along body wall	7	Decreased ability to get blood to muscle; decreased blood pressure
3	*Moderate*	Pericardial (heart) hematoma	8	Could decrease efficacy of heart
3	*Moderate*	Intestinal hematoma	9	Major portal system, decreased amount of blood flow to the rest of body.
3	*Moderate*	Renal (kidney) hematoma	10	Large amount of blood pooling in more severe cases
3	*Moderate*	Body muscles hematoma	11	Could affect swimming ability
3	*Moderate*	Swim bladder hematoma	12	Could affect ability to regulate buoyancy; could potentially affect hearing
3	*Moderate*	Fat hematoma	13	Related to swim bladder, caused from swim bladder
3	*Moderate*	Ovaries/testes hematoma	14	Potential short-term damage but potential long-term consequences for reproductive success
1	*Mild*	Blood spots on vent	15	Dilated capillaries near skin, respiratory acidosis, stress with a predisposition, or severe damage
1	*Mild*	Dorsal fin hematoma	16	Dilated capillaries near skin, respiratory acidosis, stress with a predisposition, or severe damage
1	*Mild*	Caudal fin hematoma	17	Dilated capillaries near skin, respiratory acidosis, or stress with a predisposition, or severe damage
1	*Mild*	Pelvic fin hematoma	18	Fin is near intestinal portal system
1	*Mild*	Pectoral fin hematoma	19	Fin is near the heart portal system
1	*Mild*	Anal fin hematoma	20	Dilated capillaries near skin, caused by respiratory acidosis, stress with a predisposition, or severe damage
1	*Mild*	Fully deflated swim bladder (no ruptures)	21	Negatively buoyant, which could be beneficial for less barotrauma, quick recovery by surface air gulp
1	*Mild*	Partially deflated swim bladder (no ruptures)	22	Negatively buoyant, which could be beneficial for less barotrauma, quick recovery by surface air gulp

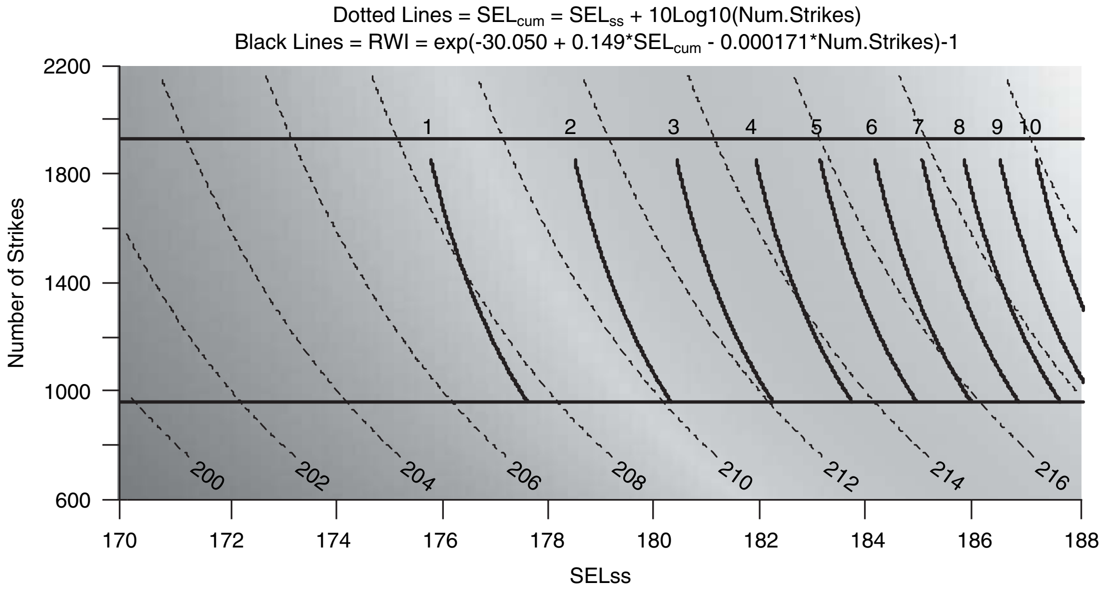

Figure S-1 Treatment RWI and SEL_{cum} by SEL_{ss} and number of strikes for all treatments. A contour plot of RWI (the darker curved lines labeled 1-10) illustrates value increases as SEL_{ss} increase. The dashed lines represent the SEL_{cum} curves. The upper horizontal line indicates the 1,920 strike-line, and the bottom horizontal line indicates the 960 strike-line. The darker curved RWI linear contours are the result of testing at only 1,920 and 960 strikes. It is not known whether the functional relationship shown would persist if additional levels of strike numbers were tested. (Note: the two unlabeled curved lines in upper right corner of plots are 218 and 220 dB.)

Potential Criterion

Based on the study results and findings, an option is to use an RWI biological response criterion of 2, which establishes a new biological response criterion for barotrauma. The corresponding acceptable exposure bounds include impulsive sounds that are less than or equal to 179 dB re 1 $\mu Pa^2 \cdot s$ SEL_{ss} for 1,920 strikes and less than or equal to 181 dB re 1 $\mu Pa^2 \cdot s$ SEL_{ss} for 960 strikes, combined with a SEL_{cum} of no more than 211 dB. These impulsive sound exposure criteria would allow up to two *Mild* injuries and would not allow for a single *Moderate* injury. An RWI biological response criterion of 2 is conservative, while it also raises the current interim exposure criteria to a higher level for impulsive sounds, which take into account more acoustic metrics. These options are for juvenile Chinook salmon of an average standard length of 103 mm and mean weight of 11.8 grams. Application of these data to other species could be done with care, but specific options for other species are beyond the bounds of this study.

CHAPTER 1 BACKGROUND

Pile driving is becoming increasingly important in the United States and throughout the world for construction projects both near shore and offshore, and includes construction of bridges, docks, liquid natural gas piers, and the like. Although such construction typically has been limited to relatively shallow waters near shore and in rivers and streams, more recent pile driving efforts now include deeper water offshore wind farm construction. Because of the increase in pile driving, there is growing concern that the sounds produced by pile driving activity have the potential to harm or kill fishes and/or result in behavioral changes that could affect the survival of populations or even of species.

Despite this increased concern, a recent critical review of the literature detailing the known effects of pile driving on fishes has revealed a significant dearth of information (Popper and Hastings, 2009). Most of the work on effects of pile driving has significant experimental problems that may include experimental design, inadequate use of controls, and/or inappropriate data interpretation (Popper and Hastings, 2009).

The lack of data is related to the considerable difficulty in doing experiments on effects of pile driving under conditions in which the investigators could not control the stimulus. In most pile driving studies to date, fishes were exposed to actual pile driving operations. However, the frequency, magnitude, and other aspects of the pile driving were controlled by the construction engineers and not the investigators. Consequently, investigators did not have control of any factors needed to understand and quantify the effects of pile driving on fishes (Popper and Hastings, 2009).

The ideal pile driving experiments would enable the investigators to fully control the pile driving operation and define parameters such as number of strikes, intervals between strikes, and sound intensity. However, this is generally not feasible in the field. At the same time, it is imperative that quantifiable data be obtained on the effects of pile driving on fishes so that scientists, industry representatives, and regulators can make science-based assessments of potential harm to fishes from a specific pile driving operation.

One suggested approach to circumvent the issue of control of signal parameters has been to replicate pile driving sounds in the laboratory. However, this has not been possible until now because the sounds need to be far more intense than those producible by even the best of underwater projectors. Further, even if such sounds could be produced in the laboratory, they might be sufficiently loud as to prevent humans from being anywhere near the experiment for fear of personal injury. Most important, any pile driving sounds used in the laboratory must be accurate representations of actual pile driving strikes and not just sounds that are very loud.

Potential Effects of Pile Driving Sounds on Fish

Pile driving impulsive sound may produce several types of effects on fishes. The one addressed here is referred to as barotrauma, or damage resulting from rapid change in pressure that directly affects the body gases and thus affects body tissues. More specifically, two changes of gases in the body of fish can lead to injury. The first is when free gas in the swim bladder, or in bubbles in the blood and tissues of fishes expands and contracts during rapid pressure changes, leading to tissue damage. The second is when the solubility of gas in the blood and other fluids changes with pressure, thereby increasing when pressure increases and decreasing when pressure decreases. The swim bladder in the abdominal cavity of most fish species is critical for buoyancy control (as well as hearing and sound production in some species). Changes in external pressure may cause rapid and substantial changes in the volume of the swim bladder, causing its walls to move excessively and/or rupture. A ruptured swim bladder compromises the fishes' swimming performance, thereby increasing the risk for further injury or predation because it cannot maintain buoyancy. A swim bladder that changes in size rapidly (whether it bursts or not) can result in damage to nearby tissues.

In addition to the presence of a swim bladder in most species, fishes have gasses dissolved in their blood and body tissues. At decompression, the amount of gas that can remain in solution decreases. When gas leaves solution, it forms bubbles in the blood and body tissues. The presence of these bubbles increases the pressure in the vessels and, in the case of veins in particular, can cause their rupture. Gas bubbles in a fish's circulatory system can disrupt the function or damage vital organs such as the heart, gills, kidney, gonads, and brain. The most severe effects, such as bubbles in the gills or heart, may result in immediate death at exposure from pile driving sounds. Even if an injury is not immediately *Mortal,* there may be delayed mortality resulting from injury processes such as hemorrhaging, or there may be indirect mortality resulting from predation if fish performance is decreased.

Study Rationale

Origin of Current Interim Criteria

To date, the only regulation of the sound levels from pile driving activities are interim physiological injury onset criteria being used for pile driving projects on the U.S. west coast. These levels were established in 2008 by a group of state agencies on the west coast working in collaboration with the National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife Service offices in that region (Woodbury and Stadler, 2008; Stadler and Woodbury, 2009). The interim criteria were peak sound pressure (SPL_{peak}) of 206 dB re 1 μPa and a cumulative sound exposure level (SEL_{cum}) of 187 dB re 1 $\mu Pa^2 \cdot s$ for fishes above 2 g and a SEL_{cum} of 183 dB re 1 $\mu Pa^2 \cdot s$ for fishes below 2 g. However, the agreement specifically designated the criteria as interim, and the agencies were committed to "review the science periodically and revise the threshold and cumulative levels as needed to reflect current information" (Stadler and Woodbury, 2009).

The NMFS also recognized that there is a "resetting" of SEL_{cum} after 12 hours of non-exposure (Stadler and Woodbury, 2009). Thus, the SEL_{cum} for a fish during a pile driving operation is reset to 0 for the next set of exposures if there is a 12-hour period between the end of the first pile driving exposure and the start of the next. This "resetting" was specific for recovery from temporary effects to the hearing of exposed fish, not barotrauma.

In preparation for the 2008 decision, the California Department of Transportation (Caltrans) asked a group of internationally known investigators to review the literature on effects of sound on fishes and to make recommendations on possible criteria. This resulted in two memos (Popper et al., 2006; Carlson et al., 2007) that examined the best available science and then proposed interim criteria based on those data. In the 2006 memo, Popper et al., (2006) developed a strong case for using a single-strike sound exposure level (SEL_{ss}) of 187 dB re 1 $\mu Pa^2 \cdot s$ and a SPL_{peak} of 208 dB re 1 μPa. This was the first attempt to use dual-criteria to protect fishes from physiological injury resulting from exposure to pile driving. The dual-criteria was adopted by the authors, and later by NMFS, with the idea that the SEL_{ss} value confines the total acoustic energy fishes may experience by exposure to a single impulsive sound, while the peak sound pressure level protects fishes from an especially strong excursion in pressure within the sound impulse.

Carlson et al. (2007) used additional data to that available to Popper et al. (2006) to propose SEL_{cum} values for onset of tissue damage that depended on fish mass. Carlson et al. (2007) suggested that for fishes above 2 g (small larvae), the SEL_{cum} value for non-auditory tissue damage should be 190 dB re 1 $\mu Pa^2 \cdot s$, and for fishes below 1 g, they suggested an SEL_{cum} of 183 dB re 1 $\mu Pa^2 \cdot s$. Carlson and his colleagues made the important point that as fishes get larger the exposure value must be increased further. Most pertinently, Carlson et al. (2007) recommended a conservative value of 197 dB SEL_{cum} for fishes above 8 g, and a value above 213 dB SEL_{cum} for fishes over 200 g.

Recent Studies Relevant to Interim Criteria

Subsequently to setting the U.S. west coast interim criteria, Ruggerone et al. (2008) investigated the effects of pile driving exposure on caged yearling Coho salmon (*Oncorhynchus kisutch*) measuring approximately 90–121 mm in fork length (FL, weight not given). Fish were placed in cages near the piles being driven and exposed to sound from 1,627 strikes over a 4.3-hour period. Peak sound pressure levels were as high as 208 dB re 1 μPa, and SEL_{ss} reached 179 dB re 1 $\mu Pa^2 \cdot s$, leading to a SEL_{cum} of approximately 207 dB re 1 $\mu Pa^2 \cdot s$. The study used controls, and there were no reported effects on body tissues. However, this study did not permit test fish the opportunity to fill their swim bladders prior to exposure; therefore, the study results are not applicable to coho salmon in the wild. Absence of acclimation to neutral buoyancy prior to exposure to changes in pressure effectively removes changes in the volume of the swim bladder as a source of barotrauma either to the swim bladder or other tissues and organs that may be affected by changes in swim bladder volume (i.e., fish would be protected from barotrauma damage).

In a study at Mad River, California, juvenile steelhead salmon (*Oncorhynchus mykiss*), measuring 55–117 mm FL and weighing 1.49–17.43 g, were exposed to pile driving signals at different distances (ranging from about 35 m to 150 m) from the source (Caltrans, 2010a, 2010b). The juvenile salmon were exposed to peak SPLs ranging from 169 to 188 dB re 1 μPa and SEL_{cum} ranging from 179 to 194 dB re 1 $\mu Pa^2 \cdot s$.

The Mad River study was well designed and had appropriate controls, properly performed pathology, and appropriate recordings of received sound levels. On-site necropsies and histopathology results showed no mortality and no tissue damage that could be related to pile driving to fish exposed to SEL_{cum} as high as 194 dB 1 μPa2·s, and no statistically significant differences between experimental and control animals were detected (Caltrans, 2010b). Higher sound levels were not used, but considering that there were no differences in tissue effects between exposed and control, it is reasonable to suggest that injury onset is at sound levels above 194 dB re 1 $\mu Pa^2 \cdot s$ SEL_{cum}, and likely well above this level.

In yet another study, Houghton et al. (2010) exposed 133 caged juvenile coho salmon (*Oncorhynchus kisutch*) measuring approximately

90–121 mm FL (weight not given) to sheet pile driving in the Port of Anchorage. In this study, fish were exposed to as many as 2,781 pile driving strikes at distances ranging from 1 to 50 m from the source. Acoustic monitoring during the tests measured peak SPLs as high as 195 dB re 1 μPa and SEL_{ss} values as high as 166 dB 1 $\mu Pa^2 \cdot s$, with SEL_{cum} as high as 191 dB re 1 $\mu Pa^2 \cdot s$. No mortalities were observed and no tissue damage was reported as late as 48 hrs post-exposure. As in the case of the Ruggerone et al. (2008) study, the test fish in this study were not given the opportunity to fill their swim bladders prior to exposure. The results of this study are only applicable to unacclimated (negatively buoyant) salmonids for this reason.

Study Goal and Objectives

The goals of this study were to assess the effects of exposure to high-intensity pile driving sounds on Chinook salmon physiology and to develop an understanding of the sound exposure(s) that result in the onset of physiological impact on fish. An additional goal was to provide quantitative data that can be used to define criterion levels for tissue damage onset for use in design of pile driving projects and in identifying options for protection of animals.

Initially, an additional goal was to measure the effects of exposure to sounds on hearing capabilities. However, due to technical difficulties, it was agreed by the investigators, the NCHRP advisors, and outside experts, that hearing measures would not be continued or included in this report (see Appendix H for details of those studies).

Previous Studies Using Similar Equipment

The original approach of designing a rigid tube for acoustical studies was an attempt to measure hearing thresholds of a fish in the laboratory with an ideal plane-wave sound field (Hawkins and MacLennan, 1976). The Hawkins and MacLennan (1976) study used a steel tube 80 cm long with a 13-cm wall thickness and 27-cm inner diameter fitted with a sound projector at each end. The hearing thresholds of the plaice, *Pleuronectes platessa,* were measured in terms of sound pressure and particle motion.

A similar chamber was designed several decades later (Rogers and Lewis, 1999), again with a rigid steel tube but with mechanical shaker-driven pistons at either end. This chamber was used to study the effects of sound exposure on the lungs of mice (Dalecki, 2002) as well as the effects of sonar exposure on the vestibular system of guinea pigs. In both cases, it was demonstrated that the traveling wave sound field to which the animals were exposed was equivalent to a far-field scenario and that the response of organs and tissues were comparable to studies done in far-field conditions.

CHAPTER 2 METHODS

The sound exposure paradigms used in this study were designed, in part, to test the validity of the "equal energy" hypothesis that has been widely cited for management of activities that generate impulsive sounds. In addition, the paradigm was designed to obtain data necessary to derive a stress-response function. The equal energy hypothesis states that the risk of injury to fishes is a function of the SEL_{cum}, and there is no need to consider other sound metrics, such as SEL_{ss} and/or the number of strikes. In other words, the "equal energy" hypothesis predicts that no matter how a SEL_{cum} value is reached (e.g., a few strikes with higher energy per strike, many strikes with lower energy per strike), the effects on fishes would be the same.

The methodology used in the experiments to test this hypothesis is documented in this section in brief, with details provided in referenced Appendices. Each aspect of the study is addressed:

- Fish source and fish maintenance;
- The sound exposure device, including design and operation; and
- Barotrauma assessment and characterization.

In each case, details are provided for the methods and approaches used to conduct the study.

Study Fish

This study used juvenile Chinook salmon with an average standard length of 103 mm ± 8.75 mm (standard deviation) and an average weight of 11.8 g ± 3.47 g (Figure 1). The Chinook salmon were provided by Pacific Northwest National Laboratory from the Priest Rapids Hatchery in Mattawa, Washington. Additional details on study fish are found in Appendix F.

Figure 1 Juvenile Chinook salmon used in this study. Note: caudal fin clipped for identification purposes.

Fish Maintenance

Fish were kept in a dedicated aquarium room of the laboratory in the Biology/Psychology building at the University of Maryland. This room met all federal standards for animal care. The care and maintenance of the room, as well as the conduct of all experiments described in this report, were done under protocols reviewed and approved by the Institutional Animal Care and Use Committee (IACUC) of the University of Maryland (see Appendix D). Fish were held under authority of the Maryland Department of Natural Resources (Natural Resources Articles 4-602 and 4-11A-02). Details of fish maintenance are provided in Appendix F which can be found online at http://apps.trb.org/cmsfeed/TRBNetProject Display.asp?Project ID=763.

Sound Exposure Apparatus and Methods

Sound exposure was conducted in a system called the High Intensity Controlled Impedance Fluid-filled wave Tube (HICI-FT). The HICI-FT is a specially designed wave tube that used large shakers to produce sounds that accurately reproduce actual pile driving sounds. It enabled presentation of actual pile driving sounds in the laboratory and allowed for control of the number, duration, and other aspects of the pile driving sounds. Thus, it was possible to present stimuli at different cumulative sound levels, single-strike levels, and total number of strikes, using eight different pile driving signals. Essentially, the HICI-FT enabled the investigators to provide the first quantified data on effects of pile driving signals on fish physiology. Details of the design, operation, and control of the HICI-FT are provided in Appendix G.

Sound presentation was controlled using LabVIEW (National Instruments Corporation, Austin, Texas). In the HICI-FT, the presented stimuli were captured during experiments with a hydrophone (Brüel & Kjær Sound & Vibration Measurement A/S, Naerum, Denmark, Model 8103), and digitized by LabVIEW. In addition, Dazzle MovieStar software (http://dazzle-moviestar.software.informer.com/) captured digital images of a 45° region inside the HICI-FT during experiments. Digital images allowed the observer an occasional glimpse of a fish if it swam into the angle of view. (Note these observations were primarily to check on fish survival and cannot be used for behavioral studies.)

The HICI-FT chamber (Figures 2 and 3) was a circular tube 0.45 m long with a 0.25-m internal diameter and 3.81-cm-thick stainless steel walls filled with water. At either end of the tube was a rigid lightweight circular piston held by a membranous seal in the center of the steel end cap. Each piston was connected to a linear electrodynamic motor (moving coil shaker) anchored to the end caps. The motors of the shakers were driven separately with signals appropriate to create the desired pressure and velocity fields within the tube for the sound exposure of the fish.

Sounds

The HICI-FT chamber was designed to produce propagating plane waves with a peak sound pressure level (SPL) of at least 215 dB re 1 μPa. The HICI-FT was able to generate pressure and particle motion levels that were very similar to those produced by pile driving activity.

The pile driving signals used in this study were analogues of field recordings of both pressure and particle motion taken at a range of 10 m from a steel shell pile driven using a diesel hammer at the Eagle Harbor Maintenance Facility (MacGillivray and Racca, 2005). The actual sound exposure paradigms used in the experiments described here were designed to mimic actual pile driving activities. Thus, the experimental characteristics of each sound exposure matched real-life activity, such as the time and frequency domain characteristics of each pile strike, inter-strike-interval, and number of strikes.

The signals used in the experiments consisted of eight different pile driving strikes, which were normalized to the same SEL and compiled into a single file that contained 12 repetitions of each of the eight signals, for a total of 96 strikes. MATLAB (MathWorks, Inc., Natick, Massachusetts) was used each day to generate a randomization of the 96-strike file. This file then was used by LabVIEW for the day and repeated 10 times for a 960-strike presentation or 20 times for a 1,920-strike presentation. Therefore,

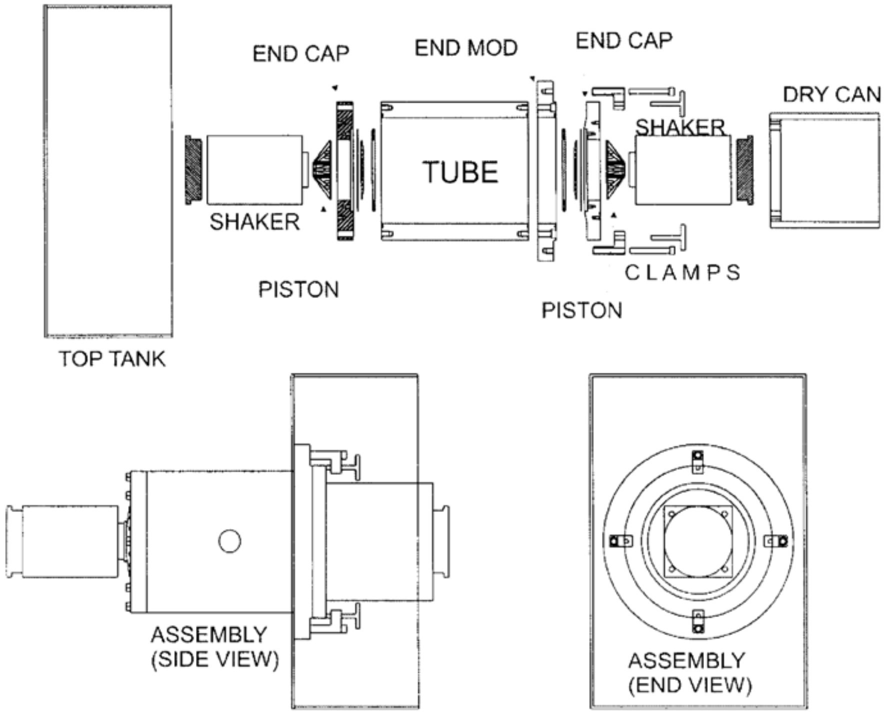

Figure 2 The HICI-FT as described in the text and in Appendix G. The section labeled top tank is an acrylic water-filled chamber in which the fish were placed prior to exposure. The HICI-FT is shown in the horizontal position used during sound exposure.

fish received a pseudorandom presentation of pile strikes, and every day was different.

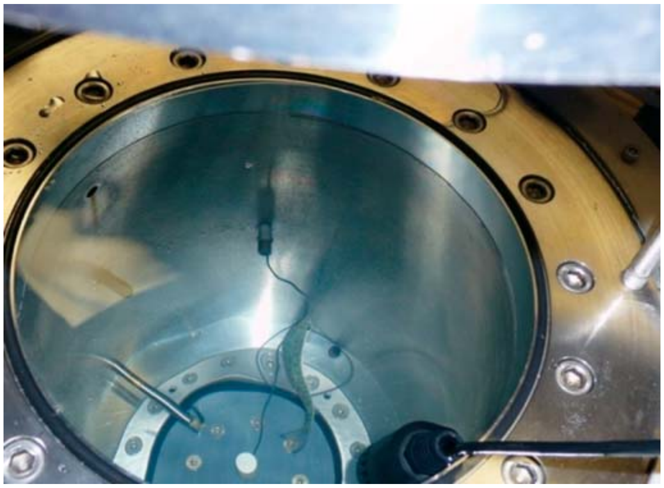

Figure 3 View inside the HICI-FT chamber (vertical position). A Chinook salmon can be seen toward the bottom of the tube. The long silver cylinder towards the bottom of the tube on the left is the light source and digital camera. Just above this on the left is the hydrophone (black, smaller tube). The wire in the center is for an accelerometer (white cylinder attached to the bottom of the tube). The large black device (lower right) measured temperature and total dissolved gas of the water in the tube after each experiment. The bottom of the tube is the faceplate for the piston coupled to the lower shaker.

HICI-FT Sound Control Operation

Signal generation and data acquisition for the HICI-FT was controlled using a Dell laptop computer and a 12-bit analog/digital (A/D and D/A) converter (National Instruments Corporation, Model PCI-MI0 16E1). Analog drive signals were generated on two separate channels of the A/D converter. These were filtered and attenuated using anti-aliasing filters and programmable attenuators (Tucker-Davis Technologies [TDT], Alachua, Florida, Model PA4). The attenuators provided the system with 100 dB of dynamic range beyond the 12-bit resolution of the A/D converter. The attenuators were controlled through a serial interface with the PC. The outputs of the attenuators were amplified by an amplifier (Crown International, Elkhart, Indiana, Model XTi 4000), one to each shaker (Vibration Test Systems, VG-150 Vibration Generator, Model VTS 150).

All information regarding each experiment was recorded on data sheets. An example of the data sheet is in Appendix C.

General Experimental Procedures

Details of experimental procedures are presented in Appendix G. In brief, two Chinook salmon were transferred into the HICI-FT's acrylic chamber and allowed to swim freely in the chamber for a 20-min acclimation period. After the 20 min, the fish were scored to be negatively, neutrally, or positively buoyant. Fish were allowed to enter the tube, and then they were closed in by lowering and locking the top shaker onto the tube. Control fish were put through the same process as treatment fish but without the pile driving sound. When the exposure was completed, fish were transferred to the barotrauma injury assessment.

The fish were exposed to one of eleven pile driving treatments (see Chapter 3 Results). These treatments varied in SEL_{cum}, SEL_{ss}, and number of strikes, which affected the duration of the exposure. For example, for fish exposed to 1,920 strikes, the exposure duration was 48 minutes, while for 960 strikes it was 24 minutes.

Barotrauma Analysis and Characterization

Following exposure in the HICI-FT, fish were examined to determine if physical injuries were associated with sound exposure. Prior to examination, fish were euthanized in a buffered MS-222 solution of 100 mg/L. The fish were examined for external and internal signs of barotrauma. All potential injuries, and a fuller treatment of this analysis, are provided in Appendix A.

The design for the assessment of barotrauma followed the procedures developed by co-investigator Carlson's group at the Pacific Northwest National Laboratory (PNNL) for their study on rapid decompression in salmonids (Stephenson et al., 2010). That study created a framework that assessed barotrauma and the effects of fish physiological conditions on barotrauma injuries, and then statistically analyzed and modeled those barotrauma injury observations.

Response Variable Derivation

The barotrauma data set was based on binary variables (0 or 1) that denoted the presence or absence of observed external and internal barotrauma injuries. After thorough review of the entire injury regime, many injury indices from the original barotrauma injury list (Appendix A) were eliminated due to lack of occurrence (i.e., embolisms were removed). A few other injuries were combined into one score because they indicated the same injury (i.e., external sign of pericardial hemorrhage was combined with internal scoring of pericardial hemorrhage). Examination of the injury panel showed that not all injuries had the same physiological significance for the health of the fish following exposure.

The physiological cost or effects of trauma and barotrauma are poorly understood in fish, thus a novel model was developed to qualitatively assess barotrauma and was applied to this study and to a concurrent study considering the effects of explosive sound from underwater rock blasting (Carlson et al., 2011). The physiological significance of each injury was determined using available literature whether fisheries or mammalian-based (Husum and Strada, 2002; Oyetunji et al., 2010) and proposed energetic costs based on an understanding of each type of injury (Woodley and Halvorsen, personal observations; Gaspin et al., 1975; Iwama et al., 1997).

Physiological significance of each observed injury was assessed and given a physiological rank and a weight (Table 1). Observed injuries were assigned to trauma categories based on the physiological significance for each observed injury, individually. The injuries were then separated into three trauma categories: *Mortal, Moderate,* and *Mild.* The *Mortal* trauma category included observed injuries that were severe enough to lead to death. The *Moderate* trauma category included observed injuries likely to adversely impact fish health, but which, when considered individually, were likely recoverable under ideal conditions (i.e., no additional stressors) without being *Mortal* (Casper et al., in prep.). Finally, *Mild* trauma category refers to observed injuries that had minimal to no physiological cost to fish, which quickly recovered under ideal conditions (Casper et al., in prep.).

A mathematical weighting was applied to the trauma categories to underscore the contribution of the observed injury to the response weighted index (RWI, see below). *Mortal* injuries (injuries categorized under *Mortal* trauma) were assigned a weight of 5, *Moderate* injuries (injuries categorized under *Moderate* trauma) weighted as 3, and *Mild* injuries (injuries categorized under *Mild* trauma) weighted as 1 (Krischer, 1979; Chawda et al., 2004). The weight assignments to the trauma categories were

Table 1 Observed barotrauma injuries by mathematical weight, category, injury, physiological rank, and brief biological significance statement.

Wt	Trauma Category	Injury Description	Physiol. Rank	Biological Significance of Injury
5	*Mortal*	Dead within 1 hr	1	Dead
5	*Mortal*	Pericardial (heart) hemorrhage	2	Discrete organ, main body blood pump, bleeding from heart; decreased blood pressure
5	*Mortal*	Hepatic (liver) hemorrhage	3	Discrete organ; bleeding from liver; decreased blood pressure
5	*Mortal*	Renal (kidney) hemorrhage	4	Non-discrete spongy organ, held in place with membrane, bleeding; decreased blood pressure
5	*Mortal*	Ruptured swim bladder	5	Lost ability to maintain buoyancy, sank to bottom; may affect hearing
3	*Moderate*	Intestinal hemorrhage	6	Blood filling the abdominal cavity; decreasing blood pressure
3	*Moderate*	Burst capillaries along body wall	7	Decreased ability to get blood to muscle; decreased blood pressure
3	*Moderate*	Pericardial (heart) hematoma	8	Could decrease efficacy of heart
3	*Moderate*	Intestinal hematoma	9	Major portal system, decreased amount of blood flow to the rest of body.
3	*Moderate*	Renal (kidney) hematoma	10	Large amount of blood pooling in more severe cases
3	*Moderate*	Body muscles hematoma	11	Could affect swimming ability
3	*Moderate*	Swim bladder hematoma	12	Could affect ability to regulate buoyancy; could potentially affect hearing
3	*Moderate*	Fat hematoma	13	Related to swim bladder, caused from swim bladder
3	*Moderate*	Ovaries/testes hematoma	14	Potential short-term damage but potential long-term consequences for reproductive success
1	*Mild*	Blood spots on vent	15	Dilated capillaries near skin, respiratory acidosis, stress with a predisposition, or severe damage
1	*Mild*	Dorsal fin hematoma	16	Dilated capillaries near skin, respiratory acidosis, stress with a predisposition, or severe damage
1	*Mild*	Caudal fin hematoma	17	Dilated capillaries near skin, respiratory acidosis, or stress with a predisposition, or severe damage
1	*Mild*	Pelvic fin hematoma	18	Fin is near intestinal portal system
1	*Mild*	Pectoral fin hematoma	19	Fin is near the heart portal system
1	*Mild*	Anal fin hematoma	20	Dilated capillaries near skin, caused by respiratory acidosis, stress with a predisposition, or severe damage
1	*Mild*	Fully deflated swim bladder (no ruptures)	21	Negatively buoyant, which could be beneficial for less barotrauma, quick recovery by surface air gulp
1	*Mild*	Partially deflated swim bladder (no ruptures)	22	Negatively buoyant, which could be beneficial for less barotrauma, quick recovery by surface air gulp

based on the assessment of physiological significance, which considered the significance of multiple injuries and inspection of data for the occurrence of injury combinations. For example, the occurrence of two injuries categorized as *Moderate* was assessed to have physiological costs similar to that of one injury categorized as *Mortal*.

An RWI was calculated for each treatment fish and each control fish. The formulas used were:

$$\mathrm{RWI}(\mathrm{Control}) = \sum_{i}^{m} (\mathrm{W_i} \times \mathrm{C_i}) \qquad \text{Equation 1.1}$$

$$\mathrm{RWI}(\mathrm{Treatment}) = \sum_{i}^{m} (\mathrm{W_i} \times \mathrm{T_i}) \qquad \text{Equation 1.2}$$

Where

RWI = response weighted index,
i = injury type index,
m = 22, number of injury types (Table 1),
$\mathrm{T_i}$ = the proportion of the sample of fish exposed to a treatment that experienced injury type i,
$\mathrm{W_i}$ = the Trauma Category weight (5, 3, or 1) for injury type i,
$\mathrm{C_i}$ = the proportion of the sample of control fish for a treatment that experienced injury type i.

Statistical Analysis

The response variable RWI was transformed, as shown in Equation 1.3, before analysis in order to stabilize variance and linearize the response curve.

$$y_i = \ln\,(\mathrm{RWI_i} + 1) \qquad \text{Equation 1.3}$$

In addition, cumulative energy was expressed as:

$$\mathrm{SEL_{cum}} = \mathrm{SEL_{ss}} + 10\log_{10}(\text{number of strikes}) \qquad \text{Equation 1.4}$$

Analyses of covariance (ANCOVA) were performed regressing y_i against $\mathrm{SEL_{cum}}$ and assessing whether number of strikes (960 or 1,920) had an additional effect on fish response beyond that described by $\mathrm{SEL_{cum}}$. Initial analyses were conducted on Treatments 2 through 11 to balance the design. Treatments 2 through 11 were paired while Treatment 1 lacked a counterpart. Once a model was selected using the balanced design, Treatment 1 was added to the analysis to refine the results. A complete statistical analysis is shown in Appendix E.

CHAPTER 3 RESULTS

Sound Exposures

A primary objective of this project was to test the hypothesis that the magnitude of barotrauma effects increased with increasing exposure to pile driving sounds as measured in terms of cumulative sound exposure level ($\mathrm{SEL_{cum}}$). Each experimental animal was exposed to one of the pile driving treatments shown in Table 2. The maximum exposure had an average $\mathrm{SEL_{ss}}$ of 187 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$ and a $\mathrm{SEL_{cum}}$ of 219 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$. This level of $\mathrm{SEL_{ss}}$ had an average peak SPL of 213 dB re 1 μPa, which was the maximum amount of energy that could be safely generated by the HICI-FT. Therefore, for Treatment 1's "pair," a $\mathrm{SEL_{cum}}$ of 219 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$ could not be generated with 960 strikes since this would have required a peak SPL above 215 dB re 1 μPa. The remaining treatments were conducted in pairs since the same $\mathrm{SEL_{cum}}$ could be reached with both 1,920 and 960 strikes by having a higher $\mathrm{SEL_{ss}}$ (and thus higher peak SPL) for 960 strikes than for 1,920. In each treatment pair, the goal was to present the same $\mathrm{SEL_{cum}}$ value but vary the number of pile strikes, which altered the $\mathrm{SEL_{ss}}$ value.

Holding the $\mathrm{SEL_{cum}}$ steady was done to implement treatments that could be used to explore the equal energy hypothesis while providing insight into the relative importance of $\mathrm{SEL_{ss}}$ and $\mathrm{SEL_{cum}}$ in determining effects of sound on fish.

Each treatment pair was aimed at a specific SEL value. However, many variables affect the ability to present the precise signal level, and thus the range of $\mathrm{SEL_{cum}}$ treatments was continuous, rather than discrete points. Each treatment blends with the next $\mathrm{SEL_{cum}}$, such that each treatment is ± 1.5 dB of its specified value, i.e., 216 ± 1.5. Because the data are continuous, an RWI was calculated for each individual fish. However, in Table 2, the average RWI is reported for each treatment.

Barotrauma

Inspection of the log-transformed RWI values show that fish with 960 strikes had a statistically significant higher RWI value than fish exposed to

Table 2 Study exposure treatments and exposure details.

Treatment No.	Avg. SEL_{cum}	Number of Strikes	Avg. SEL_{ss}	Avg. Peak SPL	Duration, min	Exposed Fish, n	Control Fish, n	Avg. RWI
1	219	1920	187	213	48	44	33	15.318
2	216	1920	183	210	48	36	16	5.971
3	216	960	186	213	24	28	10	6.071
4	213	1920	180	207	48	26	5	2.346
5	213	960	183	210	24	31	7	4.323
6	207	960	177	203	24	24	8	1.042
7	207	1920	174	201	48	43	17	0.581
8	210	960	181	208	24	31	10	4.032
9	210	1920	177	204	48	30	11	3.433
10	203	960	174	201	24	32	11	0.656
11	204	1920	171	199	48	31	12	0.419

1,920 strikes at the same value of SEL_{cum}. This can be seen when comparing the ln (RWI+1) regression lines for each 960- and 1,920-strike treatment. In other words, for common values of SEL_{cum}, higher values of SEL_{ss} resulted in significantly higher values of RWI for 960 strikes (Figure 4).

The ANCOVA demonstrated that ln (RWI+1) was linearly related to SEL_{cum}, and fish exposed to a common value of SEL_{cum} using 960 or 1,920 strikes had statistically different RWI values. Using a balanced design for Treatments 2 through 11 (i.e., these had pairs of common values; Treatment 1 did not), common slopes were found for the regression of ln (RWI+1) versus SEL_{cum}, but different intercepts for fish exposed to either 960 or 1,920 strikes (Table 3).

Adding treatment 1 (i.e., SEL_{ss} = 187, SEL_{cum} = 219, number of strikes = 1,920) to the analysis did not change the linearity of the data on the natural log scale or the regression relationships (Table 4, Figure 4). The final model was based on the use of all Treatments 1-11.

The RWI values were calculated and plotted for each fish as shown in Figure 5.

Distributions of 1,920 and 960 strikes in Figure 5 show an increase of RWI values correlated with an increase of exposure severity (SEL_{cum}). The increase in RWI was the result of both the number of injuries

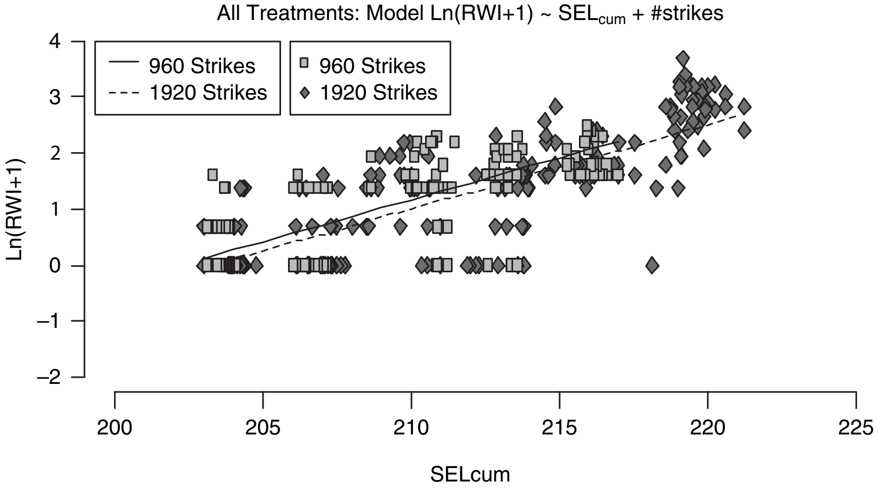

Figure 4 Scatterplots of SEL_{cum} vs. ln (RWI+1) for all treatments. Solid line shows predicted ln (RWI+1) values for 960 strikes and dashed line for 1,920 strikes. Red squares denote the 960 strikes and blue diamonds denote the 1,920 strikes.

Table 3 Sequential analysis of covariance (ANCOVA) results for Treatments 2–11. Response: ln (RWI+1). Best model contains the covariate $\mathrm{SEL_{cum}}$ followed by number of strikes.

Treatments 2–11					
Source	**df**	**SS**	**MS**	***F*-value**	***P*-value**
$\mathrm{SEL_{cum}}$	1	103.22	103.22	281.240	<0.0001
Residuals	309	113.41	0.37		
Source	**df**	**SS**	**MS**	***F*-value**	***P*-value**
$\mathrm{SEL_{cum}}$	1	103.22	103.22	289.679	<0.0001
Strikes	1	3.95	3.95	11.077	0.0010
Interaction	1	0.07	0.07	0.196	0.6583
Residuals	307	109.39	0.36		
Best Model					
Source	**df**	**SS**	**MS**	***F*-value**	***P*-value**
$\mathrm{SEL_{cum}}$	1	103.22	103.22	290.437	<0.0001
Strikes	1	3.95	3.95	11.106	0.0010
Residuals	308	109.46	0.36		

each exposed fish experienced as well as the biological significance of those injuries. The increase in the number of injuries per test fish with increase in severity of exposure is shown in Figure 6.

Additional insight can be obtained by examining Figure 7. As $\mathrm{SEL_{ss}}$ increases, RWI increases as well. However, the indication is that as $\mathrm{SEL_{ss}}$ increases, the severity of barotrauma response is differentially amplified as the number of strikes increases. There is a higher level of RWI values for the 960 strike treatments, which can be seen when comparing the ln (RWI+1) regressions lines for each 1,920 and 960-strike treatment (Figure 4).

Figure 8C summarizes study findings. However, because of the complexity of the response of fish to exposure over the $\mathrm{SEL_{cum}}$ treatments as they are defined by the $\mathrm{SEL_{ss}}$ and number of strike variables (Figure 8), Figures 8A and 8B, are presented separately to show the construction of 8C.

Figure 8A is the background layer of the plot and represents the sample space for the study. The *x*- and *y*-axes are $\mathrm{SEL_{ss}}$ and number of strikes, respectively, while the *z*-axis is $\mathrm{SEL_{cum}}$. The blue dashed contours represent $\mathrm{SEL_{cum}}$ values, which were generated by calculating the relationship between the number of strikes and the $\mathrm{SEL_{ss}}$ (see Equation 1.4). For example, a $\mathrm{SEL_{cum}}$ of 208 dB is produced when there are 960 strikes at a $\mathrm{SEL_{ss}}$ of 178 dB, or when there are 1,920 strikes at a $\mathrm{SEL_{ss}}$ of 175 dB.

Figure 8B shows the RWI contour lines in black. Axes are the same as for Figure 8A with treatment RWI in the *z*-axis for this layer. Note that the top

Table 4 Analysis of covariance (ANCOVA) from the best model from Table 6 applied to all Treatments 1–11. Response: ln (RWI+1).

All Treatments					
Source	**df**	**SS**	**MS**	***F*-value**	***P*-value**
$\mathrm{SEL_{cum}}$	1	201.30	201.30	542.039	<0.0001
Strikes	1	2.24	2.24	6.033	0.0145
Residuals	352	130.72	0.37		

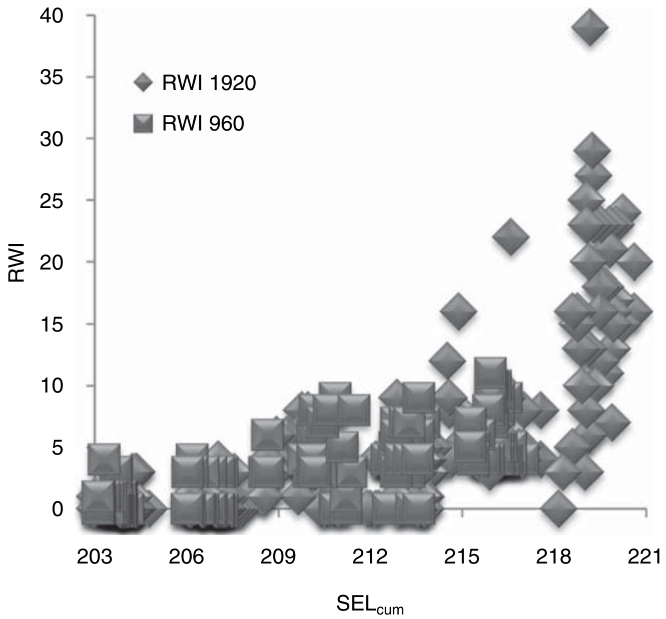

Figure 5 RWI values for each fish by SEL$_{cum}$ for 1,920 and 960 pile strikes.

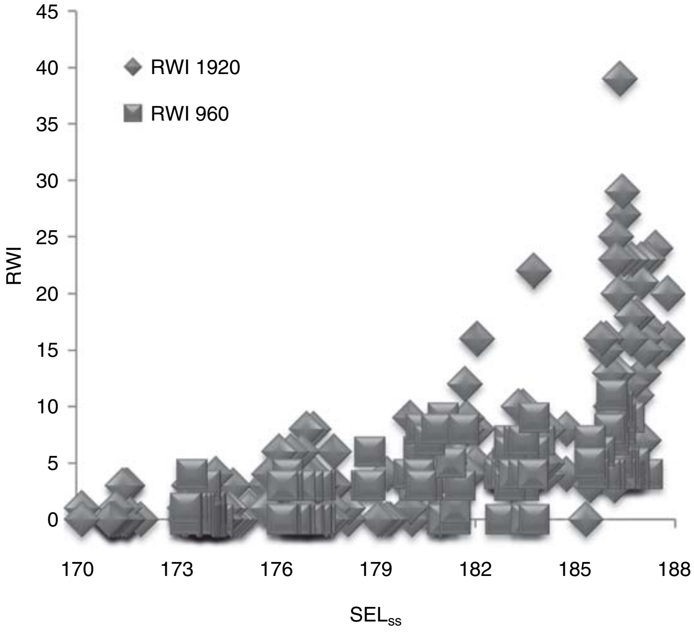

Figure 7 Individual RWI values by SEL$_{ss}$.

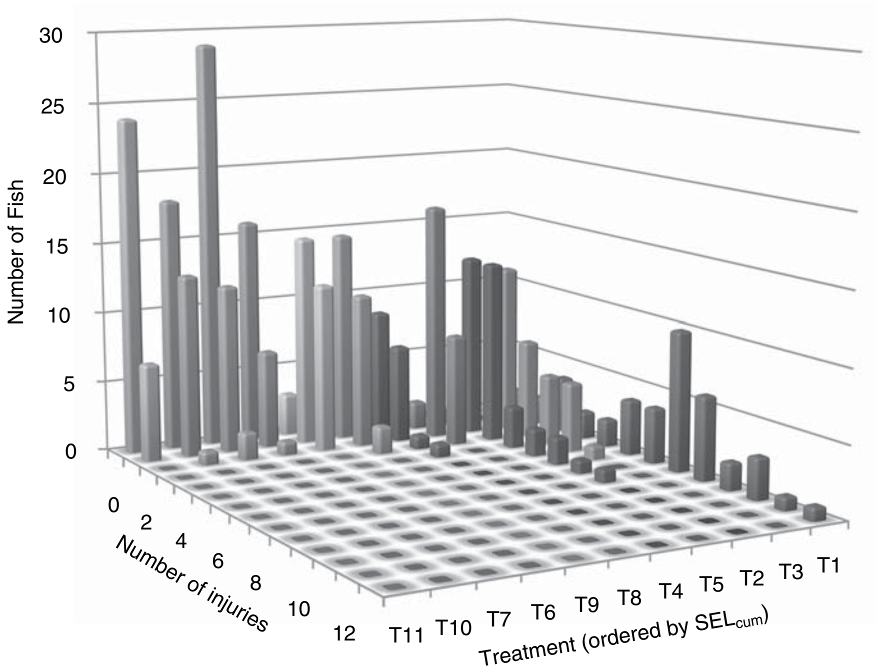

Figure 6 Frequency of barotrauma injury occurrence per fish. The number of test fish (z-axis) with number of unweighted-barotrauma injuries (y-axis) by each treatment (x-axis). For example, in the most severe exposure (Treatment 1 = T1), 1 fish had 13 injuries, and 10 fish had 8 injuries. Similarly, for the least severe exposure (T11), 6 fish had 1 injury, and 24 fish had 0 injuries.

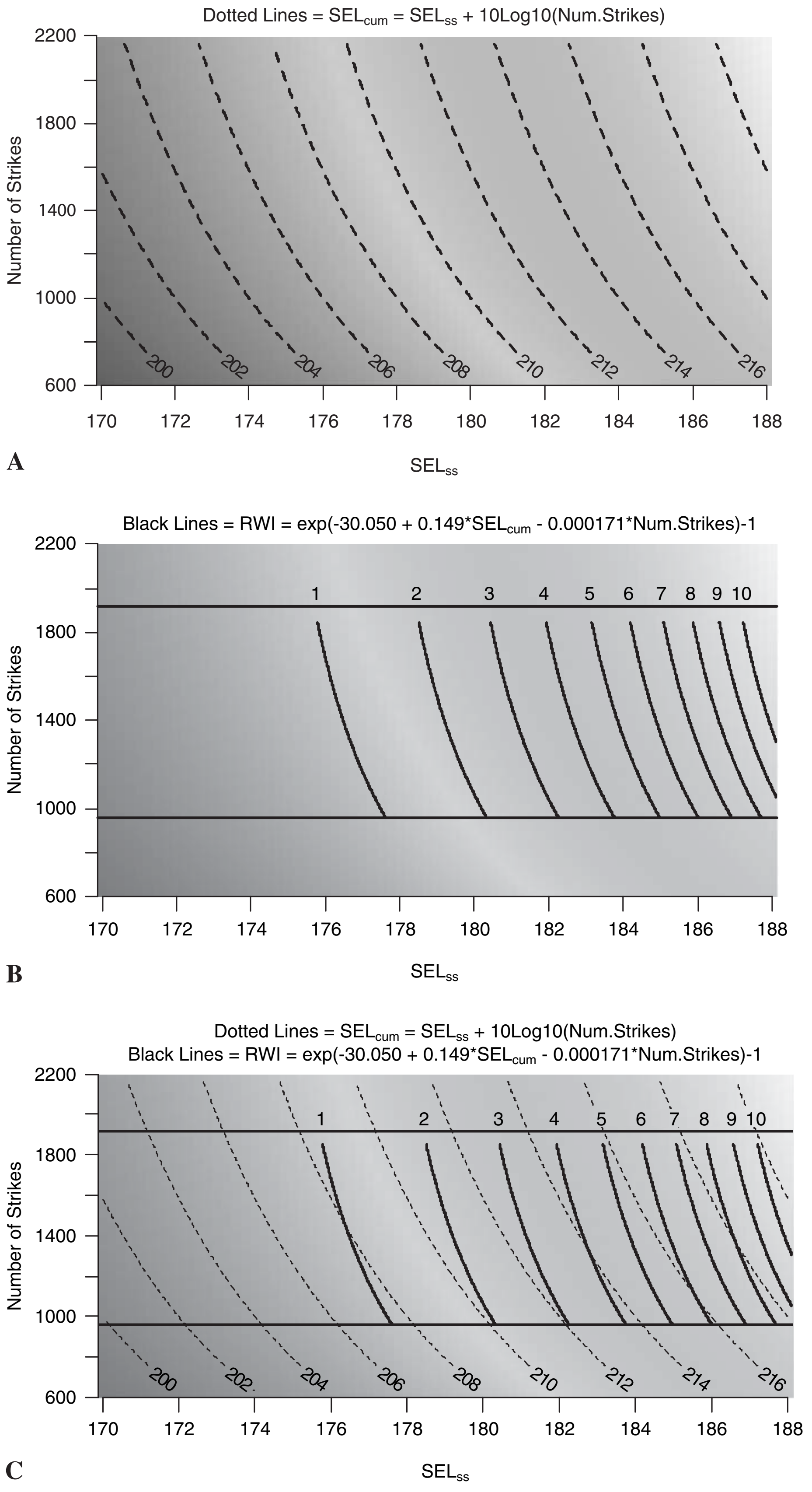

Figure 8 Panel A is the background layer plotting the SEL$_{cum}$ contours (dashed lines) by SEL$_{cum}$, by SEL$_{ss}$, and number of strikes within the treatment range. Panel B is a contour plot of ln (RWI+1) (the solid lines labeled 1-10), which illustrates values increase as SEL$_{ss}$ increase. The upper horizontal line indicates the 1,920 strike-line, and the bottom horizontal line indicates the 960 strike-line. Panel C is the composite of B on top of A, and shows where the RWI contours fall over the SEL$_{cum}$ and SEL$_{ss}$ in relation to number of strikes. See text for further discussion.

horizontal line represents 1,920 strikes and the lower horizontal black line represent 960 strikes, the curvilinear contours between represent the RWI values (1-10) derived using the results of testing at 1,920 and 960 strikes. It is unknown whether the derived relationship plotted would persist if additional levels of strike numbers were tested. However, at both strike number levels the RWI values increase with increase in SEL_{ss}. The graph of RWI as a function of number of strikes and SEL_{ss} is interpreted the same way as SEL_{cum} in Figure 8A. Thus, an RWI of 2 would be achieved when the SEL_{ss} is about 181 dB for 960 strikes, and an SEL_{ss} of 179 for 1,920 strikes.

Figure 8C brings both contour layers, SEL_{cum} and RWI, together onto one graph, thereby showing their relationship to each other as well as their relationship to SEL_{ss} and number of strikes. While complex, it links a common metric used to manage the exposure of fish to impulsive sound generated by pile driving, SEL_{cum} through its constituent parts, SEL_{ss} and number of strikes, along with the derived RWI in this study. Mathematically, RWI and SEL_{cum} are both dependent variables defined by the independent variables SEL_{ss} and number of strikes. The composite plot (Figure 8C) identifies the criteria for acceptable pile driving sound exposure given a selected response outcome or RWI value. For example, if a RWI of 2 was selected as the maximum acceptable level of biological response for a pile driving project, during project planning the likely SEL_{ss} and number of strikes needed to drive each pile could be considered to identify alternative pile driving strategies to avoid exposures that would risk exceedance of the selected RWI value. These expectations would be dynamically managed during the project as actual SEL_{ss} values were observed. Practically speaking, SEL_{ss} with the addition of mitigating actions such as bubble curtains are the primary means available to control the exposures fish experience to pile driving sound. The results of this project suggest that a RWI of 2 or less does not lead to physiological effects that reduce either the immediate or long-term performance and energetics of Chinook salmon, or probably other species as well.

CHAPTER 4 DISCUSSION

Overview

The work presented here represents the first study to test the effects of pile driving sounds on fish in a controlled plane-wave acoustic field. Thus, the design enabled systematic exploration of the relationship between potential injury to fish and specific sound characteristics such as number of strikes and sound level, expressed as both single strike (SEL_{ss}) and cumulative sound exposure levels (SEL_{cum}). In contrast, all earlier studies on pile driving used caged fishes under conditions in which the investigators were unable to control any aspects of sound presentation (e.g., number of strikes, sound intensity), or provide adequate biological control groups (reviewed in Popper and Hastings, 2009).

Many aspects of pile driving could have been explored during these experiments. These included sounds from various types of piles (e.g., steel, concrete), inter-strike intervals, or total number of strikes. After discussion with the NCHRP advisory group for this project, it was decided to limit parameters and the variables to allow for collecting meaningful and statistically valid data and analyses in a reasonable amount of time. Examination of the literature and talking with scientists, regulators, and industry representatives, found the most important variables were SEL_{ss} and number of strikes. These two variables can be used to control driving piles, either through management of the energy applied to a pile during each strike or by implementation of mitigating actions such as bubble curtains. Since the study focuses on sounds, it is reasonable to conclude that these sound level metrics could be extrapolated to other impulsive sounds from pile driving, as long as the sound spectra are reasonably similar to striking steel piles.

The study's experimental strategy was designed to evaluate the relationship between SEL_{ss} and SEL_{cum}, number of strikes, and barotrauma damage. To accommodate concerns regarding the variability in impulsive sound amplitude distribution, the exposure stimulus included eight different impulsive pile strike sounds, pseudorandomly presented, all with the same SEL_{ss} differing in details of their amplitude (SPL_{peak}) characteristics. At the same time, a detailed examination of the variables selected allowed for the quantitative examination of relationships between sound exposure level and injury. Techniques developed during and results collected from this study have been incorporated into follow-up studies examining the recovery from *Mild* and *Moderate* injuries and responses in Chinook salmon as well as other fish species; these will be published in subsequent papers (Casper et al., in prep.).

Rejection of the Equal Energy Hypothesis for Pile Driving

The equal energy hypothesis was suggested to be irrelevant for fishes exposed to pile driving (discussed in Carlson et al., 2007). The significant difference ($p = 0.015$) between the 1,920- and 960-strike regression lines (Figure 4) strongly supports this suggestion, and similar results have been shown for mammals exposed to impulsive sounds (Hamernik et al., 2003). As a result, the use of a single metric, typically $\mathrm{SEL}_{\mathrm{cum}}$, is not sufficient to determine regulatory criteria but remains an important variable to observe during pile driving activity. Other metrics related to $\mathrm{SEL}_{\mathrm{cum}}$, such as $\mathrm{SEL}_{\mathrm{ss}}$ and number of strikes need to be taken into consideration.

Relationship Between Pile Driving Exposure and Biological Response

This study has shown that the severity of barotrauma is a function of the energy in each strike ($\mathrm{SEL}_{\mathrm{ss}}$) summed over the total number of strikes needed to drive a pile, $\mathrm{SEL}_{\mathrm{cum}}$. For each strike that occurs during pile driving activity, the energy delivered to the pile is used to overcome resistance encountered from substrate changes and other factors. Furthermore, for each strike, the energy delivered to the pile is managed by manipulating the stroke (the distance the hammer travels). For a particular pile, generally the greater the energy in the strike on a pile, the higher the energy level in the impulsive sound generated (Carlson and Weiland, 2007). This means that the elemental unit of exposure for fish to pile driving sound is the energy in individual strikes, $\mathrm{SEL}_{\mathrm{ss}}$. This complex relationship between exposure and response is summarized for juvenile Chinook salmon in Figure 8.

Data from this study demonstrate that as energy levels of pile driving exposures increase there is a statistically significant increase in the severity of barotrauma injuries. The highest energy levels presented in this study caused injuries that resulted in substantial physiological costs to the fish. The less severe exposures caused fewer barotrauma injuries, and these tended to be *Mild* injuries, which imposed minimal or no physiological effects on the fish.

The survival of fish exposed to pile driving sound that experience injury is dependent on the cumulative effect of those injuries on the performance and energetics of the fish. The most severe injuries have a clear impact on performance because of the consequences, likely mortality and/or damage to organs. Severe injuries would require considerable opportunity for recovery, which under most circumstances would not unlikely be available to the fish (e.g., predator-free refuge, ideal flow rates, easily accessed nutrition-rich foraging). In contrast, the *Mild* physiological injuries seemingly would not affect the performance of fish because life functions would not be compromised and recovery needs would be minimal.

The biological response metric, RWI, derived in this study, permits identification of impulsive sound exposure thresholds, expressed in terms of common sound measures, which protect fish from levels of physiological injury that would likely affect their performance and ability to survive. None of the *Mild* injuries singularly or in combination would be likely to reduce individual performance or affect ecological endpoints. This is not necessarily the case for *Moderate* injuries and certainly not the case for *Mortal* injuries. At the lower end of RWI values, an RWI level of 1 or 2 can only be realized by 1 or 2 *Mild* injuries respectively. An RWI of 3 can occur with 3 *Mild* injuries or 1 *Moderate* injury. While 3 *Mild* injuries would not likely reduce performance of fish, the same may not be true of 1 *Moderate* injury.

With this in mind, an option would be that an RWI level of 2 be used as an acceptable level of physiological injury for juvenile Chinook salmon exposed to pile driving sound. This level of injury is not overly cautious, but still very protective of fish exposed to pile driving sound. This recommendation is specifically for juvenile Chinook salmon in the range of 93–115 mm (standard length) and an average wet weight of 11.8 g. An RWI of 2 could be carefully extrapolated to include other fish within the salmonid family of similar size. It may also be possible to extrapolate to other species, but that would be beyond the scope of this report. In addition, based on predictions made by Carlson et al. (2007), it is likely that larger fish would show less effects at the same exposure levels as those used here. Thus, at higher exposure levels, it is possible that larger fish would potentially have an RWI of 2 or below.

Figure 8 can be used to identify fish responses (RWI) to impulsive pile driving sound, in terms that map directly to the pile driving activity. This mapping will protect fish from having a biological response that is greater than an RWI of 2, for example. If an

RWI of 2 were selected as the maximum acceptable physiological response, then pile strikes that can generate impulsive sound with SEL_{ss} values up to 180 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$ could be used, as long as the number of strikes required to drive the pile was less than 960. If the sound generated by each strike contained less SEL_{ss} energy, then the number of strikes available to drive the pile could be increased, as long as the combination of SEL_{ss} and number of strikes were to the left of the RWI 2 contour in Figure 8. The data from this study do not permit the RWI curves to be extrapolated beyond the 960 and 1,920 strike bounds of this study.

It should be noted that the current west coast interim criteria use a dual approach for decisions on potential onset of physiological effects, either a specific SEL_{cum} or a single-strike peak level of sound pressure (SPL_{peak}). Under those criteria, if the SEL_{cum} is reached over multiple strikes, or any one strike exceeds the SPL_{peak}, mitigation occurs (Popper et al., 2006; Carlson et al., 2007; Stadler and Woodbury, 2009). Furthermore, Carlson and Weiland, (2007) found that SEL_{ss} and SPL_{peak} are highly correlated. In their study of pile driving sounds, they determined that SPL_{peak} could be estimated given SEL_{ss} using Equation 4.1. The linear fit of SPL_{peak} to SEL_{ss} had an r^2 of 0.85. Using equation 4.1, all of the impulsive sound metrics, used in previous criteria, can be defined for operating criteria obtained from a selected RWI value and Figure 8.

$$\mathrm{SPL}_{peak} = 18.02 + 1.05\,\mathrm{SEL}_{ss} \qquad \text{Equation 4.1}$$

CHAPTER 5 APPLICATION TO PILE DRIVING PROJECTS

Background

Exposure criteria for fishes exposed to pile driving sound are almost always given as one or two sound metrics such as SEL_{ss}, SEL_{cum}, SPL_{peak}, or SPL_{rms}. During pile driving operations, monitoring is conducted at one or two points in the sound field. Over time, a convention has evolved to monitor the sound field at 10 m from the pile being driven at one or two depths in the water column, with one of the depths being near the midpoint of water depth. As long as the regulatory criteria are not exceeded, the pile driving activity is determined to be in compliance with operating permits.

The specified exposure criteria are typically conservative or precautionary in nature. Pile strikes generate a sound field that is seldom known or modeled. Furthermore, the presence, distribution, and behavior of fishes of concern, particularly species within regions at risk of high level sound exposures, are also unknown. Over time, information from monitoring activities has accumulated, and it is now possible to review available reports and peer reviewed publications. These reports can be used to provide initial estimates of the observed level of sound likely to be found at various monitoring ranges for a variety of pile types, hammer types, and environmental settings.

The same cannot be said for observations of the behavioral effects on fishes from pile driving exposure. Because of the lack of behavioral information, regulators tend to preferentially permit operations during times when species of concern are unlikely to be present or only present in small numbers. Pile drivers seem to have accepted restrictive schedules in consideration of the expected high cost and complexities of assessing the exposure and impacts to fishes during times when the species of concern may be present.

While exposure criteria are defined for a point in the volume of water ensonified by pile driving sounds, both the generated sound field and the risks to exposed fishes are four-dimensional (time and three-dimensional location in the ensonified volume). The energy in the generated sound field is continuously variable from the pile to the range at which the energy falls below the ambient noise. The amount of energy at any point in the field depends upon many factors, and it is transient because of the intermittent nature of pile driving with one pile strike every 1.5 seconds or so.

A fish would experience sound exposure on the order of 0.01 seconds in every 1.5 seconds, with the amount of exposure energy highly dependent on the location of the fish in the water column relative to the pile being driven. The instantaneous amount of energy a fish may be exposed to decreases rapidly with distance from the pile. In sound propagation models, the decrease in energy is referred to as transmission loss. Typical models for transmission loss, in decibels relative to a μPa in deep and shallow water, are 20 log R and 15 log R respectively, where R is the range (i.e., distance) from the sound source and log is the logarithm base 10. However, the majority of pile driving projects take place in shallow water. Yet, given a measure of the sound at a short range from the source, such as SPL_{peak} at 10 m, it is possible to obtain an estimate of the SPL_{peak} of the sound impulse at greater ranges from the source (Au and Hastings, 2008).

The barotrauma risk to a fish is a function of the probability of its location in the sound field and the energy in the incident sound on the fish (for each strike impulse and cumulative over all impulses) while it is in that location. Because of the absence of behavior-based exposure models, it is usually assumed that the fishes of interest are stationary in the sound field over the duration of exposure, which is typically defined as the time required to drive a pile.

It is interesting to consider the risk of barotrauma to fishes from particular exposure criteria, considering the characteristics of a propagating sound field generated by pile driving. Assume that an RWI value of 2 was selected as the maximum acceptable physiological exposure response of juvenile Chinook salmon to pile driving sound. Referring to Figure 8, it can be seen that if SEL_{ss} was limited to 180 dB re 1 $\mu Pa^2 \cdot s$ and the number of strikes required to drive the pile was less than 960, the SEL_{cum} received by the fish would be less than 210 dB re 1 $\mu Pa^2 \cdot s$. The exposure criteria by permit would then be $SEL_{ss} \leq 180$ dB re 1 $\mu Pa^2 \cdot s$ and $SEL_{cum} \leq 210$ dB re 1 $\mu Pa^2 \cdot s$. The SPL_{peak} corresponding to the SEL_{ss} criteria can be estimated, using Equation 4.1, to be 207 dB re 1 μPa. If permitting and monitoring convention were followed, this would be the criteria at a range of 10 m from the pile at mid-depth.

As the range to the pile decreased from the 10 m monitoring location, two factors would change. First, the amount of energy in the sound exposure would increase and second, the affected region around the pile would decrease. For example, moving from a range of 10 m to a range of 5 m, the energy in a single impulse, SEL_{ss}, would increase by 2.25 dB (a doubling in energy would be 3 dB), from 180 to 182.25 dB re 1 $\mu Pa^2 \cdot s$, assuming cylindrical spreading. Additionally, the region of volume affected would decrease in proportion to the square of the distance by a factor of 4, assuming no water depth change, from approximately $314 \cdot H$ m^3 to 78 H m^3, where H is water depth. At a 10 m range and 180 dB re 1 $\mu Pa^2 \cdot s$ sound exposure, the expected biological response would be an RWI of 3. An RWI of 3 would be 3 *Mild* injuries or 1 *Moderate* injury. Given the example criteria, as the distance to the pile decreases from 10 m to 5 m, sound exposure increases by 2.25 dB, the volume affected decreases by a factor of 4, then the biological response would increase by 1 *Mild* injury (totaling 4 *Mild* injuries), or by 1 *Moderate* injury (totaling 2 *Moderate* injuries). The non-linearity of biological response, RWI, with increasing severity of exposure is evident in Figure 8.

Conversely, for this example, as range from the pile doubles from 10 m to 20 m, SEL_{ss} would decrease to 177.75 dB from 180 dB re 1 $\mu Pa^2 \cdot s$, affected volume would increase from $314 \cdot H$ m^3 to 1,257 H m^3, and the expected biological response would decrease to an RWI of approximately 1, the equivalent of 1 *Mild* injury.

Derivation of Exposure Criteria

Terms used to express exposure criteria relate directly to the pile driving activity and the maximum acceptable impulsive sound exposure at the identified monitoring location in an operating permit. The entity performing the pile diving is typically expected to monitor the generated sound and to mitigate their activities as needed to avoid exceedance of exposure criteria. Possible mitigating actions for underwater sound could include management of the applied energy such as bubble curtains, which might reduce the amount of energy that propagates away from the immediate vicinity of the pile.

The research results reported here permit derivation of exposure criteria by starting with a selected level of biological response that protects the individuals in an exposed area from injuries that affect performance and/or energetics. The selected biological response level and the results of this study can be used to identify the level of exposure that should not be exceeded, i.e., exposure criteria, to assure protection of the fish of concern. The results of this research are specific to juvenile Chinook salmon. Extension of juvenile Chinook salmon's biological responses to other species and size groups may be possible with consideration of potential differences in biological responses resulting from species' physiological differences.

Two cases for derivation of exposure criteria are considered. The first case is for examples where the pile driving duration is short and/or the number of strikes required to drive a pile are less than 960. This is the most likely scenario for the majority of piles driven. The second case is for occasions where the number of strikes required to drive a pile is more than 960 but less than 1,920.

Both cases were developed using an RWI of 2 as an acceptable level. The research team's findings during this study and those of subsequent and ongoing research (Carlson et al., 2011) permit us to conclude that 2 *Mild* barotrauma injuries do not reduce fish performance and are a conservative threshold for barotrauma injury from exposure to impulsive sound generated by pile driving.

Case 1: Number of Strikes ≤ 960, RWI = 2

The lower bound for exposures in this study at the 960 strike level was a SEL_{ss} of 174 dB re 1 $\mu\mathrm{Pa}^2 \cdot \mathrm{s}$ with corresponding SEL_{cum} of 203 dB re 1 $\mu\mathrm{Pa}^2 \cdot \mathrm{s}$ (see Table 2). Exposures with fewer strikes were not considered, and extrapolation of RWI to exposures with less than 960 strikes using the function relationships of Figure 8 is not advised. However, for pile driving durations less than 960 strikes the relationships between RWI, SEL_{ss}, and SEL_{cum} shown in Figure 8 can be used to obtain conservative exposure criteria.

The exposure criteria would be the SEL_{ss} and SEL_{cum} shown in Figure 8 where the RWI curve intersects the horizontal 960 strike line. For an RWI of 2, these values would be a SEL_{ss} of approximately 180.25 dB re 1 $\mu\mathrm{Pa}^2 \cdot \mathrm{s}$ and a SEL_{cum} of 210 dB re 1 $\mu\mathrm{Pa}^2 \cdot \mathrm{s}$. These criteria would be conservative because if the SEL_{ss} is not exceeded, the SEL_{cum} would always be less than 210 dB re 1 $\mu\mathrm{Pa}^2 \cdot \mathrm{s}$. For an exposure maximum of 960 strikes at an RWI of 2, more precise estimates of SEL_{ss} and SEL_{cum} can be found using the equations presented in Figure 8.

Case 2: Number of Strikes between 960 and 1,920, RWI = 2

If the expected number of strikes to drive a pile is greater than 960 and the selected biological response threshold is an RWI of 2, then the equations in Figure 8 may be used to identify the SEL_{ss} and SEL_{cum} exposure criteria. The relationships between number of strikes, SEL_{ss}, and SEL_{cum} presented in Figure 8 are shown below as equations 5.1 and 5.2.

$$\mathrm{SEL}_{cum} = \mathrm{SEL}_{ss} + 10 \, \mathrm{Log} \, (\mathrm{Strike}) \quad \text{Equation 5.1}$$

$$\mathrm{RWI} = (\exp(-30.050 + 0.149 \ \mathrm{SEL}_{cum} - 0.000171 \ (\mathrm{Strike}))) - 1 \quad \text{Equation 5.2}$$

In both Equations 5.1 and 5.2, Strike means the number of strikes. Given two of the four variables in these equations, the other two variables can be found.

For a pile driving project, the variables most likely to be known *a priori* will be the RWI and SEL_{ss}. The reason is that acceptable biological responses will be the initial selected variable in consultation between regulatory agencies and those wanting to drive piles. In addition, the type of pile, hammer, and pile driving conditions will likely be determined during project planning, and available information will permit estimation of the expected SEL_{ss} value.

Given SEL_{ss} and RWI, it is most likely accurate to use Figure 8 to estimate SEL_{cum} and the number of strikes available to drive a pile. In practice, the expectations intended for fish protection are implicit in the selection of an RWI value and the implication for underwater pile driving sound generation that will require negotiable tradeoffs using Figure 8 and/or Equations 5.1 and 5.2.

For example, if the selected RWI is 2 and the expected SEL_{ss} is greater than 181 dB re 1 $\mu\mathrm{Pa}^2 \cdot \mathrm{s}$, a solution for SEL_{cum} and number of strikes is not possible within the bounds of the data for this study. Either the RWI value would need to be increased or the pile driver would need to identify strategies that would reduce SEL_{ss}. Alternatively, the negotiating parties might elect to extrapolate the RWI curves outside the range of experimental data to obtain solutions.

Other strategies for exposure criteria derivation could be to permit higher SEL_{ss} outside of the solution range of experimental data, or limiting SEL_{cum} and RWI within the solution range. An example would be permitting SEL_{ss} of 182 dB re 1 $\mu\mathrm{Pa}^2 \cdot \mathrm{s}$ but limiting SEL_{cum} to 208 dB re 1 $\mu\mathrm{Pa}^2 \cdot \mathrm{s}$. Such strategies would most likely pose a high risk of exceedance of RWI; however, an SEL_{cum} of 208 would seem adequate to prevent exceedance of an RWI of 2 (Figure 8). The risk of exceeding the RWI threshold would be particularly high if the majority of barotrauma injuries at a particular SEL_{ss} occurred during the initial stages of exposure when the number of strikes was low.

CHAPTER 6 FUTURE RESEARCH

This study was designed to explore the relationships between the number of pile strikes, SEL_{ss}, and SEL_{cum}, with particular reference to Chinook salmon. The results provide a highly quantified view of the most important variables in pile driving and their effects on fish. Yet, this is just the first critical step in the goal of fully quantifying the effects on fishes from impulsive pile driving sounds and developing a full array of criteria to protect fish. However, to fully understand effects of pile driving, it is imperative to get quantitative data on other variables associated with pile driving. These range from impulsive sounds generated by different pile types to responses by different species from impulsive sounds. Future studies should also be directed at refining knowledge and extrapolating to other sounds, other species, and fish of different sizes. The following are a number of such studies that the research team believes are the most critical next steps:

- Temporary threshold shifts in hearing sensitivity are called TTS, and are a temporary loss of some hearing. Both TTS and barotrauma tissue injury have been used to assess the response of fish to sound exposures. However, their respective positioning along a biological response continuum has not been determined for any species. It would be useful to learn if the biological responses for each assay lies along a continuum for impulsive sound exposure. If the responses fall on a continuum, then a useful comparison would be TTS and barotrauma sensitivities modeled as measures for the onset of effect and/or injury in fish from exposure to impulsive sound.
- Studies on the effects of decompression on fish have shown that the magnitude of the ratio of pressure to which fish are acclimated and the pressure at which fish are exposed is proportional to the severity of barotrauma injury. If this ratio extends to pile driving and seismic impulsive sounds, it would introduce depth as a variable into the assessment of the effects of these sounds. The result would be a rapid decrease in the severity of exposure and response from relatively small changes in depth, given that the static pressure in water increases by about 100k Pa per 10 m of depth. Research is needed to determine the relationship between acclimation- and exposure-pressures, and if response severity is the same for impulsive sound exposure as it is for decompression.
- The results of this study show that severity of responses increases with increased exposure to impulsive pile driving sounds. However, the scope of the study did not permit investigation into how injuries accrued during exposure. It is possible that injury accumulation was almost complete within the initial exposure-strikes and that the increase in injury accumulation rate and their severity was not uniform over the course of exposure. Understanding the growth of effects is essential to more accurately estimate biological response.
- The use of the results from studies such as the one described here must deal with the question of applicability across fish species and sizes within species. The most conservative approach is not to extrapolate the results of a study to other species and size groups. However, the reality is that data are few and quite difficult to obtain. Thus, in most situations, it is better to use available data to inform a decision. Indeed, and as discussed in Chapters 4 and 5, it is possible to generalize the results of this study with caution. While the most thorough approach would be to do the same detailed studies as done here on many other species, the time and expense of such studies make that approach prohibitive. However, it would be possible, and of great value, to do a limited set of studies using a defined array of exposures across a range of carefully selected species to represent the diversity of fish structure and physiology, as well as fish under the most regulatory-concern. This, combined with the extensive results reported here, would permit a broader understanding of the comprehensive effects, which could serve as a guide for extrapolation to a wider range of species.
- The least significant class of barotrauma injury defined in this study (*Mild*) includes those injuries that are not likely to impose a physiological burden that will affect the health of a fish. This assessment is the basis for selection of a RWI value of 2 as an acceptable response threshold for derivation of exposure criteria to impulsive sound. However, it is also possible that higher levels of injury would not pose physiological risk to fish health. Through experiments that assess the fitness of fish with *Moderate* injuries, it would be possible to estimate the level of injury fish can experience without impact on overall health. In the absence of such data, regulation to protect fish must be very conservative to assure protection

for exposed animals, which is why this study recommends an RWI of 2.

- Exploration of assays to detect the presence of specific proteins (biomarkers) in blood offer the potential for non-lethal assessment of injury from exposure to impulsive sound and other exposures. Biomarkers used to detect traumatic brain injury (TBI) in humans have been found to be a candidate biomarker to detect sub-mortal injury in fish exposed to decompression and impact. There is a growing literature that impulsive signals can cause TBI and that the effects do not show up for some time post exposure. Thus, biomarkers could be an important response assessment tool particularly for fish that are difficult to necropsy because of value (such as adult breeding females), handling challenges, or size limitations (larval fish or full-grown adult).
- There have been suggestions that the cumulative effects on fish from the natural pauses that occur during pile driving activity result in a resetting of the injury accumulations. For example, would the effect on fish be the same from a group of 960 continuous strikes compared to a group of 96 strikes presented 10 times with a defined time separation? It would be useful for mitigation purposes to determine the injury response levels from these two paradigms and address whether or not natural pauses lead to different injury response levels than continuous activity.
- While it has been predicted that effects of pile driving would decrease as fishes get larger (e.g., Carlson et al., 2007), this could not be examined in the results reported here due to the size of the HICI-FT. Understanding such effects would have significant implications for setting criteria for effects of sound on fish.

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ACRONYMS

A/D	analog/digital
AEP	auditory evoked potentials
ANCOVA	analysis of covariance
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
Caltrans	California Department of Transportation
EVREST	evoked response study tool (software/hardware system)
HAT	hearing assessment tube
HICI-FT	High Intensity Controlled Impedance Fluid-filled wave Tube
IACUC	Institutional Animal Care and Use Committee
ln	natural log
MS-222	tricaine methanesulfonate
MSL	Marine Sciences Laboratory (Battelle)
NMFS	National Marine Fisheries Service
PVC	polyvinyl chloride
RWI	response weighted index
SEL	sound exposure level
SEL_{cum}	cumulative sound exposure level
SEL_{ss}	single-strike sound exposure level
SPL	sound pressure level
SPL_{peak}	peak sound pressure level
SPL_{rms}	root mean square sound pressure level
TBI	traumatic brain injury
TTS	temporary threshold shift

APPENDICES A THROUGH H

Appendices A through H can be found on the TRB website at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=763.

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