The Underwater Sound Field from Impact Pile Driving and Its Potential Effects on Marine Life

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The increased use of impact driving to install steel piles for in-water construction has with it a responsibility to assess the possible effects of related underwater noise on aquatic life.

Introduction

Impact pile driving is a method used to install piles for marine and inland water construction projects using high-energy impact hammers. The installation of hollow steel piles in this manner can produce extremely high sound levels in the surrounding waters (as well as in the air). Given the large-scale development of offshore wind in European waters and plans for such development in US waters, along with an increasing need for upgrades in the in-water infrastructure, there is a growing concern about the potential effect of construction-related underwater sounds on marine mammal and fish populations.

The impact hammers (**Figure 1**) must accommodate piles with diameters typically ranging from ~0.5 to 6.5 m, with increasing hammer energy required for increasing pile diameter. Both full-scale observational (Robinson et al., 2007; Dahl and Reinhall, 2013) and detailed (Zampolli et al., 2013) numerical studies suggest that ~0.5 % of this hammer energy goes into acoustic energy that ultimately gets into the water column. Examples of peak underwater sound pressure levels (see Met-

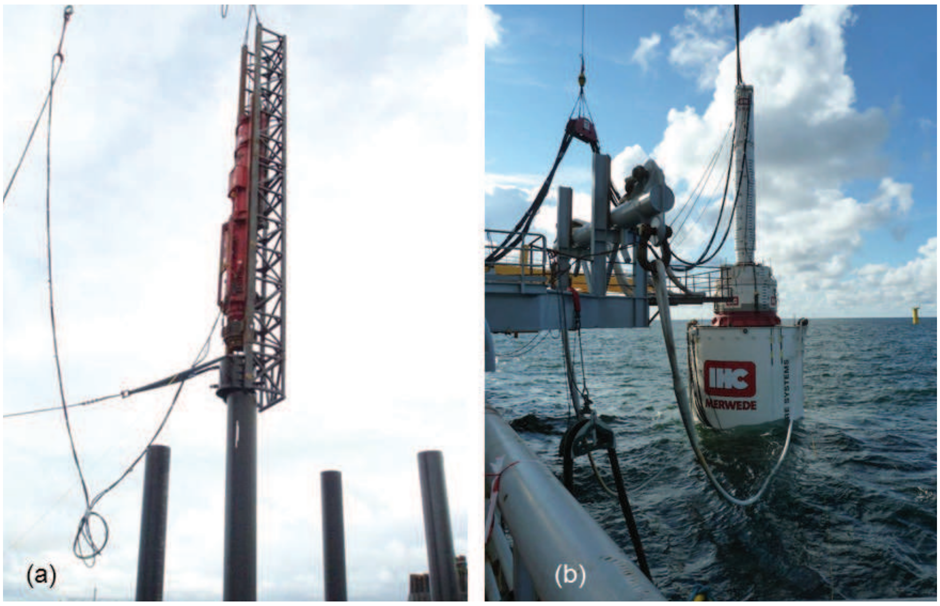

Figure 1. (a) Typical hammer for impact driving of ~1-m-diameter steel piles often used in bridge and ferry dock construction, delivering a hammer energy of ~200 kJ. (b) Typical hammer for impact driving of ~4-m-diameter and larger steel piles larger used in construction of offshore wind turbine foundations in the North Sea, delivering a hammer energy of ~2,000 kJ. The piles are enclosed in an IHC Noise Mitigation System.

rics) measured from impact pile driving are on the order of 220 dB re 1 µPa at a range of ~10 m from 0.75-m-diameter piles (Reinhall and Dahl, 2011) and on the order of 200 dB re 1 µPa at a range of 300 m from piles that are 5 m in diameter (Lippert and von Estorff, 2014b). Loud impulsive underwater sounds can potentially have physiological effects on fish (Halvorsen et al., 2012a,b; Casper et al., 2013a,b) and on marine mammals (Southall et al., 2007; Lucke et al., 2009; Kastelein et al., 2015). At greater distances from the source or at lower sound levels, the potential effects include masking of biologically important sounds and/or the effects on behavior (Southall et al., 2007; Popper et al., 2014). Therefore, both environmental monitoring and noise mitigation efforts invariably accompany impact pile driving particularly in biologically sensitive underwater habitats.

The Predominant High-Pressure Underwater Noise Field

There is both theoretical consensus and experimental evidence that the predominant high-pressure underwater noise field from impact pile driving on hollow steel piles can be attributed to a "Mach wave" effect (Reinhall and Dahl, 2011; Dahl and Reinhall 2013; Zampolli, et al., 2013; Lippert and von Estorff, 2014a). This effect arises from a rapidly moving sound source generated by a deformation of the pile wall that is traveling down the pile on hammer impact. This deformation, or bulge, is the consequence of the Poisson effect where a material compressed in one direction (here vertically by hammer impact) expands in another direction, in this case producing the momentary outward swelling (**Figure 2**) that behaves as a sound source. The downward traveling speed of this sound source, c_S, although mildly dependent on sound frequency, is approximately equal to the longitudinal sound speed of the steel material, $\sqrt{Y/\rho}$, where Y and ρ are the material Young's modulus (~ 200 GPa) and density (~7,850 kg/m^3), respectively. These values put c_S equal to 5,050 m/s, and this value that can be indirectly observed by measuring the angle of the Mach cone that develops in the water where the sound waves travel at sound speed, c_W, ~1,500 m/s.

Although highly idealized, a notional idea of the Mach cone is readily obtained by the sketch (**Figure 2**) of the wave fronts expanding in time from a moving sound source or bulge in the pile wall. The source that moves successively down the pile is shown in two arbitrary positions: first in red and then at a time delay L/c_S (in seconds) in blue, where L is the separation between these two arbitrary positions. The wave fronts from the earlier upper source emission (red) expanded farther out in the water than those emitted from the later lower source emission (blue). The progression of wave fronts from all positions up to and including the latest are shown in black. Addition of these wave fronts form a Mach cone centered around the pile axis (only one side shown here). This simple construction also illustrates how the coherent addition of a line distribution of time-delayed sources, such as the red and blue sources in **Figure 2**, generates a sound field with a quasi-planar wave front at angle θ with respect to the horizontal line. Imagining a vertical line array of hydrophones placed in such a sound field (black dot in **Figure 2**), this array would detect the sound first on the shallow hydrophones and later on the deeper hydrophones. The array could also measure the angle, $\theta = \sin^{-1} c_W/c_S$, which, depending on the precise values of c_W and c_S puts θ in the neighborhood of 15 - 19°.

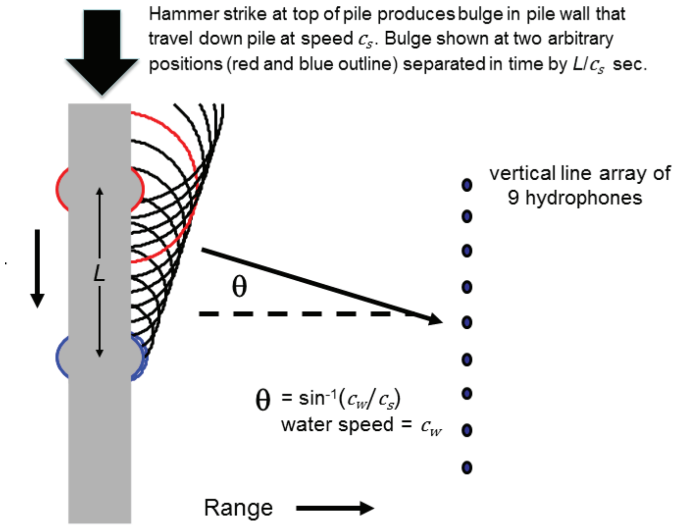

Figure 2. Bulge in the pile wall (red lines) as result of impact hammer strike (symbolized by large arrow) and subsequent compression of pile material. The bulge, which acts as a source of sound, travels successively down the pile at speed $\mathbf{c_S}$ *and at* $\mathbf{L/c_S}$ *s later (blue line). Wave fronts from the earlier emission (red) and later emission (blue) are shown with all prior emissions (black lines); they add up to form a quasi-planar wave front characterized by angle θ. This angle and the associated time delays can be measured with a vertical array of 9 hydrophones (circles).*

A pressure-time series versus depth taken from such vertical line array during impact pile driving (**Figure 3**) clearly shows the expected delay with the measurement depth of the very strong arrival (first peak in the yellow shaded area) that can be attributed to the kind of quasi-planar wave front illustrated in **Figure 2**. Beam-forming analysis on the yellow shaded portion of these data (Dahl and Reinhall, 2013) gives angle θ as 18°. This also establishes an important range scale, $R^* = H/\tan\theta$, where H is water depth at the pile installation, setting R^* to ~3 water depths. For ranges less than R^* the underwater sound field varies greatly with the measurement

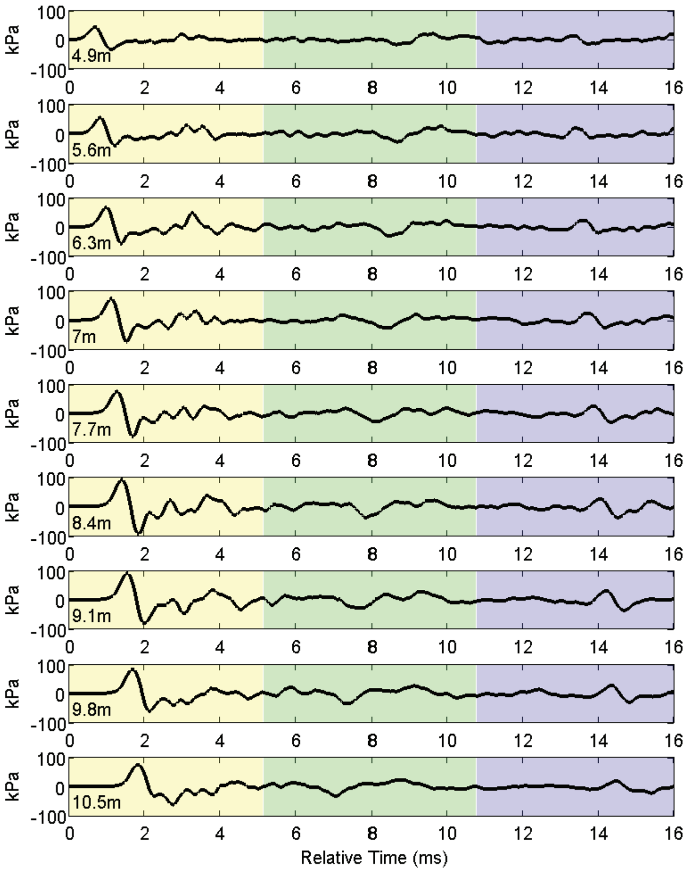

Figure 3. Sound pressure-time series for the radiated underwater noise measured at a 12-m range from a pile undergoing impact driving. Three phases are identified by the different shadings. Hydrophone measurement depth is given at the beginning of each time series. Reprinted from Dahl and Reinhall (2013).

depth, with the greatest variation occurring at range/R^*= 0.5 (Dahl et al., 2012). The next area (green shade) corresponds to the effect of reflection from the bottom of the pile, with the reflected bulge now traveling up the pile wall. A different propagation angle, θ, now results, and this is directed upward and is of greater magnitude (as can be inferred by the reduced time delays between vertically separated hydrophones) because the sound speed in the sediment is higher than the sound speed in water.

The last area (blue shade) corresponds to the effect of a reflection from the top of the pile that again produces a downward-traveling bulge of the pile wall acting as a moving source of sound. The time difference, T, between the peaks in the yellow- and blue-shaded areas is ~12.6 ms, which corresponds to the round-trip travel time of the shape disturbance (bulge) for this particular pile with a length of 32 m. This defines a characteristic frequency of $1/T$ or ~80 Hz, the effect from which can be observed in a depth-averaged energy spectral density of the underwater noise from impact pile driving, where the majority of acoustic energy is also seen to be characterized by frequencies less than ~2,000 Hz (Reinhall and Dahl, 2011). The sequence shown in **Figure 3** will repeat but at a much lower amplitude and will become difficult to distinguish from other noise emissions associated with pile vibrations (Zampolli et al., 2013) and reflections from nearby structures. However, for measurement ranges greater than a few water depths, H, the ensuing reflections from the sea surface and the seabed further confuse the picture.

Metrics

Figure 4 shows the acoustic pressure-time series measured at two ranges for the same pile strike (76-cm-diameter steel pile), with such strikes typically repeated about every 1.5 s. The acoustic pressure is here plotted in kilopascals (1,000 Pa), displaying all the details of the received signal; because many details of the signal are highly variable and probably irrelevant with respect to the effects on marine life, the signals are quantified in terms of single-number acoustic metrics expressed in decibels.

The first key metric is peak sound pressure level ($L_{p,peak}$), defined as the level of the maximum of the absolute value of the sound pressure signal in a specified time interval. For example, were the maximum value, $|p|_{max}$, be 1 kPa (i.e., 10^9 μPa), then the decibel equivalent, $20\log_{10}(|p|_{max}/p_{ref})$, equals 180 dB re 1 μPa. There is limited information retained in such an estimate of pressure, given that it is based on just a single time sample over the duration of the signal. The observed peak sound pressure values determined at the two measurement sites are identified by the circles in **Figure 4,** and it is noteworthy that for the same pile strike, the peak was initially positive at the closer range and negative at the farther range measurement. A second "peak" metric that is sometimes used is the peak-to-peak sound pressure level, which gives the level of the difference between the highest and the lowest value sound pressure signal in a specified time interval.

A more robust metric involves the time integral of pressure squared (the "signal energy"). In an ideal acoustic propagating wave, this signal energy is related to the acoustic energy through the characteristic acoustic impedance of the medium in which it is propagating, but in real conditions, this relationship is much more complex. The decibel equivalent of this integral result is the sound exposure level (SEL) in decibels re 1 $\mu Pa^2 \cdot s$. The integral can be taken over the duration

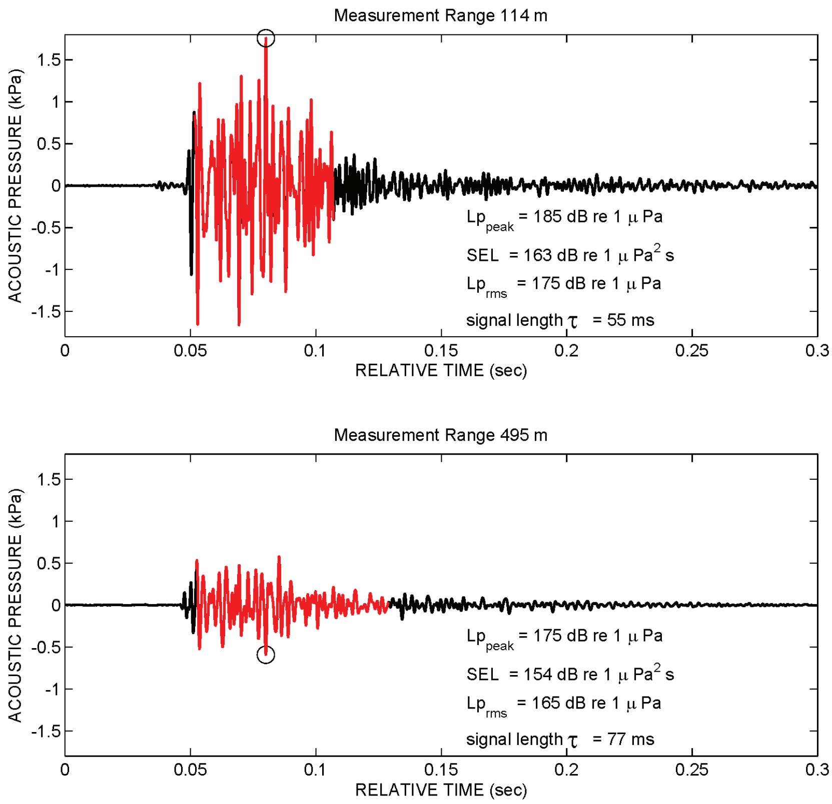

Figure 4. *Sound pressure-time series for the radiated underwater noise from a pile undergoing impact pile driving measured at a 114-m (top) and a 495-m (bottom) range with the same signal. Red segments represent the time segment within which 90% of the signal energy resides. Circles identify the maximum absolute value of pressure.*

of a single strike (SEL_{ss}) as well as cumulated over multiple strikes (SEL_{cum}). This is a useful metric to assess cumulative noise exposure and allows for the comparison of sound with a varying duration, giving an indication of the total energy received by an organism over the course of an event or over a day (Popper and Hastings, 2009).

Dividing the signal energy by signal duration (τ) gives the mean square pressure from which arises the root-mean-square pressure on taking the square root, with the decibel equivalent being the root-mean-square sound pressure level ($L_{p,rms}$) metric in decibels re 1 μPa. A meaningful definition of the signal duration is the time segment of the signal within which 90% of the signal energy resides (Madsen, 2005). This segment begins when the cumulative signal energy exceeds 0.05 of the total signal energy and ends when it reaches 0.95 of this value; hence the term "90% of signal energy." It is important to observe that SEL is immune to changing τ; in contrast, computing the $L_{p,rms}$ metric using a different τ changes its value, usually in a nonmeaningful way.

Potential Effects on Marine Mammals and Fishes

It is necessary to understand the potential effects of the sound produced during pile driving on marine mammals and fishes to determine whether mitigation is developed to protect the animals from exposure to high-energy sounds. The best way to determine the degree of mitigation required is to understand how various sound levels affect animals. Mitigation is not necessary when there is sufficient evidence that the animals are not affected. This also applies to how much mitigation is required for a particular project. If it is known that a certain level of sound is being produced and that this signal level is only 5 dB above the level where no effects are seen, then there is no need to have 10 or 15 dB of attenuation of the signal. The following sections provide a global overview of the current knowledge of the potential effects on marine mammal and fish species and of the status of current protective regulations.

Potential Effects on Marine Mammals and Protective Regulations

The intense sound impulses of the impact piling are likely to disrupt the behavior of marine mammals at ranges of many kilometers (Tougaard et al., 2009; Brandt et al., 2011) and have the potential to induce hearing impairment at close range (Madsen et al., 2006). In environmental impact assessment studies, it is becoming increasingly clear that the most significant population consequences are likely to occur as a result of a behavioral response rather than direct physical injury or mortality due to the sound (Ellison et al., 2012). The implies that the focus has turned toward assessing a longer term impact of the behavioral responses through changes in energy costs related to food-foraging costs, survival, or fecundity (Bailey et al., 2014). However, because of a lack of data, the current impact assessment methods are still largely based on expert judgment (Thompson et al., 2013; Harwood et al., 2014).

An assessment of the effects of piling sound on marine mammals starts with determining the number of animals that may be exposed to sound levels that are likely to cause injury or behavioral disturbance. This requires information on the sound distribution around the pile, on the abundance of animals in the area, and on threshold levels above which sound exposure might have a significant impact on protected animals. The initial scientific recommendations for marine mammal noise exposure criteria proposed by Southall et al. (2007) summarized the (limited) state of the art of the knowledge on noise-induced physical injury and behavioral response. Because of the urgent need for this kind of information for permitting offshore activities, the proposed criteria are widely used in impact assessment studies despite the many caveats in this work.

The most abundant cetacean in the European coastal waters is the harbor porpoise (*Phocoena phocoena*). There is substantial evidence that harbor porpoises are easily disturbed by man-made sounds in coastal waters where offshore wind farms are being developed (Tougaard et al., 2015). During exposure to playback pile-driving sounds in a quiet pool (Kastelein et al., 2013), the respiration rate of a porpoise appeared to increase at a threshold SEL_{SS} of 127 dB re 1 μPa²·s. When exposed to a SEL_{SS} of 145 dB re 1 μPa²·s, the animal tried to avoid the sound by regularly jumping out of the water, whereas it never jumped during the baseline periods without exposure. (It should be noted, however, that one must be very cautious in extrapolating from behavioral results in the laboratory, even in very large enclosures, to how an animal will behave when it is in the wild and able to move around freely [Popper et al., 2014]).

These findings are in line with German field studies, which found their way into legislation. The German government issued a *Concept for the Protection of Harbour Porpoises from Sound Exposures during the Construction of Offshore Wind Farms in the German North Sea* (BMU, 2014) that states that it is plausible to assume that avoidance and flight behavior are likely to occur at exposure to a received SEL_{SS} of 140 dB re 1 μPa²·s. Moreover, the German authorities regard a temporary hearing loss (temporary threshold shift [TTS]) in an animal as injury. Therefore, based on the findings of Lucke et al. (2009), the German regulations further established noise-induced injury prevention thresholds that call for a SEL_{SS} not to exceed 160 dB re 1 μPa²·s and a peak-to-peak sound pressure level not to exceed 190 dB re 1 μPa at a distance of 750 m from the pile. It is assumed that complying with these criteria will reduce the avoidance distance to ~8 km.

The German regulation has triggered the development of various noise mitigation systems such as bubble curtains, screens, or cofferdams (Bellmann, 2014) that reduce the sound output of the pile by at least 10 dB. Other North Sea countries apply different regulations. The United Kingdom requires marine mammal observers to visually, and sometimes acoustically, monitor an exclusion zone around the pile to ensure the absence of marine mammals. In The Netherlands, no piling may occur in the seasons with the highest abundance of sensitive species. And there is an obligation to deter animals from the vicinity of the pile by applying acoustic deterrent devices before the actual start of the piling or by a "soft start" of the pile driving at a lower hammer energy (Robinson et al., 2007) to avoid permanent hearing loss (permanent threshold shift [PTS]) that might occur up to distances of ~1 km from a typical North Sea wind turbine foundation piling without noise mitigation.

Potential Effects on Fishes and Protective Regulations

The issues discussed for marine mammals parallel those for fishes, although knowledge of the effects and the degree of research currently underway is far less than that for marine mammals. Although fishes are starting to be written into regulations, the only promulgated numbers for the protection of fishes were developed in 2008 by the US National Marine Fisheries Service (NMFS) for migrating salmon on the US west coast (Stadler and Woodbury, 2009).

NMFS interim criteria involve dual criteria for both cumulative sound exposure and peak sound pressure (reviewed by Popper and Hastings, 2009). The intent of the dual criteria was that if either value was exceeded, construction could potentially stop until a "recovery period" of 12 h was reached (Stadler and Woodbury, 2009). The actual levels were a SEL_{cum} of 187 dB re 1 μPa²·s for fishes above 2 grams and 183 dB re 1 μPa²·s for smaller animals. The peak sound pressure level was 206 dB re 1 μPa. In each case, these levels were considered to be that for the *onset* of physiological effects and that lower levels would not cause any effect.

These interim criteria, however, were based on very limited data, most of which were not peer reviewed (Popper and Hastings, 2009). The lack of data generally resulted from an inability to control the pile-driving sounds to which fish were exposed because the studies were done with caged fish near actual driving operations (Popper and Hastings, 2009). To bring pile-driving sounds under control and to bring them into the laboratory, a device was developed that enabled exposing animals to a far-field signal in a small chamber (Halvorsen et al., 2012a,b; Casper et al., 2012, 2013a,b).

About a half percent of the hammer impact energy goes into waterborne acoustic energy.

In these studies, five species were exposed to a controlled number of pile-driving strikes at known sound levels to produce a predetermined SEL_{cum}. The investigators examined the fish for external and internal physiological effects such as hematomas (bleeding), damage to the swim bladder (a bubble of air in the abdominal cavity of most), and damage to internal organs using standard necropsy (autopsy) methods.

The five fish species differ in life style and anatomy (chinook salmon, Nile tilapia, hybrid striped bass, hogchoker, and lake sturgeon), and four species showed the same general effects and onset of damage (Halvorsen et al., 2012a,b; Casper et al., 2013a,b). The only species that showed no effect was the hogchoker, a species without a swim bladder (Halvorsen et al., 2012b). The investigators concluded that the causal factor producing internal damage was the repeated motion of the walls of the swim bladder in response to the impulsive pile-driving signals. Because the hogchoker has no swim bladder, nothing would move internally in the body and thus no tissues would be damaged. Further supporting this hypothesis is that the major internal damage was to organs most closely positioned to the swim bladder, such as the kidney, gonads, and spleen (Halvorsen et al., 2012a,b).

Based on a quantitative analysis of the effects encountered with different SEL_{cum} values, it was found that the onset of physiological effects never occurred until the SEL_{cum} was above 203 dB re 1 $\mu Pa^2 \cdot s$ and in most species above 207 dB re 1 $\mu Pa^2 \cdot s$. These levels are supported by the results in studies by other groups for both larval (Bolle et al., 2012) and juvenile (Debusschere et al., 2014) fishes. These results led to the conclusion that the SEL_s proposed earlier need to be changed and that it takes substantially more acoustical energy to damage fish tissues than assumed in the current interim regulations.

These data, and current guidelines, focus on the physiological effects, something only likely to occur if the fish are close to a sound source and stay there long enough to be exposed to a sufficient SEL_{cum}. However, because most (although not all) species are likely to move away from a sound source that is too loud, physiological damage is not of greatest concern. What is of far greater concern is, as for marine mammals, the behavioral response that could result in fishes moving from a breeding or feeding site or masking the ability of a fish to hear biologically important sounds ranging from the overall acoustic scene (or soundscape) (Fay and Popper, 2000) to sounds produced by the same species.

However, almost nothing is known about fish behavioral responses to pile driving or, for that matter, to any man-made sound, and it is thus not possible to provide guidance as to potential behavioral effects. In part, the lack of data results from the difficulties inherent in examining fish behavior in the wild (Hawkins and Popper, 2014; Hawkins et al., 2014a). Unlike marine mammals that come to the surface on a regular basis and are large enough for tags, fishes must be observed underwater and even though some tags are available, they only work over short distances and near to underwater receivers. It is possible to use sonars (Hawkins and Popper, 2014; Hawkins et al., 2014b) but only close to the fish where individuals can be identified and their behaviors observed. Another issue is the extraordinary diversity of fishes (more than 32,000 species), in terms of anatomy, physiology, ecology, and behavior. Thus, the likelihood of "one number fitting all species" is probably nil (Hawkins and Popper, 2014; Hawkins et al., 2014a; Popper et al., 2014). Moreover, how fish respond to a particular sound is likely to vary based on the motivational state of the animal at time of sound exposure, further complicating any attempts to define criteria levels for potential behavioral effects.

An approach to setting new interim guidelines for fishes (and sea turtles) came in a recent set of guidelines (Popper et al., 2014). This report evaluated all the data on the effects on fish hearing up to 2013 and presented a set of tables for the potential effects from different types of sound sources, including pile driving. These guidelines are considered interim, and there is the expectation that the criteria will change as there are more data. However, the report does suggest the adoption of the criteria proposed in the aforementioned studies by Halvorsen, Casper, and colleagues.

Conclusions

There is little debate concerning the high level of underwater sound associated with impact pile driving. Further details on the mechanism of sound generation remain to be uncovered, particularly on quantifying the influence of the seabed on the sound spectrum and level. However, large challenges remain on understanding the potential effects on marine mammals and fishes and thereby improving sound exposure guidelines for all aquatic life. The successful completion of these challenges will be pivotal in future policy decisions.

Biosketches

Peter Dahl is with the University of Washington where he is a senior principal engineer at the Applied Physics Laboratory, and professor in Mechanical Engineering. His primary research field is underwater sound, for which he and his students have conducted numerous at-sea experiments and developed interpretative models, to address basic and applied problems of interest to the navy. He is also actively involved in research on generation and propagation of high-level underwater sound such as from pile driving and explosives, and also consults on these issues through info@hydrodb.com. He recently completed serving as Vice President of Acoustical Society of America.

Christ de Jong is a senior scientist in the Acoustics and Sonar department of the Netherlands organization for applied scientific research TNO, where he is working in the fields of underwater acoustics and ship acoustics. He has been involved in various projects for the Royal Netherlands Navy aimed at managing the underwater acoustic ship signatures. Since 2007 his field of interest has expanded into studies of the environmental impact of anthropogenic underwater sound: (standardization of) measurement methods, characterization of sound sources and studies of the impact of sound on marine mammals and fish.

Arthur Popper is professor emeritus of Biology at the University of Maryland and editor of *Acoustics Today*. His research interests have most recently evolved into a focus on applied issues on effects of man-made sound on aquatic animals. He is also the editor of the Springer Handbook of Auditory Research (SHAR), a series of over 51 books that are very widely used in the auditory community. Among his other activities in "retirement," Dr. Popper is co-director of Terrapin Teachers (tt.umd.edu), a program that gives college STEM majors an added career option as high school science or math teachers.

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