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.

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