Acoustics Ecology
Aquatics Issues

Assessing the Impact of Pile Driving Upon Fish

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Abstract

Pile driving associated with the removal and reconstruction of a jetty was monitored at a busy harbor in the North East of Scotland, adjacent to an important Atlantic salmon river. The main concern was with the impact of noise upon salmon migrating through the lower part of the river estuary. Pile driving was allowed to proceed subject to an agreed program of works to monitor sound levels and ensure least disturbance to salmon.

Both percussive and vibratory pile driving took place. Sound-pressure levels from both were measured. Percussive pile driving involved the repeated striking of the head of a steel pile by a double-acting hydraulic hammer, with a 5 tonne ram weight operated with a mean stroke of about 1 m. Vibratory pile driving was achieved by means of a variable eccentric vibrator attached to the head of the pile.

The majority of piles were initially driven into the substrate by vibration, over a period of several minutes. Each pile was then subsequently driven to its full depth with a sequence of repeated hammer blows. Steel facing piles were inserted adjacent to the quayside and subsequently backfilled to provide a new frontage to the quay. Diagonal-bearing piles were also inserted well behind the quay to strengthen the adjacent roadway.

Sound pressure levels generated by pile driving in water were measured using a calibrated hydrophone suspended 1 m above the bottom. The hydrophone was connected to a low-noise amplifier, which controlled the signal gain and bandwidth. The output was connected to a laptop PC by a digital audio interface. When recording at close range, where sound levels were especially high, a less-sensitive hydrophone transducer was used, connected directly to the audio interface. All sound recordings were made as 16-bit WAV files. For some of the piles, particle-velocity amplitudes were measured by means of an assembly of three orthogonally mounted, calibrated geophones placed on the seabed.

The sound-pressure levels (SPL) of the background noise and vibro-piling noise were measured as a root-mean-square (rms) level expressed in decibels relative to a reference level of one micro Pascal (dB re 1μPa). The shorter-duration impulsive sounds generated by the individual blows of the pile-driver hammer were measured in several different ways: the peak pressure reached during the impulse, the rms pressure measured over the time period that contained 90% of the sound energy (rms impulse), and as the sound-exposure level (SEL) expressed in dB re 1μPa2-s. The latter was defined as the constant sound level of 1s duration that would contain the same acoustic energy as the original sound. Sound levels were converted to source levels (SL), i.e., normalized to an equivalent noise level at a distance of 1 m. In all SL calculations, it was assumed that the spreading loss was represented by the expression 15 log R where R was the distance in meters.

Received sound level in water may be expressed in terms of sound pressure, particle velocity, or intensity, all of which can vary with time over the duration of the sound. In this study, the majority of measurements were expressed in terms of sound pressure. However, it was recognised that it was really necessary to determine the particle velocities as this is the stimulus which is received by the ear of a fish like the salmon. On a few occasions, the particle velocities were measured and the acoustic intensity calculated.

Background-noise levels within the harbor and even within the river itself were high, within the range 118 – 149 dB re1μPa rms over a bandwidth of 10 Hz-10 kHz. Much of the noise derived from manoeuvring and stationary ships. The sound-pressure levels generated in water by percussive pile driving were very high, but variable depending on the pile type, the substrate being penetrated, the distance from the source, and whether the bubble curtain was in operation. Within the harbor, they ranged from 142-176 dB re 1μPa peak, with sound exposure levels (SELs) of between 133-154 dB re 1μPa2-s, without the bubble curtain in operation. Estimated source levels ranged from 177-202 dB re 1μPa peak. Within the river, more than 220 meters away from the pile driver and separated from it by a spit of land, the sound-pressure levels reaching the fish ranged from 162-168 dB re1μPa peak, with SELs of between 129-145 dB re 1μPa2-s. Sounds measured at a distance from the source within the harbor consisted of a low-frequency pre-pulse, followed by the main sound pulse. In this case, and in the river itself, the sound was propagated through the substrate, as well as the water, perhaps accompanied by flexural waves at interfaces between strata. Particle velocities within the harbor and in the river reached 110 dB re 1 nms-1, mainly in a vertical direction, and intensities of up to 0.023 Wm-2 were registered.

The main energy generated by the percussive pile driver extended up to and above 10 kHz close to the source, with most of the energy below 2 kHz. By the time the sound reached the river the higher frequencies had been removed and the predominant frequencies were below 1 kHz, still with considerable energy within the hearing range of salmon (which declines above 250 Hz).

Vibro-piling also generated high sound levels in water, with sound-pressure levels within the harbor ranging from 142-155 dB re1µPa rms and source levels between 173-185 dB re 1µPa rms. Levels in the river ranged from 140-143 dB re 1µPa rms.

A bubble curtain was successful in reducing the peak amplitude of the sound from the pile driver by up to 5 dB and in reducing the high-frequency content of the sound. The bubbles therefore reduced the likelihood of damage or injury to fish. However, they did not reduce energy at the lower frequencies to which fish are sensitive, especially at a distance from the source.

The principal purpose of monitoring the pile driving was to assess the impact upon salmon. There is some controversy and uncertainty about the actual levels of pile-driving sound which affect fish adversely. It is evident that sound affects different species to a differing degree. Thus, although in some instances a level of 180 db re1µPa has been adopted as a standard, above which sounds are likely to kill or cause damage to fish, this is a very uncertain figure which is open to question. It was concluded that the sound pressure levels (SPLs) and sound exposure levels (SELs) generated by percussive pile driving within the harbor were not likely to have killed fish, whether the fish were within the river or the harbor itself. However, the sound levels were high enough close to the pile driver to injure or induce hearing loss in some species of fish. The noise from pile driving in the harbor was certainly high enough to be detected by salmon in the river at considerable distances from the source. The levels of sound from both percussive and vibro-piling were well above the hearing thresholds of the fish. As salmon could not be observed during this exercise, it was not possible to determine whether salmon reacted adversely to the sounds. However, there was a risk that their upstream migration may have been delayed or prevented with consequent effects upon spawning populations. The measurements indicated that any pile driving within the river itself would have the potential to injure or induce hearing loss in salmon and might have adverse effects upon their behavior.

During this exercise, trains of low frequency ‘thumping’ sounds were recorded within the River Dee, similar to those made by fish. The sounds may be emitted by European eels, which are common at the location.

Biographical Sketch: Tony Hawkins is the managing director of Loughine Limited and an honorary professor at the University of Aberdeen in Scotland. His research interests include underwater acoustics and the sounds made by fish. He is a former director of fisheries research for Scotland and is currently chair of the North Sea Commission Fisheries Partnership, which brings scientists and fishermen together from around the North Sea.Loreetue molor sum zzrit praestrud ent lametum zzrit lore ming ectet ex er sit alisl doloreetue consed exeril utat adignisl duisit lummolore modolorem in ut dolortis acilis elit, con vel dolore min eugiatu sandre mod erit in endigna adip el dolenis odipsum dolenim doluptat.

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Barotrauma Injury of Physostomous and Physoclistous Fish by Non-Explosive Sound and Pressure Cycling

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Abstract

Barotrauma injury has historically been a concern for fish exposed to underwater explosions and passage through hydroturbines. Recently this concern has been extended to include underwater sound generated by pile driving, particularly that generated during impact driving of larger-diameter steel casing. Description of the characteristics of sound impulses generated by impact pile driving that are a threat to fish is lacking and current protective criteria that rely on simple peak overpressure do not have a clear scientific basis and appear too restrictive. This paper considers the mechanisms for barotrauma injury to both physostomous and physoclistous fish as a function of acclimation depth and the criteria developed for protection of fish from barotrauma pressures generated by explosions and passage through hydroturbines. These mechanisms and criteria are discussed within the context of observations of impact pile driving generated pressure time histories and observations of barotrauma injury to fish made during pile driving projects on the West Coast of the United States. Also considered are the results of recent sound-mitigation efforts, including driving of steel casing pile in the dry, the use of both confined and unconfined bubble curtains, and the success of these mitigation efforts as measured by comparison with fish-protection criteria.

Pile Driving and Bioacoustic Impacts on Fish

How Did We Get Into This Mess? Where Do We Go From Here? Status of Developing Best Available Science to Improve Decision-Making Processes

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Abstract

How did those of us in the transportation industry suddenly find ourselves in need of knowing about underwater pressure waves and fish barotrauma? On October 17, 1989, a portion of the East Span of the San Francisco Oakland Bay Bridge collapsed. That event was the catalyst for the State of California to institute a comprehensive seismic retrofit program for its bridge structures. The bridge is considered a “vital lifeline structure” to San Francisco. Therefore, the bridge was to be designed to withstand the maximum expected credible quake with a design-life of 150 years. The criticality of the structure, the design life, and the soil conditions in San Francisco Bay precipitated the need for an innovative foundation design that was the nexus to use steel piles as the preferred structural support material. Ultimately, there was no structural alternative. When we began driving the steel piles, we realized that underwater pressure waves were being generated that caused stunning and even death to fish near the pile.

Pressure waves are generated when the hammer strikes the pile, imparting a flexural wave that moves down the pile at approximately 5000 feet per second. As the wave does this, it interacts with the air, creating a localized pressure perturbance, resulting in airborne noise. It then moves through the water column creating compressional waves. This results in what we refer to as a hydroacoustic pulse. Finally, the energy moves down into the more-resistant substrate, where it is dissipated through the physical displacement of soil particles. A wave travels down, then back up, and it continues to reverberate until all of the energy has been dissipated, into the air, water, and soil.

Our efforts to develop a better understanding of the acoustic properties of pile driving and its effects on fish began with examining the findings from past research for their relevance and applicability while looking at a variety of wave forms. The U.S. Army Corp of Engineers, Canada’s Department of Fisheries, the US Navy, and others have done many studies on the effects of explosive blasts on fish. There is a relatively small, but high-quality, body of literature that exists for effects of long-term continuous noise exposure on fish, such as that found in active sonar arrays. There is almost no information on pile driving impacts.

We have also been designing and testing various noise-attenuation technologies. The bubble-tree attenuation device used to surround piles being driven for the Benicia-Martinez Bridge Project successfully reduced peak noise levels to an approximate 20m radius around the pile. This equated to a 99.8% reduction in radiated energy compared to an unattenuated pile.

What are some of the lessons we have learned so far? First, one needs to understand the ramifications of permit terms and conditions for these types of projects. These have to be meaningful and measurable criteria. They need to be biologically relevant and technologically possible conditions. For instance, underwater noise-monitoring equipment needs to be able to measure the target frequencies committed to within the permit. Second, one needs to develop and follow monitoring protocols with specific objectives and study controls. In other words, don’t go out and collect a bunch of data and then try and make something of it. Third, one needs to obtain incidental take authorization to avoid unanticipated work stoppages. Last and most important, avoid jeopardy and avoid and minimize the incidental effect of take to the extent practicable.

What else have we learned? This is a highly complex issue, and we need to be very careful to ensure we base decisions on credible and relevant information. Just because it is in print does not mean it is useful, credible, or relevant. As the Endangered Species Act (ESA) clearly states: “The best available information is to be used in the implementation of the ESA and this information must be reliable, credible, and represent the best scientific and commercial data available.”

We soon realized other states and industries were struggling similarly with this issue and that by working together we could be more effective in our efforts. Therefore, two years ago we formed the Fisheries and Hydroacoustic Working Group. The three key goals of the Fisheries and Hydroacoustic Working Group are to summarize: 1) what we currently know (what is the best available science); 2) what we need to know (define future research needs); and, 3) what is the best application of current information for consistent interim standards. As new information is developed, the cycle repeats itself, and we will continue to update our summary of current understanding, re-evaluate further research needs, and re-evaluate and possibly modify noise-criteria standards based on what we have learned. In support of this effort, Caltrans funded preparation of the report titled “Effects of Sound on Fish” by Mardi C. Hastings, Ph.D., and Arthur N. Popper, Ph.D., that was completed in January 2005. The final report constitutes a comprehensive literature review and analysis of relevant research, recommendations for preliminary guidance, areas of uncertainty, and recommended research.

Caltrans also submitted a proposal to the Transportation Research Board, National Cooperative Highway Research Program to fund a national research study to evaluate hydroacoustic impacts on fish from pile installations. That proposal was accepted and is underway. It is Project 25-28, Hydroacoustic Impacts on Fish from Pile Installation.

The Federal Highway Administration has also sponsored a pooled-fund project titled “Structural Acoustic Analysis of Piles.” The study’s goals are to develop and validate models of sound fields and the effects of attenuation systems, to develop and validate acoustical source models of pile driving, to synthesize information from this project with other pertinent research, and to develop a guidance document for practitioners.

The three most recent efforts that Caltrans has underway are: 1) the development of an Interim Guidance Manual that identifies procedures for assessing and mitigating effects of pile driving sound on fish; 2) the development of an underwater sound-pressure compendium; and, 3) development of a methodology for measuring and reporting underwater sound pressure.

Biographical Sketch: Deborah McKee is a senior environmental planner, aquatic resource biologist for the California Department of Transportation (Caltrans). Ms. McKee oversees research, regulatory compliance, and inter-agency coordination for aquatic resources including fisheries bioacoustics.

What Do We Know About Pile Driving and Fish?

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Abstract

There are growing concerns about the potential effects of in-water pile driving on aquatic organisms. These concerns arise from an increased awareness that high-intensity sounds have the potential to harm both terrestrial and aquatic vertebrates (e.g., Fletcher and Busnel 1978; Kryter 1984; Richardson et al. 1995; Popper 2003; Popper et al. 2004). The result of exposure to intense sounds may extend over a continuum running from little or no effects to the death of the ensonified organism. This paper is a brief review of what is known about the effects of pile driving on fish. It also provides some ideas about the design of future experiments that can be used to test these effects. The conclusions and recommendations presented here are explored in far more detail in a recent review on effects of pile driving on fish (Hastings and Popper 2005). In addition, a broader examination of the general effects of sound on fishes can be found in Popper (2003) and Popper et al. (2004).

It is widely believed that fish close to pile-driving activities may be killed by exposure to very intense sounds. There is also some evidence that fish at some greater (but undefined) distance may survive exposure to pile-driving activities. However, experimental data are very limited. Moreover, nothing is known about non-life-threatening effects on fish of some (undefined) distance from the pile-driving operation. Such effects may include (a) non-life threatening damage to body tissues, (b) physiological effects including changes in stress hormones or hearing capabilities, or (c) changes in behavior (discussed in Popper et al. 2004). These effects could be temporary (e.g., a temporary loss of hearing that recovers over time) or of sufficient length to lower long-term survival and/or reproductive potential of individual animals or communities. There are also no data on effects of cumulative exposure to pile-driving sounds.

The concerns about currently available pile-driving data arise because there is very little quantification and replication of experiments and because the investigators were not able to control the stimulus to which the fish were exposed. Thus, little is known about the stimulus actually received by fish during experiments. It therefore becomes difficult to evaluate the effects of pile driving on fish that are at different distances from the source. Moreover, there are no studies to date that included observations of the behavior of fish during exposure to pile-driving signals (but see paper by Hawkins in this volume).

Because of the dearth of data on effects of pile driving on fish, it has been suggested that data from other types of experiments involving intense signals be extrapolated to pile driving. A problem, however, is that the sounds used in other studies, such as the effects of sonar (Popper et al. 2005a), seismic air guns (Pearson et al. 1992; Engås et al. 1996; Wardle et al. 2001; McCauley et al. 2003; Popper et al. 2005b), and pure tones (Enger 1981; Hastings et al. 1996) differ greatly from sounds produced during pile-driving activities. Moreover, there are also concerns about extrapolating effects between species, and particularly between species that have different life styles, sound-detection capabilities, and responses to adverse stimuli (see Hastings et al. 1996; McCauley et al. 2003; Popper et al. 2005b). Furthermore, there is some evidence to suggest that it may not always be possible to generalize the effects of high-intensity sounds between different age classes of the same species (e.g., Popper et al. 2005b).

Since there are issues with the way pile-driving experiments have been done to date, it is worth considering how one might design an experiment that would provide the data needed to understand the effects of pile driving or, for that matter, any intense sound, on fish. One caveat with these suggestions, however, is that they require that fish be kept in a limited locale (e.g., a cage or tank) so that they can be observed before, during, and after the sound exposure, and that the fish can be retrieved for physiological and morphological analysis. Such requirements preclude direct observations on how fishes might behave if they were free from constraints or confinement during the exposure to pile driving, as has been done in one study on the effects of seismic air guns on fishes on a reef (Wardle et al. 2001).

In bullet form, the characteristics of an appropriate experiment should include:

- Sound fully under control of the investigator to ensure that the sounds to which the fish are actually exposed are calibrated and of known duration and intensity.
- Detailed analysis of the received sound, with calibration not only in terms of RMS and peak pressure levels, but also in terms of exposure over time (sound exposure level) and, where appropriate, in terms of particle displacement (see Popper et al. 2005b).
- Healthy fish from known sources that are carefully acclimated to the experimental site and situation prior to start of sound exposure.
- Recording of fish behavior during the whole experiment by video from multiple angles to enable later analysis.
- Quantitative design of the experiments to ensure statistically valid results.
- Multiple test groups to replicate results.

- Control and baseline animals, with control animals being subject to precisely the same paradigm as exposed animals, other than the presence of sound. Baseline animals serve as “controls for the controls” in that they are subject to all of the same conditions as control and exposed animals, other than for being placed into the experiment itself.
- Use of standard procedures to determine loss of hearing, both immediately after exposure and then over several days post exposure to determine if there is late onset hearing loss and/or recovery from hearing loss (e.g., Hastings et al. 1996; Scholik and Yan 2001; Smith et al. 2004; Popper et al. 2005).
- Necropsy and histopathology of a variety of organ systems done by experienced fish pathologist to determine if the ear and/or other organ systems are affected by the sound (e.g., Marty 2004; Popper et al. 2005a).
- “Blind” analysis wherever possible so that the experimenters do not know whether the fish being analyzed were exposed, control, or baseline animals. It should be recognized that this is often not possible due to the need to do experiments in a limited time frame, which often requires constant feedback to maximize the data obtained. However, when blind experiments are not possible, it is important to have more than one person independently analyze the data.

While this paradigm has yet to be used in any pile-driving study, it has been employed, with appropriate modifications for specific experimental sites and experimental questions, at least twice, once for investigation of the effects of seismic air guns on fish in northern Canada (Popper et al. 2005b) and in examining effects of high-intensity, low-frequency sonar (Popper et al. 2005a, in prep.). In the air-gun study (Popper et al. 2005b), three species of fish were exposed to air guns at a received mean level of 207 dB re 1 µPa (peak) (or 197 dB re 1 µPa (RMS); 177 dB re 1 µPa2·s sound exposure level (SEL)). Results showed no mortality and no damage to the fish (though it should be noted that a pathologist was not involved in this study due to costs and logistics). There was some hearing loss in some, but not all, of the species, and full recovery from hearing loss within 24 hours after exposure.

The sonar study (using SURTASS LFA sonar) exposed caged fish to 324 seconds of sound at frequencies below 500 Hz. The received level of the sound was 193 dB re 1 µPa and the experiment was done in a very deep lake where the fish were well into the acoustic far field of the sound source. The acoustic conditions were very similar to those that a fish might encounter if exposed to this low frequency sonar in the ocean. The results showed no mortality or adverse pathology in any organ system (examined by a trained fish pathologist) to two species, rainbow trout and channel catfish. There was some hearing loss. Preliminary data suggests recovery within 96 hours. Behavioral effects, as observed by video, were minimal for both species.

However, there is still the question as to whether these two studies can be extrapolated to pile driving for reasons discussed above. At the same time, the levels of the sounds to which the fish were exposed in these two studies was well above the 180 dB re 1 µPa (RMS) “criteria” that is now being promulgated for pile driving. Since the exposure in both the air gun and sonar tests were substantially longer than it is likely any fish would be subject to in pile driving (assuming the fish survives the first exposure and can swim away), it may be tentatively suggested that the 180-dB criteria is far too conservative.

Finally, there are a range of questions that need to be answered before the effects of pile driving can be understood and fully effective criteria be applied to protect animals. These can be divided into: (a) obtaining information about the pile-driving sounds and (b) determining the responses of fish to the exposure.

It is important to analyze pile-driving sounds from different types of piles and then construct “standard” sounds for use in fish experiments. This is critical since it is impossible to define every type of sound produced by every type of pile in every water depth and in every substrate. Thus, an appropriate group of acousticians and pile-driving experts need to develop a set of “representative” sounds that will fulfill the characteristics of the broadest possible set of pile-driving activities.

Once a set of sounds is developed, there needs to be a set of studies that examine the sounds’ effects on a small and manageable set of species that are generally representative of the fishes that are most likely to be exposed to and most affected by pile-driving activities. To obtain the necessary data, there needs to be a set of studies, most of which will have to be conducted at different levels of pile-driving signals (in order to simulate fish at different distances from the source). These studies include:

- Measures of hearing sensitivity of selected species that are potentially exposed to pile driving (to serve as a baseline for effects of exposure).
- Mortality of exposed fish.
- Effects on hearing capabilities (e.g., temporary or permanent).
- Effects on eggs and larvae of select species (e.g., Banner and Hyatt 1973).
- Behavioral responses to pile driving of exposed fishes (swimming activities, etc.).
- Long-term behavioral and physiological effects on fish.

- Effects on the structure of the ear, lateral line, and non-auditory tissues and whether these repair over time or ultimately lead to death.
- Cumulative effects of exposures on fish to pile-driving sounds.

In all cases, sufficient amounts of data are needed to enable the development of “models” to “predict” the effects of particular pile-driving operations on fish (e.g., Smith et al. 2004 for responses to narrow bands of noise). Thus the work must be done using a very highly quantified sound field with specific knowledge of the stimulus, and the stimulus must be controlled by the investigator.

Clearly, the studies described need to be done with animals in cages or in the laboratory where the fish can be closely observed and retrieved for study. These results, however, do not provide insight into the behavior of fish that are able to respond to pile driving by showing normal behaviors such as swimming away from the source. Thus, while studies of non-captive fish are substantially harder to do than controlled experiments, data on “natural” behaviors are of great interest since they provide needed insight into whether fish would actually be impacted in any significant way by pile driving.

Biographical Sketch: Arthur N. Popper is professor of biology at the University of Maryland, where he is also co-director of the Center for Comparative and Evolutionary Biology of Hearing. He served as chair of the Department of Biology for 10 years and, after that, as director of the Neuroscience and Cognitive Science Program at the University. His research interests are in mechanisms of sound detection and processing by fish, the evolution of vertebrate hearing, and the effects of sounds on fish hearing. He is co-editor of the Springer Handbook of Auditory Research, a series of 27 volumes (to date), each of which is a comprehensive treatment of one aspect of hearing.

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