Interim Criteria for Injury of Fish Exposed to Pile Driving Operations: A White Paper

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Summary

This paper presents science-based, *interim* noise exposure criteria for the onset of direct physical injury in fish exposed to the impact sound associated with pile driving. This paper provides an objective, scientific assessment of pile driving exposures which are injurious to fish. It does not explicitly consider policies of regulatory agencies which are based on mandated legal requirements and consequently result in the application of sometimes limited information for management decisions. The authors recognize that fish may respond to pile driving without experiencing injury, but the paper does not directly address behavioral responses of fishes or other sub-injurious auditory effects in setting interim criteria, largely due to the absence of underlying information.

The interim criteria presented here are based on the best science available at the time of writing. We have used professional judgment and, for the most part, the existing, peer-reviewed literature, to make conservative decisions where data are lacking, or present a range of options. That is, in the face of uncertainty criteria are set at exposures somewhat lower than the present peer-reviewed literature suggest may be the levels that would result in the onset of injury. A dual criteria approach is developed which includes an interim single-strike criterion for Sound Exposure Level (SEL) combined with an interim criterion for Peak Sound Pressure Level. Possible applications of SEL metrics to account for the accumulation of exposure energy across multiple exposures are discussed, although it is pointed out that the available data supporting multiple strike criteria are highly limited. The assumptions on which the criteria developed here are based are listed in an Appendix along with suggestions for the research that is needed to test the assumptions. Because of the high likelihood that this research will call for modifications of the interim criteria, the criteria presented must be clearly understood to be provisional and part of

an iterative, self-correcting process that, along with policy guidelines, will continue to evolve for decades as new data become available.

Introduction: approach to exposure criteria

The initial approach to linking biological consequences with impulsive sound exposure has focused on the sources of the sound because that is how information is presented in the peer-reviewed literature. The major sources of impulsive sound are explosions, seismic devices, and percussive pile driving. However, any impulsive signal can exhibit a wide range of characteristics as described using various metrics that may include, among others, peak pressure, rise time, duration, and spectral composition. Overlap of impulse characteristics between sources is a fact. It is possible for seismic sound impulses to have key characteristics, such as peak pressure, that are very similar to percussive pile driving sound or to explosions. This is true because of the wide range in the characteristics of sources and the rapid modulation of the composition of impulsive sound signals as they propagate, particularly in shallow water.

In terms of biological consequences, it is not the source of the energy that affects exposed fish that is important. Instead, it is the received exposure conditions, attributable to the particular characteristics of a signal of interest, the specific environment in which the sound is produced, and the physical orientation of source and receiver. Also of importance may be factors such as the rise time of the signal, the number of exposures of an animal to a particular signal, the time between each exposure, and the physiological accumulation of effects.

The mapping function of ultimate interest to science is between metrics such as peak pressure and rise time for both sound impulse pressure and particle motion, and also biological consequences of effects such as barotrauma or hearing loss. The objective of scientific investigation is to describe the mapping functions between biological consequence and impulsive sound characteristics. In such a mapping, impulsive sound characteristics will be grouped as data vectors similar to the familiar (X,Y) coordinates that identify a point in a plane. These data vectors, instead of identifying the location of a point, will map to the biological consequences of impulsive sound exposure, which will most likely be probabilistic in nature, for that particular impulsive sound data vector. This paper presents the initial step in this process by proposing a science-based data-driven approach that consists of two impulsive sound metrics that map to the boarders of a biological response space that is poorly understood.

Scope and Purpose

Fish species are sometimes injured or killed by the impact sounds generated by percussive pile driving. Their hearing may also be affected or their behavior altered. The specific effects of pile driving on fish depend on a wide range of factors including the type of pile, type of hammer, fish species, environmental setting, and many other factors. The fish species affected depend on the location of the operation, and the habitat, which varies from rivers to reefs on the continental shelf. Ultimately, noise exposure criteria for fish are needed for the onset of injury, behavioral disturbance, and possibly other auditory effects such as noise interference with hearing (masking) or temporary loss of hearing (temporary threshold shift -

TTS). Unfortunately, available data are currently too sparse to set clear-cut science-based criteria for behavioral disturbance of fish or auditory masking from pile driving. Therefore, only criteria for the onset of direct physical injury from exposure to pile strikes are presented in this paper.

Sounds from Percussive Pile Driving

The sounds from percussive pile driving result from the impact of the hard surface of the hammer with that of the pile (See Hastings and Popper, 2005, for a fuller description of the sounds from pile driving and associated acoustics). The sounds are short, sharp and often very high in amplitude. They are repeated, usually at intervals greater than one second, for some minutes and sometimes for some hours. Figure 1 shows typical sound pressure impulses from a single strike at different locations within a harbor area. The individual impulses may vary in their characteristics and amplitude even at one location within a sequence, as the driven pile encounters different substrates. Moreover, the shape and amplitude of the impulse varies as the sound travels through different pathways to different locations. The impulses are generally shorter than one second, have a steep rise-time (although this may change with distance from the source), and may reach a sufficiently high level to result in non-linear effects in the water and in fish tissues. Because of their brevity and sharpness they have a wide frequency spectrum, and any monitoring or recording equipment must reflect this.

To fully describe the characteristics of the sounds it is necessary to look at those features which may create damage to the tissues and organs of fish. Particularly at risk are the gas-filled swim bladder and surrounding tissues as they expand and contract with passage of a pressure wave. In addition, the ear of fish may be vulnerable to extreme pressures and motions. Sound characteristics currently believed to be most germane to assessing damage to fish include:

- The peak pressure excursion, including the negative and positive peaks.
- The accumulation of energy over time within a single impulse, including not only the direct signal, but also the signal as received via multipaths (e.g., due to surface reflections and/or transmission through the substrate).
- The "sharpness" of the sound (*e.g.*, ratio of peak to rms pressure, or "crest factor") and its rise time.
- The repetition of the sound and accumulation of energy over multiple exposures - receipt of further sound impulses before organs and tissues have recovered from the impact of the first.
- The particle motion stimulus associated with the sound.

Metrics

As indicated, it is not yet clear which aspect(s) of a signal are relevant when considering how a sound may impact a fish. In order to provide some understanding of the possible metrics for describing sound characteristics relevant to potential injury, a number of such metrics are discussed below.

Peak Sound Pressure Level

The peak SPL is the maximum excursion of pressure within the sound. The maximum excursion may take place within a single cycle of sound, but the highest positive peak and the lowest negative peak may be separated in time within the sound impulse. The peak pressure will determine whether the swim bladder and ear are subjected to extreme mechanical stress. Currently the peak SPL is often the only measurement utilized to evaluate the impact of pile driving.

Accumulation of Energy with Time

The time over which energy is applied to a tissue or organ may affect the degree of damage which is inflicted. With a continuous signal a measurement of the root mean square (rms) sound pressure is an appropriate metric. With a sound impulse, however, a metric must be chosen which adequately describes the potential for damage of pulses of different lengths and energy distribution; that is, which measures the acoustic energy in the transient. The sound exposure level (SEL) is one such metric. The SEL is defined as that level which, lasting for one second, has the same acoustic energy as the transient and is expressed as dB re: $1\mu Pa^2$ •sec.

Formally, the SEL is measured over a stated time interval. Ten times the base-10 logarithm of a given time integral of squared instantaneous sound pressure is divided by the product of the squared reference sound pressure and the reference duration of 1 sec. The time interval over which the sound is measured must be long enough to include most of the sound source's acoustic energy.

Note that in the context of this paper the SEL is used to compare impulses, or short single event sounds. SEL may also be used to examine and compare continuous sounds which fluctuate in level and there is evidence from the mammalian hearing literature that total energy measures are relevant in describing cumulative fatiguing effects under certain conditions (*e.g.*, Ward, 1997; Hamernik *et al*., 2003). The relevance of these observations to physical injury in fish is unknown, however. At this time, these and other significant limitations in available data preclude a definitive assessment of whether or how SEL should be used to account for the repetition of impulse exposures. While it is likely that in certain situations, the SEL of multiple strikes may be a meaningful metric in describing exposure dose and assessing effects, there are numerous variables such as the additive effects of multiple signals on physiology and hearing that are not at all understood for fish.

Sound "Sharpness"

A number of studies have shown that the presence of a strong transient within a sound correlates with increased damage to the ears of mammals. There are well documented increases in auditory damage with pulsed as opposed to non-pulsed sounds, or with "sharp" sounds as opposed to "dull" sounds. Pile driving may generate sharp transients where the peak SPL and conventional SEL metrics may not, alone, be sufficient to describe the stimulus in terms of the damage it may cause. As discussed below, explosives have an even sharper rise time. Price (1983) has shown that a rifle shot may have a more damaging effect upon the mammalian auditory system than a cannon shot of higher SEL. Based on measured spectral differences, Price predicted that rifle impulses would cause permanent threshold shifts at approximately 9 dB lower peak pressures than cannon impulses. This threshold shift was later confirmed by experiment.

After studying a large number of chinchillas during exposure to high level continuous non-Gaussian noise, Hamernik *et al* (2003) concluded that the statistical metric, kurtosis, in conjunction with an energy metric, can identify hazardous exposure conditions not identified by conventional energy based metrics alone. Formally, the kurtosis (β) of the sample distribution is the ratio of the fourth-order central moment to the squared second-order central moment of the distribution. Kurtosis is sensitive to the various parameters that define a complex noise such as the levels and durations of the transients, temporal structure of the noise, the numerical relationship between peak and rms pressure ("crest factor"), as well as to the duration of the noise sample over which β is computed. The crest factor itself is often monitored as a potential cause of damage in mechanical systems exposed to a continuous sound.

For impact sounds, the rise time (the time taken for the impulse to reach its peak pressure), or other metrics, may be more appropriate for measuring the sharpness of onset than kurtosis or crest factor. Accordingly, reduction of the sharpness of the impact sounds from pile driving may play a significant role in the reduction of damage. However, one issue with pile driving is the variation from strike to strike of rise times, and the lack of any data on the effect of rise time differences on fish.

Sound Repetition

If another impulse is experienced before an organism has fully recovered from the effect of an initial impulse, then cumulative effects may occur, leading to greater risk of injury. The SEL may or may not be an appropriate metric for measuring repetitive impact sounds in this context as the period of silence between impulses will dominate the measurement. In the present state of knowledge the impulse repetition rate may be the most suitable metric, but it is not possible to use this metric at this point since nothing is known about cumulative effects, and thus repetition rate, on fish. As discussed in the Appendix, these are areas that are critical components of future research.

Particle Motion

Sound consists of two mechanical effects. As well as the change in the pressure above and below the hydrostatic pressure – the sound pressure – which is normally monitored there is also a back and forth motion of the component particles of the medium, of the order of nanometers, which can be expressed as the particle velocity, particle displacement or particle acceleration. Particle motion is aligned along a particular direction and is therefore a vector quantity.

Many species of fish are sensitive to particle motion in addition to, or instead of, sound pressure (Popper *et al*., 2003). In these fishes it is not yet clear whether high levels of particle motion may damage the auditory system. There is no experimental evidence on this point, although it is evident that particle motion is the important stimulus in considering behavioral responses of many species of fish, particularly when they are close to the source. In these species, pressure waves may also remain a source of injury to the fish, even though the auditory system may be relatively insensitive to sound pressure.

Setting Criteria for Damage

Only recently has impact sound been managed with the intent of mitigating adverse effects on fish. The interim noise exposure criterion which the relevant regulatory authority in the U.S. NOAA's National Marine Fisheries Service has set in managing pile driving is a peak sound pressure of 180 dB re: 1 μPa_{peak} (meaning the sound pressure level at the instant of maximum absolute pressure). While it appears that this value is often cited (e.g.,, http://mapping.orr.noaa.gov/website/portal/pies/piledriving.html), the scientific basis for this value is obscure, if not completely absent (see discussion in Hastings and Popper, 2005). It is an oversimplification that has likely resulted from regulators trying to apply a single exposure criterion for exceedingly wide-ranging exposure conditions.

Recent research (Popper *et al*. 2005) indicates that for seismic impulses, 180 dB re: 1 μPa_{peak} is considerably lower than the sound pressure levels that could cause actual injury in three taxonomically diverse species of fish. Furthermore, application of the peak pressure criterion on its own fails to account for the temporal characteristics of the single impulse (the rise time and the variation in peak or rms pressure within the impulse) and the cumulative effects upon the animal of multiple strikes from pile driving (note that the peak pressure units contain no reference to time). For these reasons it is critical to consider that a series of metrics should be examined for setting protective criterion.

Hastings and Popper (2005) reviewed all pertinent peer-reviewed and unpublished papers on noise exposure of fish through early 2005. They proposed the use of SEL to replace peak Sound Pressure Level in pile driving criteria. After deliberation and discussion, we of this paper have concluded that while SEL is an important criterion, it too has drawbacks and uncertainties when used exclusively. Instead, we advocate using both SEL and peak SPL simultaneously to describe the characteristics of a single impulsive sound. This combination is likely to account for those impulsive sound characteristics implicated in injury to fish better than either metric alone.

At the same time, we want to point out that the addition of SEL to the current criteria must be considered provisional. Future research may very likely show that other metrics, either alone or in combination, may provide even better indices of injury than the present choice. Kryter (1985), ANSI (1986), and Hamernik *et al*. (2003) review all the metrics that have been found to correlate with physical injury to humans and other animals. Of these, kurtosis or another metric describing the sharpness of the impulse seem particularly promising for future investigation in fish (see Appendix). Particle motion may also be a relevant parameter especially where behavioral responses are being considered, or where fish lack swim bladders. It is also necessary to consider the effects of repetition of the impulse and/or the rise time of the signal. However, selection of additional, or alternative, metrics can only take place after considerably more research on the effects of sound on fishes. Indeed, there are no studies either in the peer-reviewed or unpublished literature that have even attempted to examine these alternative metrics in studies of the effects of sound on fishes.

In the dual criterion approach adopted here, the SEL value limits the total acoustic energy fish may experience within a single impulsive sound, while the peak sound pressure level protects fish from an especially strong excursion in pressure within the sound impulse. In practice, we recommend that both SEL and peak pressure are measured during pile driving operations and that neither criterion should be exceeded. We note the likely relevance of some means of accounting for the cumulative effects of multiple exposures and the fact that peak pressure fails entirely in this regard.

Selecting Values for the Criteria from the Available Data

The following discussion proposes that interim criteria for pile driving be set at an SEL level of 187 dB re: 1 μPa^2 •sec *and* a peak sound pressure level of 208 dB re: 1 μPa_{peak} in any single strike. The scientific basis for this suggestion is presented below. Note that only one of the studies cited (Caltrans, 2004) used pile driving stimuli. This raises the question of how valid it is to use data from other sources to set criteria for pile driving. The signals produced by explosives and seismic devices have different rise and decay times and higher peak pressures than signals generated by pile driving. Waveforms from dynamite explosions (Yelverton *et al*. 1975) typically have peak pressures several orders of magnitude above that of pile driving signals (see Hastings and Popper, Appendix I, for a fuller discussion) and faster rise times. Thus, the effects of explosives (and possibly seismic activity) are likely to have a greater effect on fish than pile driving signals, and the use of data from these sources to set criteria for pile strikes would be conservative.

In an attempt to select initial interim criteria, we are only able to use four studies for guidance on effects of sound impulses on fish (Yelverton *et al*. 1975; Caltrans, 2004; Popper *et al*., 2005; Popper *et al*., in prep.). The one (unpublished) study that considered pile driving itself, Caltrans (2004) reported that there was no damage to steelhead and shiner surfperch when exposed to multiple pile driving strikes that ranged from 158 to 182 dB (re 1 μPa^2-s) at distances of 23 to 314 meters from the pile. This study showed no statistically significant mortality (i.e.

different than control groups) for SEL's as high as 181 dB (re 1 μPa^2-s) for surfperch and SEL's as high as 182 dB (re 1 μPa^2-s) for steelhead.

In a study investigating the effects of explosives on fish, Yelverton *et al.* (1975 – reviewed in detail in Hastings and Popper, 2005) predicted the likelihood of mortality on fish of different sizes for single explosions. These data were converted by Hastings and Popper (2005) to exposure in terms of SEL (Fig. 2, from Figure 8 of Hastings and Popper, 2005). In Figure 2, the lower curve suggests that the "no injury" level for the very smallest fish (0.01 g) occurs at 193 dB re: 1 μPa^2 •sec. Impulsive sound with SEL below this level has not been found to injure fish, and SEL's above it pose a risk of injury proportional to their level above 193 dB.

Based upon these data, a doubling in exposure would be required to cause an estimated 50% mortality for these small fish (upper curve in Fig. 2). Since the stimulus used by Yelverton *et al*. (1975) was impulsive and had considerable similarity to the stimulus from pile driving (Hastings and Popper, 2005), these values provide some guidance as to potential effects of single strikes of pile driving.

At the same time, since the stimulus in the figure does differ from a pile driving signal, we suggest that a more conservative value is needed for the initial SEL interim criterion. Therefore, we have reduced the levels from Yelverton *et al*. (1975) by an additional 6 dB, resulting in an energy level that is one-fourth that of the value derived from Yelverton (each 3 dB decrease in energy is ½ of the higher value). The resultant criterion becomes 187 dB re: 1 μPa^2 •sec (over a 1-second period) received level for an impulsive sound.

The conservative nature of this value is supported by a recent peer-reviewed study. Popper *et al*. (2005) found no effect on the behavior or physiology of salmonids exposed to seismic air-guns at an SEL of 180 dB re: 1 μPa^2 •s, and only temporary threshold shift (TTS) in two other species. TTS is defined as a reversible physiological fatigue and not injury (Ward, 1997). Fish, like mammals, show complete recovery from TTS and return to normal hearing. The Popper *et al*. (2005) study leads to the suggestion that an SEL somewhat higher than 187 dB would still be conservative as a criterion for injury from seismic impulses.

In addition, Popper and colleagues (in prep.) exposed fish to low frequency sonar for 324 seconds, with an SEL of 188.5 dB re: 1 μPa^2 •s. This long-duration exposure caused some TTS but no injury to two species of fish (including rainbow trout as a surrogate for endangered salmon), but not to a third.

The above data, along with an evaluation of the peer and unpublished literature (reviewed in Hastings and Popper, 2005) also demonstrate that there is absolutely no scientific justification for establishing a peak pressure criterion for injury of 180 dB re: 1 μPa_{peak} for low frequency signals. Indeed, a more reasonable value is likely to be in the range of 205-215 dB re: 1 μPa_{peak} for continuous sounds. This is supported by findings of Popper et al. (2005) who showed that TTS onset (physiological fatigue and not damage) in three species of fish exposed to seismic air-gun pulses occurred within the range of 205-210 dB re: 1 μPa_{peak}. Moreover, the peak pressures recorded in the Caltrans (2004) study which showed no damage to fish at SEL's of over 181 dB re: 1 μPa^2 •s had peak levels in this same range. We recognize that pile driving sounds have different characteristics than the seismic signals, making direct comparisons less than optimal. Using the combined information and acknowledging the differences in stimulus parameters, we propose a value of 208 dB re: 1 μPa_{peak} (*i.e.*, from the low end of the range) as the interim peak pressure criterion for injury to fish from pile strikes.

The suggestion that these values are conservative is also supported by research on barotrauma which has shown that changes in overpressure less than 0.4 times acclimation pressure at rates of change in pressure on the order of 150 $Pa\text{-}sec^{-1}$ do not cause injury to tested species and sizes of physoclistous or physostomous fish (Cada 1990). The 208 dB re: 1 μPa_{peak} criterion is equal to a peak overpressure of 25.1 kPa which would be approximately 0.25 times the acclimation pressure for fish located at the water surface. The criterion becomes increasingly conservative with depth as the overpressure becomes a smaller fraction of acclimation pressure.

Finally, it is important to appreciate the reasoning behind using an exposure over a single pile driving pulse in making decisions on interim criteria *at this time*. There are no data on cumulative effects of pile driving (or any anthropogenic stimulus) on fish, nor is it known whether there is recovery from any effects of pile driving in the intervals between strikes. At the same time, when considering cumulative effects it is not correct to just add the amount of signal to which the animal is exposed since the cumulative effect must include any recovery that takes place in the animal between stimuli (Chen *et al.,* 1999). Thus, if the signals are far apart there is likely to be more recovery from each stimulus exposure than if the stimuli are close together.

Since nothing is known about cumulative effects of pile driving, it is difficult to know whether the effects of sequential strikes are in fact cumulative and, if so, what the relevant factors of exposure relative to damage and recovery are. It is well known that auditory systems show some recovery from trauma over even short periods of time (e.g., Chen *et al*., 1999). As a consequence, if one strike is quickly followed by a second, there may be a cumulative effect since there may be no time for recovery from the first strike. However, if the second strike follows the first by some greater period, the affected system may show some or complete recovery from the effects of the first strike. At this point, we know nothing of the accumulation of effects resulting from strikes that are variably spaced in time. Consequently, predicting the cumulative effects of multiple pile strike exposures remains speculative. It is clear that future research, as discussed in the appendix, will be needed to add the very important variables of multiple strikes and inter-strike intervals into subsequent exposure criteria.

While the SEL criterion given here is for a single strike, we recognize the importance of accounting for the energy contained in multiple exposures. Explicit research on this matter will inform subsequent criteria, but currently it is possible only to suggest some reasonable, and admittedly undocumented, means of approximating SEL summation. For instance, it is likely important that SEL be calculated only during the actual exposure period (including the multi-path energy from each strike) rather than including the silent intervals between strikes. Additionally, a cumulative SEL for multiple exposures, which could be assessed relative to the single strike SEL criterion, should very likely only be determined for conditions in which inter-strike intervals are on the order of seconds rather than minutes or hours.

Additional Issues

An additional issue to consider is the point at which the signals are measured for determination when the criteria are exceeded. The ideal situation is to use received level of the signal as the criterion since this is the actual signal detected by the animal. However, since regulators deal with animals at a wide range of distance from a source, it is impossible to stipulate that recordings be done at every conceivable fish location. At the same time, it is not possible to set criteria as signal levels at the source since these are often difficult (or dangerous) to measure, and the signals at this point are very complex. Thus, it is our recommendation is that a single distance from the source be selected as the point at which measurements are made to determine whether signals exceed criteria. Based on current procedures, we suggest that this distance be 10 meters from the source.

A final issue is a recognition that fish behave differently, and that criteria will ultimately have to be based on fish behavior in addition to sound levels. Some fishes are active swimmers and could be expected to swim through, or away from, areas of highest signal level with exposure to very few pile driving impulses. Other fish tend to be resident in areas and would not move away from impinging sounds, and thus would be exposed to signals for the duration of the pile driving activity. The effects of pile driving on the latter fishes is potentially much greater than upon the former.

Conclusions

Based upon the best available science, and using conservative estimates, we conclude that it is reasonable and appropriate at this point to use a combined *interim* single strike criterion for pile driving received level exposure; an SEL of 187 dB re: 1 μPa^2 •sec and a peak sound pressure of 208 dB re: 1 μPa_{peak} as measured 10 m from the source. We have considered the important issue of cumulative effects of multiple exposures, but emphasize the current absence of any empirical information which would allow cumulative effects to be taken into account. Our expectation is that our interim criteria will change as we obtain more data on effects of pile driving and other sounds on fishes. However, since these values, based upon current data, are *conservative*, they are far more realistic than the value of 180 dB re: 1 μPa_{peak} which is currently in use, and for which there is no scientific justification.

Appendix: Assumptions and Research Needed to Test them

Assumptions

In proposing the interim criteria, we make a number of conservative assumptions about pile driving and the behavior of fish during exposure to the pile driving sound. However, there are few or no data to indicate whether these assumptions are valid, and any deviation from these assumptions will result in lesser effects on fish.

1. Fish have no avoidance reactions nor are they carried by water currents or otherwise affect a change in position (i.e. their position relative to the sound source is static) that would alter their exposure from strike to strike throughout a pile driving operation. They will experience the same received level from every strike required to drive a pile. This is possibly a conservative assumption because it has not been shown, and is probably unlikely, that many fish will remain static during driving of a pile, although how far they can/move between strikes is an open question, and will depend upon the normal "fright behavior" of fish and their swimming speed. They are probably likely to change orientation, actively move away from the area of highest ensonification, or be transported by flow through the more intense regions of the sound field. But, since few data now exist, the conservative approach is to assume that none will move.

2. At a given range, the received level is the same at all depths in the water column and the sound field does not change with the angle of the fish from the pile. Therefore exposure varies as a function of range but not depth or direction from the pile. Sound propagation models for piles are not well developed, particularly for the shallow water environments common to most pile driving work. Sound propagation models developed for other impulsive sound sources, such as explosions and seismic devices, indicate that the sound fields generated by such devices can vary with depth and angle from the source, particularly for shallow water environments.

3. Fish susceptibility to pile strikes in the form of barotrauma is uniform at all depths. This assumption is known to be false. Indeed, the risk of barotrauma is known to decrease as the acclimation depth of exposed fish increases and the overpressure in the sound impulse remains constant. However, the data are currently insufficient to set criteria for all species of interest that incorporate depth of exposure.

4. The SEL criterion is based on exposure of fish weighing 0.01 g, and assumes that such fish are present at every pile driving operation at any season of the year. This is a conservative assumption because in most cases only fish larger than 0.01 g are present, and fish susceptibility to impulsive sound decreases with size (see Fig. 2, upper line).

5. The SEL criterion assumes that sound impulses generated by pile driving strikes have the same potential for injury as the sound impulses generated by explosions (explosions were used as the basis for the initial 193 dB re: 1 μPa^2 •sec estimates of a safe SEL). However, comparison of sound impulses from pile driving and those from explosions show that the latter have a faster rise time, higher peak pressure, and a different frequency spectrum.

6. The pressure criterion uses TTS to define effects, which is conservative given that TTS is considered to be physiological fatigue from which there is complete recovery (Ward, 1997) and permanent threshold shift (PTS) is considered to be injury. TTS and PTS are likely produced by different mechanisms (Liberman and Dodds. 1987; Nordmann *et al*.. 1999). At present, data are insufficient to estimate PTS onset from TTS onset in fish, so TTS is used as a general proxy for injury (very highly conservative).

Recommendations for Research

This document proposes the first round of interim criteria for impulsive sound. To refine these criteria, determine more accurate SEL and peak pressure levels, and determine whether metrics other than these would better index injury to fish, a long-term series of studies is needed. The following list outlines the needed studies. Additional studies are presented in Hastings and Popper (2005).

1. Studies are needed that expose fish to simulated pile driving sound impulses while independently varying pressure and particle motion. Fish should be tested levels up to and exceeding the proposed injury criteria for both peak pressure and SEL.

2. Studies are needed that examine cumulative effects of sound exposure on fish. Factors to be considered include cumulative effects of multiple strikes and the effects of different inter-strike intervals on cumulative effects. In other words, is it appropriate to define a criterion based on one strike or many strikes, and if on many strikes, how many and over what period of time?

3. Studies are required to examine the effect of the temporal characteristics of single impulses, including the rise time, in causing injury or hearing loss in fish. Questions need to be asked regarding effects of different rise times on the trauma imposed upon fish, as well as potential temporary effects such as hearing loss.

4. Hardware and software should be acquired or developed so that operators can monitor pile driving signals in SEL in near real time for both single strike and multiple strike exposures. Ultimately, operators may need to measure particle motion as well.

5. A study should be instituted to investigate the behavioral reactions of non-restrained fish to actual pile driving using visual or acoustic detection methods. This project would test the key assumption that fish have no avoidance behavior.

6. The results of this behavioral study should be incorporated into a model, such as the Acoustic Integration Model (AIM), that models accumulated acoustic exposure for simulated fish moving through an ensonified water column.

7. Data are required to determine which approaches (SEL, Kurtosis, peak pressure, something else) are the best descriptors of effects on fish. These should be considered in terms of effects on behavior, hearing, and barotraumas, It should be recognized that different measures may best describe different impacts on fish.

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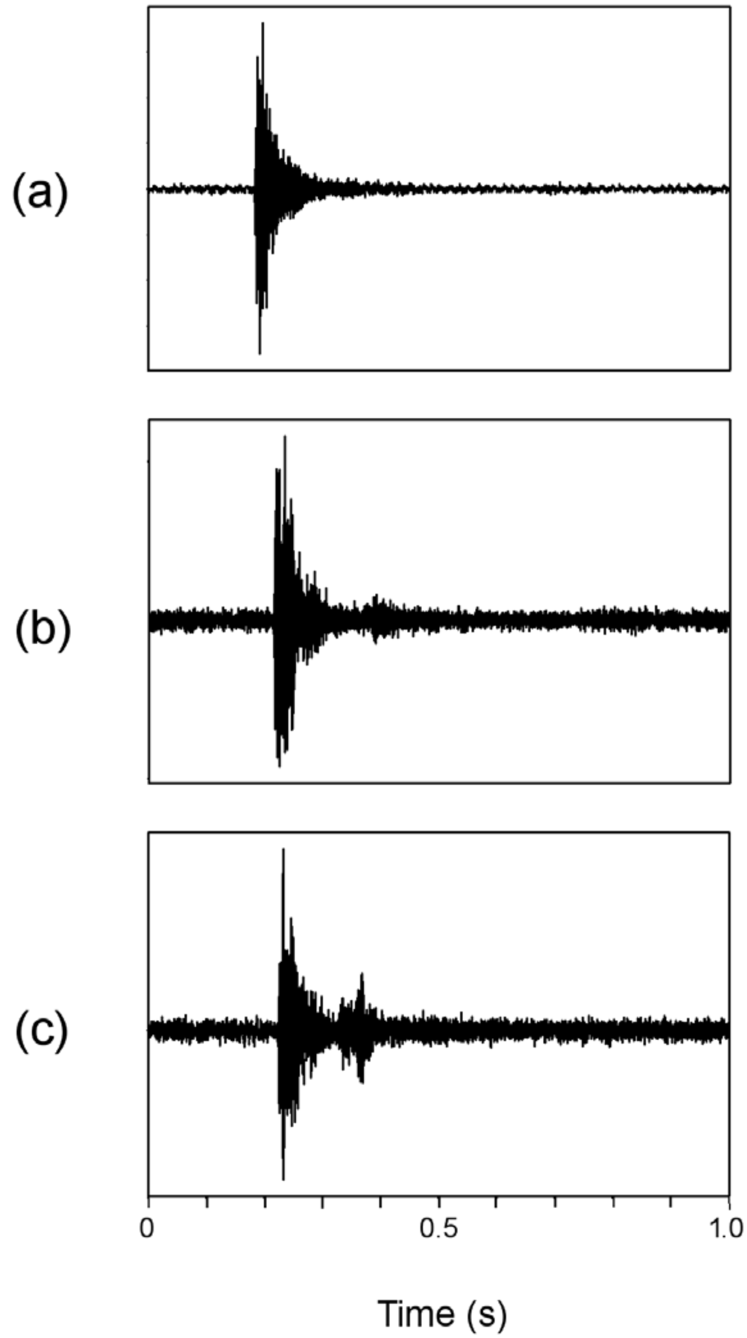

Figure 1. Three impulses from percussive pile driving obtained at different locations in a shallow water environment. a) at 189m, b) at 552m and c) at 906m. Note the short duration, sharp onset, and uneven distribution of energy over time

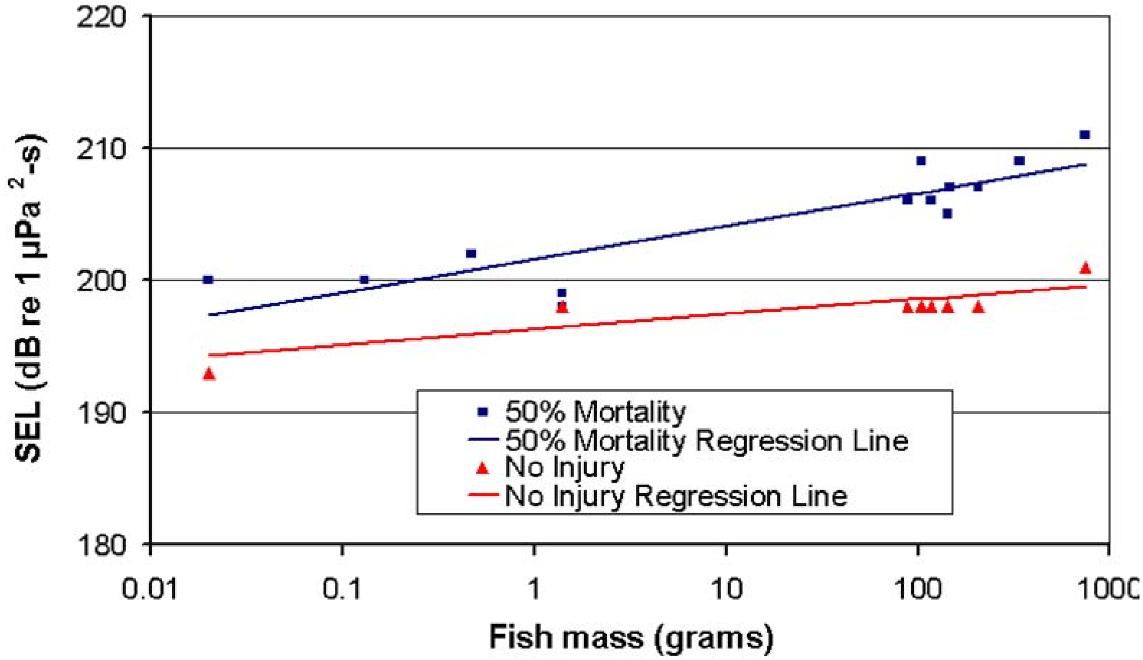

Figure 2: Estimated sound exposure level (SEL) that results in no mortality and 50% mortality based on data for exposures to a single explosive sound as reported by Yelverton et al. (1975) and modeled as an ideal impulse wave as described in Hastings and Popper (2005). (Friedlander waveform as described by Hamernik and Hsueh 1991). (Figure from Hastings and Popper 2005, Figure 8)