THE IMPACT OF PILE DRIVING UPON FISH

A D Hawkins Loughine Limited, Kincraig, Blairs, Aberdeen, UK

1 BACKGROUND

Pile driving is commonplace in construction work, both on land and at sea. A stake, post, sheet, tube or beam made of wood, steel or reinforced concrete is driven into the ground, the bed of a river or the seabed to support a superstructure such as a building, bridge, jetty, pier or the sub-sea foundations for a structure like an oil platform or wind turbine. Percussive or impact pile driving involves the repeated, impulsive striking of the head of the pile, either by the dropping of a weight or by the use of a hydraulic hammer. Energy is transmitted to the pile, driving it downwards. The process is repeated at strike rates of 30-50 times per minute until the pile has reached the required depth. The whole process may take minutes or hours, depending on the size of pile and the substrate conditions. Successive strikes have different energy levels depending on the hammer setting and the substrate material.

The energy applied to the pile is dissipated either as downward movement of the pile or as radiated wave energy. The transient wave pulses last for a fraction of a second and are usually described as changes in sound pressure with time, or as the instantaneous peak sound pressure level (SPL) during the impulse. The peak pressure is the instantaneous maximum or minimum overpressure observed during each pulse and can be presented in Pascals (Pa) or decibels (dB) referenced to a sound pressure of 1 microPascal (µPa). Close to the pile the peak pressures may be very large (> 200 dB re 1 µPa at one metre). The rise time, the time it takes for the waveform to reach the peak level, may be short (values of c 2-40 ms are commonplace). Although the spectrum is dominated by low frequencies (mainly below 1 kHz) a broad range of frequencies is present.

Pile driving often takes place close to rivers, or in coastal waters, where fish are found. In some cases, those fish may be protected by law from disturbance or damage. There are several documented instances of pile driving affecting fish and in some cases causing physical harm to fish. In particular, the driving of very large steel piles associated with the construction and repair of bridges in San Francisco Bay area has resulted in the death of protected species of fish (McKee, 2005). However, despite strong interest in eliminating adverse effects upon fish and other aquatic animals very little is known about the characteristics of the pile-driving stimulus that are responsible for those effects, or how the physical environment may affect the impact upon fish. It has also become apparent that pile driving may affect different species of fish to a differing degree. A recent and rigorous review by Hasting & Popper (2005) has shown how poorly informed we are in terms of assessing the impact of pile driving upon fish.

If man-made sound or any other form of energy is harming aquatic animals, and especially those with legal protection, then it is important to regulate, eliminate or reduce that damage. Regulation usually involves the setting of standards or criteria defining the levels of sound which cause a specified degree of response. The response itself may vary. Individual fish may be injured or killed; their hearing may be affected; or their normal behaviour may be disrupted. Sound exposure criteria may be needed for several different levels of response.

In setting sound exposure criteria it is necessary to have regard to the particular animal or animals being exposed, and their particular sensitivity to sound. It is difficult to extrapolate from one species to another, especially for fish, which are the most diverse of vertebrate animals. It is also necessary to have some knowledge of the sounds received by the fish from the particular type of source, specified by appropriate metrics. Those metrics must themselves be related to a particular response, which in some cases may be serving as a proxy for death or risk of harm to the animal. A level is then set which, if exceeded, will constitute a breach in a regulation.

2 THE SENSITIVITY OF FISH TO SOUNDS

There is much uncertainty over the sensitivity of fish to sounds. There are two problems which must be overcome in designing suitable experiments. The first problem is in deciding whether a sound is detected by the fish. The second lies in presenting a sound with known characteristics.

2.1 CONFIRMING SOUND DETECTION

Although fish may respond spontaneously to the presentation of a sound by changing their behaviour or showing a startle reaction, such responses often diminish with time, especially with captive fish. Fish may habituate to repeated sounds (Hawkins, 1973), making it difficult to present a full range of sound stimuli and fully explore their hearing characteristics. Various training and conditioning techniques have therefore been developed to ensure that fish will always respond to sounds which they can hear. Thus, fish have been trained to press a lever, or swim through an aperture when they hear a sound, in anticipation of a subsequent reward of food. Or the electrocardiograph of the fish is monitored and fish conditioned to show a delay in the heart-beat when presented with a sound, in anticipation of a mild electric shock applied later. Once a fish is trained the sound level can be reduced progressively until the fish no longer responds. The threshold for detection may then be bracketed by raising the sound level if the fish does not respond and reducing it when the fish responds. Although application of these techniques is labour intensive, the thresholds obtained are repeatable and reliably reflect the hearing abilities of the fish. The thresholds are usually determined for pure tones and plotted against frequency to give an audiogram (Figure 1).

Physiological techniques may also be applied to examine the hearing capabilities of fish, where an electrical response is recorded from the nervous system of the fish as a sound is presented. Microphonic potentials may be detected from the auditory hair cells of the ear with an embedded electrode; or an auditory brainstem response (ABR) may be monitored by surface electrodes typically placed on the head of the fish, as done with mammals. It is probably more correct to call the latter auditory evoked potentials (AEPs) rather than ABRs, as they may not be strictly from the brainstem. Thresholds at different frequencies may be determined by reducing the sound level until the potentials can no longer be detected; or frequency response curves may be prepared by comparing the sound levels which yield a given level of electrical response. Typically, the response curves show less dynamic range than those determined by behavioural techniques. Thresholds are often higher, as they may be determined by the ability of the experimenter to distinguish electrical potentials against the background rather than any limitations on the part of the fish. However, such techniques are easy to apply and may be especially valuable for registering major changes in the hearing characteristics of fish exposed to damaging levels of sound.

2.2 SOUND PRESENTATION

Presentation of measured sound stimuli to fish under experimental conditions presents difficulties. Fish are generally most sensitive to low sound frequencies, where the wavelength often exceeds the dimensions of the body of water which contains them. The sounds are presented in a variety of ways, sometimes with immersed sound projectors and at other times with the projectors in air above the water. The sound signals are usually measured with hydrophones sensitive to sound pressure. Sound transmission in small bodies of water is very different to sound transmission in a free sound field. With an immersed projector in a small, open, thin-walled container very large particle motions are associated with quite low sound pressures. With an air loudspeaker above the water the sound field consists almost entirely of sound pressure. Thresholds and audiograms presented by different workers must be treated with great scepticism, especially if the sound fields have not been carefully specified.

Relatively few experiments on the hearing of fish have been carried out under appropriate acoustical conditions. The results from many of the measurements made in tanks, and expressed solely in terms of sound pressure, are unreliable and misleading.

2.3 HEARING ABILITIES OF FISH

Experiments carried out under appropriate acoustic conditions; in carefully calibrated tanks or at depth in much larger bodies of water, have shown that fish hear only over a relatively narrow range of frequencies compared with mammals and birds (Figure 1). Sensitivity to measured sound pressures, even within this narrow range of frequencies, is poor for species, like the dab and salmon, but is much better for some other species. For example, the cod (Chapman and Hawkins, 1973) has a wider frequency range than either the dab (Chapman and Sand, 1974) or salmon (Hawkins and Johnstone, 1978) and at its most sensitive frequencies is limited only by the level of ambient noise in the sea. The catfish (Poggendorf, 1952) has an even wider frequency range. It has been shown that whereas the less sensitive fishes, like the dab and salmon, respond to particle motion (expressed as particle acceleration, particle velocity or particle displacement) rather than sound pressure. Those fish like the catfish, which respond over a wider frequency range, are sensitive to sound pressure.

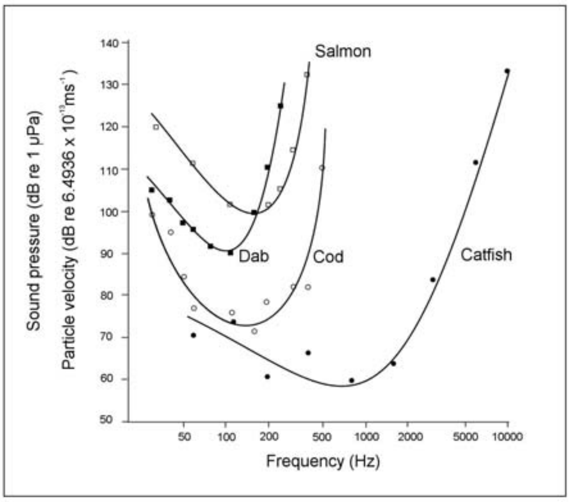

Figure1: Fish audiograms obtained under carefully controlled acoustic conditions. The thresholds for salmon, dab and cod were obtained from a mid-water acoustic range in the sea. Those for catfish were obtained in a carefully calibrated tank

Sensitivity to sound pressure is associated with the presence in some fish of a specialised hearing apparatus which takes the form of a linkage between a gas-containing body and the ear. Thus, in the goldfish there is a chain of small bones between the gas-filled swim bladder and the ear – the Weberian ossicles. In other species, like the herring and the mormyrids, there is an ancillary bubble of gas close to or in contact with the ear. In a few species, like the cod, it appears to be sufficient for the swim bladder to be placed close to the ear (Sand and Enger, 1973).

The ear itself consists of three dense bodies – the otoliths – in contact with sensory hair cells. The principle which operates is that sound moves or vibrates the body of the fish relative to each otolith, stimulating the sensory hair cells. In species like the dab, which lack a swim-bladder, this is the main mechanism for stimulation of the ear by sound. In fish where a gas bubble is present the gas expands and contracts in response to a sound pressure wave, generating particle motions at the ear which are much greater than those in the absence of the gas. The gas bubble effectively transforms pressure into motion, rendering the fish more sensitive to sound (Sand and Hawkins, 1973). Removal of gas from the swim-bladder reduces sensitivity to sound pressure (Sand and Enger, 1973). Placing a gas-filled condom behind the head of a fish lacking a swim-bladder both increases its sensitivity and enlarges the range of frequencies to which it responds (Chapman and Sand, 1974).

There is great diversity in the structure of the ear and its connection with gas-filled bodies in fish. This is perhaps to be expected with more than 30,000 different species. Hearing abilities also vary greatly between species. Some, like the anadromous herrings and menhadens are sensitive well into the ultrasound range. Other hearing specialists can hear sounds up to 3 – 5 kHz; the cod can detect sounds up to about 400 Hz; while the plaice and salmon only detect sounds at frequencies up to 200 Hz.

Most audiograms for fish show sensitivity to sound pressure or particle velocity falling off at lower frequencies (below about 100 Hz). Sand and Karlsen (1986) have confirmed earlier suggestions that the otolith organs behave as nearly critically damped mass-loaded accelerometers. They are inherently sensitive to particle motion. If the audiogram of the fish is expressed as particle velocity or sound pressure, sensitivity will fall off at lower frequencies. If the thresholds are plotted as particle acceleration there is no fall off. A range of species of fish gave a threshold value of about 10-5 ms^{-2} at 0.1 Hz; a sensitivity about 10,000 higher than in humans. Knudsen *et al*., (1997) have also confirmed that salmon show strong avoidance reactions to very low frequency sounds.

Particle motion sensitivity has been shown to be important for fish responding to sounds from different directions. With the high speed of sound propagation in water, time differences between the two ears are very small. Moreover, for animals smaller than the wavelength of a sound any sound pressure differences between the two ears will be minimal. Indeed, with a single gas bladder attached to the ear there is effectively only one receiver. Nevertheless, fish are able to discriminate between spatially separated sources, both in the horizontal (Schuijf *et al*., 1972) and vertical (Hawkins and Sand, 1977) planes. They are also able to distinguish between sources at different distances (Schuijf and Hawkins, 1983). The ability to discriminate sounds from different directions is conveyed through the sensitivity of the otoliths to particle motion. The otolith organs are acting as vector detectors. Ambiguities in determining direction through vector weighing may be resolved by the use of a sound pressure detector as a phase reference (Schuijf, 1976).

In analysing the impact of pile driving and other anthropogenic activities upon fish, the focus has always been on propagated sound pressure, rather than particle motion. Detection of particle motion is, however, important to all fish, including those which are specialised to detect sound pressure.

3 THE STIMULI PRODUCED BY PILE DRIVING

During pile driving sound or vibration propagates not only through the water but also through the ground. Indeed, most of the energy is directed towards the ground and appears either as the downward movement of the pile, or as vibration of the substrate. Three main wave types are generated; compressive, shear and surface waves (Dowding, 2000). Compressive waves, like sounds, produce particle motions parallel to the direction of propagation of the wave. Shear or distortional waves produce particle motions that are perpendicular to the direction of propagation. Surface waves, or Rayleigh waves, are transmitted along the interface between the substrate and the water (and also interfaces between different layers within the substrate) and produce particle motions in a vertical direction and also parallel to the direction of propagation.

Below-ground impacts initially produce compressive waves. These waves propagate outwards in a spherical manner until they intersect an interface or boundary where shear and interface waves are produced (Figure 2). The propagation velocities of compressive, shear and interface waves vary. The velocity is highest for compressive waves, intermediate for shear waves, and lowest for interface waves. As the waves propagate away from the pile they therefore begin to separate. In addition, the waves decay at different rates and this decay is frequency dependent. Interface waves dominate at long transmission distances, the lower frequencies showing the least attenuation. Dowding (2000) points out that interface waves begin surprisingly close to a driven pile – within a few metres. The rate of decay is dependent upon the type of substrate.

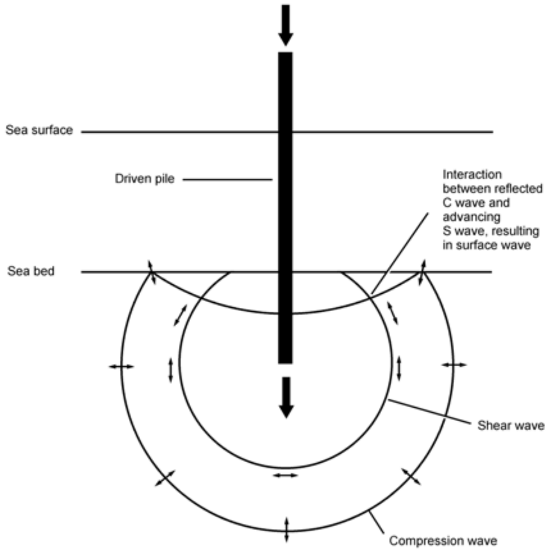

Figure 2: Particle motion generated by a pile driver. After Dowding (2000).

Although very low-frequency sound does not propagate well if it is generated in shallow water, the low frequency interface waves generated by a pile driver may travel considerable distances. Shallow water bodies overlying a substrate where pile driving is taking place will experience high amplitude low frequency particle motion from these interface waves propagating through the substrate. The motion will be transmitted several wavelengths above and below the substrate itself. Significant particle motion may therefore be evident in rivers and lakes at considerable distances from a pile driver.

Although a pelagic (mid-water) fish in a large and deep body of water, like the open ocean, may be primarily affected by the propagated sound waves generated by pile driving, in most realistic situations it is likely to be the interface waves which will have the greatest magnitude and impact upon fish. The fish likely to be affected by pile driving are living in shallow rivers or lakes, or in coastal waters close to the sea bed. In any event, the stimulus received by the fish will be greatly affected by the specific environmental conditions which prevail. Rarely are we dealing with simple expansion of a compressive wave-front under free field conditions. Under these more complicated conditions, and bearing in mind that the fish auditory system is primarily actuated by particle motion, it is especially important to measure particle motion directly – either as the particle velocity or particle acceleration. In practice, such measurements have rarely been performed.

4 METRICS

Some controversy surrounds the metrics to be applied to the stimulus received by the fish from pile driving. It is evident that both sound pressure and particle motion must be measured, and that one cannot be calculated from the other under the assumption that free field conditions prevail (except in the case of pelagic fish in a large body of water). Particle motion is a vector quantity, to be measured in three orthogonal directions, and close to the sea bed and sea surface that motion will predominately be in a vertical direction.

It is evident that pressure waves alone may damage the tissues of fish containing gas bladders. However, if damage to hearing, or to the otolith organ of fish, is being considered then shearing forces between the otolith and its sensory membrane will be especially important. Measurements of peak particle motion and sound pressure (for fish with gas-bladders), down to frequencies well below the natural frequency of the otolith structure, are necessary if clear criteria for damage are to be set. However, the potential of a given stimulus to cause damage will depend not only on its peak or rms level, but also its time-course.

In their report to Caltrans, Popper & Hastings (2005) reviewed the effects of sound (including those from pile driving activities) on fishes. They pointed out that the accumulation of energy over time may be significant in assessing the potential effects of exposure to transient sounds on fish and other aquatic animals. They considered that Sound Exposure Level (SEL) had a particular value as a metric for a single acoustic event. Because all SEL measurements are normalized to a one second time interval, SEL may be used to compare the energy content of different exposures to sound. SEL is calculated by summing the cumulative pressure squared (p^2) over time and indicates the energy dose. The unit for SEL is dB re $1\mu Pa^2.s$. Hastings & Popper also point out, however, that the calculation of SEL inherently assumes a plane wave in which the acoustic energy flux (or intensity) is directly proportional to p^2. Thus in many underwater environments, where the relationship between acoustic pressure and particle velocity is more complex, the total energy flux will *not* be equivalent to SEL.

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 US, NOAA's National Marine Fisheries Service, initially set in managing pile driving was a peak sound pressure of 180 dB re: 1 μPa peak. While this value is often cited, the scientific basis for this value is not clear (see discussion in Hastings and Popper, 2005). Application of the peak pressure criterion on its own not only fails to account for the temporal characteristics of a single impulse (the rise time and the variation in peak or rms pressure within the impulse) it also fails to take account of the cumulative effects upon the animal of multiple strikes from pile driving. For these reasons a number of different metrics must be considered when setting protective criteria.

Popper *et al*. (2006) developed new interim criteria for the onset of injury to fish from pile driving. A dual approach was adopted which included an interim single-strike criterion for SEL combined with an interim criterion for peak sound pressure level. The authors pointed out, however, that there were other characteristics of a sound which might have also an influence upon injury. The "sharpness" of a sound (e.g., ratio of peak to rms pressure, or "crest factor") and its rise time might be especially important. In addition, the repetition of the sound and accumulation of energy over multiple exposures may have an additional effect. With multiple strikes, receipt of further sound impulses might occur before organs and tissues had recovered from the impact of the first. Popper *et al*. (2006) proposed that interim criteria for pile driving be set at an SEL level of 187 dB re: 1 μPa^2 .s and a peak sound pressure level of 208 dB re: 1 μPa for any single strike.

Concern over the cumulative effect of repeated strikes has subsequently resulted in changes to these interim criteria. Consultants to the California Department of Transport concluded that cumulative SEL criteria should govern impact conclusions and mitigation requirements for most pile driving operations. A recommended cumulative SEL criterion in the range of 183 dB-SEL to 189 dB-SEL was considered more stringent than a single strike criterion. An auditory tissue damage criterion of 189 dB-SEL was proposed where fish were greater than 2 g in weight. Where very small fish (<0.5 g) were present the cumulative 183 dB-SEL criterion would prevail.

These interim criteria, expressed entirely in terms of sound pressure, are relevant where fish injury or damage to auditory tissues in fish with swim bladders is being considered. They are not appropriate if fish behaviour is the main concern. In many practical instances pile driving is taking place in shallow water or in other circumstances where substrate transmission will play an important role in determining the stimulus which reaches the fish. Many of the fish concerned are salmonid and other species which will be especially sensitive to low frequency particle motion. At present we do not know what levels these particle motions will reach, or what their effects upon fish will be. Further research is necessary.

5 BIOLOGICAL CONSEQUENCES OF PILE DRIVING

It is evident that several different sound exposure criteria will be needed for fish. At its most extreme, pile driving may cause physical damage to the body tissues of fish. Damage to the auditory tissues may be monitored relatively easily (by observing damage to the sensory hair cells) and that is the criterion chosen by Popper *et al*. (2006). Another criterion which has been put forward is hearing loss due to temporary threshold shift (TTS), which can be monitored as a diminution of auditory evoked potentials (AEPs). It can be argued that TTS may act as a proxy for change in the behaviour of the animal. In many instances, however, there will be concern that less easily observed, but nevertheless severe changes in behaviour may be occurring. The movements of migratory fish may be affected, preventing them reaching their spawning grounds. Fish may deterred from feeding, affecting their growth and reproductive success. There is a need to set criteria for true behavioural responses by fish. Establishing these behavioural criteria will require a more thorough knowledge of the range of responses shown by fish to sounds in the natural environment. Some responses will be transient, including startle responses or mild escape responses. They may not have a lasting impact upon the fish. Others, including cessation of feeding, disruption of migration or displacement from a preferred location affect key biological functions and may have more severe or even permanent effects both upon individual fish and upon fish populations.

6 CONCLUSIONS

Much of the work to date on the hearing abilities of fish has been performed under poor acoustic conditions and must be treated with great scepticism. In particular, the sensitivity of many, if not all, fish to particle motion has largely been ignored. Further investigation of the impact of large particle motions upon fish is especially important.

When pile driving is carried out, sound or vibration propagates not only through the water but also through the substrate. Compressive, shear and interface waves are generated which can result in large particle motions being generated at a great distance from the source. Conventional analysis of the pile driving stimulus as a sound pressure wave propagated through water does not adequately describe the signal which will be received by fish inhabiting lakes, rivers and shallow coastal waters. Direct measurements of these particle motions are needed.

Although much attention has been devoted to establishing criteria for auditory tissue damage in fish as a result of pile driving, those criteria have been expressed only in terms of measured sound pressures. Such criteria only apply to fish living under idealised conditions and can rarely be applied to fish exposed to real pile driving operations. Although their development has taken understanding forward in terms of considering the temporal aspects of the stimulus, and the cumulative effects of repeated strikes, they have still to address the problems experienced by the majority of fish affected by pile driving. New criteria, expressed in terms of both sound pressure and particle motion, are required.

Increasingly, regulators will be considering the impact of pile driving and other noisy activities not only in terms of injury or auditory tissue damage but also in terms of disruption to the behaviour of fish. Sound exposure criteria will be required which consider those changes in behaviour which will have a lasting impact upon individual fish and populations.

REFERENCES

1. D.C. McKee. Pile driving and bioacoustic impacts on fish. In: Proceedings of the 2005 International Conference on Ecology and Transportation (eds. Irwin CL, Garrett P, McDermott KP). Center for Transportation and the Environment, North Carolina State University, Raleigh, NC: 24-25.

2. M.C. Hastings and A.N. Popper. Effects of sound on fish. California Department of Transportation Contract 43A0139 Task Order 1, January 2005. www.dot.ca.gov/hq/env/bio/files/Effects_of_Sound_on_Fish23Aug05.pdf

3. A.D. Hawkins. The sensitivity of fish to sounds. Oceanogr. mar. Biol., Annual Review. 11: 291—340, 1973.

4. C.J. Chapman and A.D. Hawkins. A field study of hearing in the cod. In J. comp. Physiol., 85: pp. 147-167, 1973.

5. C.J. Chapman and O. Sand. Field studies of hearing in two species of flatfish. In Comp. Biochem. Physiol., 47A: pp. 371-385, 1974.

6. A.D. Hawkins and A.D.F. Johnstone. The hearing of the Atlantic Salmon. In J. Fish. Biol., 13: pp. 655–604, 1978.

7. D. Poggendorf. Die absoluten Hörschwellen des Zwergwelses. In Z. vergl. Physiol., 34: pp. 222-257, 1952.

8. O. Sand and A.D.Hawkins. Acoustic properties of the cod swimbladder. In J. exp. Biol., 58: pp. 797-820, 1973.

9. O. Sand and P. S. Enger. Evidence for an auditory function of the swimbladder in the cod. In J. exp. Biol. 58: pp. 405-414, 1973.

10. O. Sand and H.E. Karlsen. Detection of infrasound by the Atlantic cod. In J. exp. Biol., 125: pp. 197–204, 1986.

11. F.R. Knudsen, C. B. Schreck, S. M. Knapp, P. S. Enger and O. Sand. Infrasound produces flight and avoidance responses in Pacific juvenile salmonids. In J. Fish Biol., 51: pp. 824-829, 1997.

12. A. Schuijf, J. W. Baretta and J. T. Wildschut. A field investigation on the discrimination of sound direction in *Labrus berggylta*. In Neth. J. Zool., 22: pp. 81-105, 1972.

13. A.D. Hawkins and O. Sand. Directional hearing in the median vertical plane by the cod. In J. Comp. Physiol. A., 122: pp. 1-8, 1977.

14. A. Schuijf and A.D. Hawkins. Acoustic distance discrimination by the cod. In Nature, 302: pp. 143–144, 1983.

15. A. Schuijf. The phase model of directional hearing in fish. In Sound Reception in Fish (eds. A. Schuijf and A. D. Hawkins): pp. 63-86. Elsevier, Amsterdam, 1976.

16. C.H. Dowding. In Construction Vibrations. Prentice Hall, Upper Saddle River, 610 pp., 2000.

17. A.N. Popper, T.J. Carlson, A.D. Hawkins, B.L. Southall and R.L. Gentry. Interim Criteria for Injury of Fish Exposed to Pile Driving Operations: A White Paper. Caltrans. May, 2006. www.dot.ca.gov/hq/env/bio/files/piledrivinginterimcriteria_13may06.pdf