Assessing the environmental impact of underwater noise during offshore windfarm construction and operation

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ABSTRACT

Offshore wind farms offer an important source of renewable energy worldwide. The noise created during their construction and operation, however, has the capacity to adversely affect the underwater environment. Consequently, a reliable, robust and accurate means of predicting and assessing the environmental effects of noise at an early stage is of key importance in providing an iterative process in the engineering towards an optimum design for the construction, which reduces environmental effects to a minimum or acceptable level while not unreasonably constraining the project or influencing its cost-benefit. It has been found that a key part of this process is to use appropriate and objective criteria for the principal effects of noise (hearing damage and avoidance), to estimate the degree of effect using these and a suitable predictive model, and to consider the biological consequences of this prediction with a view to determining if it is acceptable, and changing the engineering design if not. This paper investigates state of knowledge for assessment of underwater noise impacts on marine fauna and the ways this is used by offshore wind developers to minimise the risk to the environment.

INTRODUCTION

The introduction of offshore wind energy has an important and increasing role in reducing dependence on fossil fuels and ensuring energy security, but has caused concern in terms of the possible effect that the underwater noise created during construction, operation and decommissioning of windfarms could have on underwater animals. Over the past few decades it has become increasingly evident that noise from human activities in and around the underwater environment may have an impact on the marine species in the vicinity.

The production of offshore wind energy is a relatively new activity in the marine environment and there are significant gaps in the knowledge regarding the effects of noise and the acceptability of these effects. The noise caused by the operation of windfarms has recently been shown to be of very low level and probably insufficient to cause any significant environmental effects (Nedwell *et al*, 2012). By comparison, however, the noise created by the impact piling required for the foundations of wind turbines has been found to be of extremely high level (Nedwell *et al* 2003, Bailey *et al* 2010, Nedwell *et al* 2007).

The cost involved with the planning, consenting and construction of large offshore windfarms may exceed that of the construction of large thermal power stations, and careful planning at an early stage is required if costs are to be constrained. The effects of construction noise on the marine environment typically is one of the biggest issues surrounding the construction of a new offshore windfarm, and engineering decisions may have to be taken months or years before construction begins. Critically, an objective scheme for evaluating the effects of noise is required so that biologists and engineers can work together to optimise the project by designing a method of construction that can proceed in an efficient, timely and cost-effective way while minimising or limiting the effect on the environment. This paper looks at the available techniques to assess the impact of noise in the underwater environment and how they can be used for consideration of offshore developments, particularly wind farm construction.

EFFECTS OF NOISE

The effects of noise may be split into physical and auricular effects. For the highest levels of sound, typically during underwater blast from explosives, sound has the ability to cause injury and, in extreme cases, the death of exposed animals. This may be due to swim bladder rupture or tissue damage. Criteria have been developed for assessing gross injury of this type based on data from blast injury at close range to explosives. While there is a level of uncertainty as to whether a blast wave criterion can be directly applied to a transient waveform arising from an impact piling operation, these criteria imply that physical effects would only occur at a range of a few metres or tens of metres from piling, and may be readily mitigated by acoustic harassment devices or observers. The data on physical effects are limited, although Halvorsen *et al* (2012) offer a useful study of the effects of piling noise on juvenile salmon. By comparison, auricular effects may occur at ranges of kilometres or tens of kilometres, and hence are much more difficult to mitigate.

The auricular effects of noise comprise four categories. At the highest levels, traumatic hearing injury (TI) may occur as a result of a single transient exposure to noise at a high enough level. For instance, a single gunshot near to an unprotected human ear can cause immediate, severe and irreversible hearing loss. At lower levels, temporary threshold shift (TTS) may occur. TTS is characterised by a temporary decrease in hearing ability. For humans, this is often characterised by a sense of "dullness" of hearing or ringing in the ears. It is reversible and full hearing is regained after a few hours or days. However, if such levels are sustained for long enough permanent threshold shift (PTS) may also occur, in which hearing is slowly and irreversibly lost over a long period. It should be noted that while these two effects happen to occur at similar levels of exposure, they occur by different processes and are, in fact, independent of one another. In other words, TTS is not a symptom of PTS. At yet lower levels of noise, the behavioural effects of noise occur. Possibly the most relevant effect in practice is avoidance, in which an animal may flee from an area of high noise level, thereby causing areas around noise sources to be excluded to that animal. Since avoidance occurs at a lower level and hence at a much greater range from a noise source than TI, TTS or PTS, it has the capacity to affect much greater areas of sea and hence numbers of individuals.

In the UK, which currently has the greatest installed capacity of offshore wind energy worldwide, the behavioural response of important and declining species of marine mammals and fish has surfaced as arguably the most critical environmental issue facing the windfarm industry. The latest turbines may require piles of 7 m diameter and more to be driven as foundations, and effects on the underwater environment have been both anticipated and observed at tens of kilometres from piling operations (Tougard, 2008).

CRITERIA FOR EFFECT

There are two criteria that have predominantly been used for evaluating these effects. Behavioural effects depend on the "loudness" of the noise to an animal, and hence require consideration of the ability of the animal to perceive the noise, which varies greatly from species to species. Individuals of species having poor hearing may perceive the level as low, and hence not react to the noise, whereas sensitive species may find the level unbearably loud and react by swimming away. Therefore, an understanding of the hearing ability of the species that may be affected is of key importance in the process. Madsen *et al* (2006) reviews underwater noise from offshore wind farms on marine mammals and concludes that the impact of underwater sound on the auditory system is frequency dependent and ideally, noise levels should (as for humans) be weighted using the defined frequency responses of the auditory system of the animal in question.

The dB_{ht} (Nedwell *et al*, 2005) incorporates this approach and may be regarded as an analogue of the dB(A) metric that is used for human noise exposure. It weights the noise according to the hearing ability of marine animals, and leads to criteria that are consequently similar to those for human exposure to noise. Evidence gathered from public domain literature on the effects of noise on marine mammals, and from tests on caged and freely-swimming fish (e.g. Engås *et al*, 1996, Terhune *et al*, 2002, Fjälling *et al*, 1993, Goold *et al*, 1996), interpreted using dB_{ht}, suggests that at levels of 90 dB_{ht} and above, strong avoidance by virtually all individuals will result and at levels of 130 dB_{ht} and above, traumatic hearing injury may occur. It must be noted that few species have been formally studied with respect to noise and reactions; there is still much research to be done.

A second criterion is offered by the use of the Sound Exposure Level, which may be regarded as the sound pressure level that would occur if all of the noise energy associated with an event were compressed, or in the case of impulsive sounds, spread, into 1 second. It therefore expresses both the level of noise, and the time over which it is received. The SEL is conventionally used for predicting human PTS, but in this case a frequency-weighted version based on the dB(A) is used (Kryter, 1994). In the marine context, use has been made of unweighted SELs to predict the injury range for fish from pile driving operations (Popper et al, 2006). Southall *et al* (2007) reviews the literature on marine mammal hearing and on responses to anthropogenic sound, and proposes exposure criteria for certain effects based predominantly on the use of a frequency band-limited SEL value for various groups of marine mammals. The criteria proposed by Southall sorts species of marine mammals into four groups by their hearing ability. There are three cetacean groups: low, mid, and high frequency cetaceans and a pinnipeds group for species of seals. Low Frequency Cetaceans include large marine mammals such as minke and humpback whales and a sensitivity to sounds between 7Hz and 22kHz is assumed, Mid Frequency Cetaceans include the bottlenose dolphin and killer whale and for which a 150Hz to 160kHz bandpass filter is used, the criterion for High Frequency Cetaceans, which includes the harbour porpoise and river dolphin assumes hearing acuity between 200Hz and 180kHz, and the pinnipeds group for species of seal uses a filter between 75Hz and 75kHz. A criterion of 198 dB re. 1 $\mu Pa^2/s$ is proposed for the three cetacean groups as a level above which hearing damage may accrue; however for species of pinnipeds a much lower criteria of 186 dB re. 1 $\mu Pa^2/s$ is proposed.

This latter low level for the criterion has lead to very large hearing damage ranges being estimated for seals, and also a discrepancy whereby the hearing damage range calculated using the Southall SEL criterion was larger than the behavioural avoidance range using the Nedwell dB_{ht}; that is, it implied that seals were having their hearing damaged while apparently unaware of and not reacting to the level of noise.

OPTIMISING A PROJECT

The process of optimising environmental impact for an offshore windfarm project involves considering starting-point engineering parameters for the project, generally based on the most cost-effective method, assessing the environmental impact of this for various classes of animal and types of impact, using these results to eliminate low priority issues and hence focussing on matters of concern, and amending the engineering parameters or introducing other mitigation to achieve a project that is optimised, acceptable and consentable. This process ideally occurs at an early stage in the design process and will usually involve the project managers, acoustic and piling engineers, biologists and regulators. While estimates of numbers of individuals affected can be made using the noise dose model of the preceding section, a single contour predicting the range within which a given effect occurs is generally sufficient for optimisation purposes.

Given a suitable criterion, it is possible to model a proposed piling operation to assess the project and, where necessary, modify it in order to minimise environmental impact. In many cases, the early modelling separates impacts that may be considered negligible from those which require further attention.

As an example, Figure 1 illustrates the output from a rank-ordering model, *SPEAR*, which estimates approximate avoidance ranges and consequent habitat exclusion in km^2-hrs using typical values from a large database for the noise level and time of each activity. In this case, it has been calculated for the herring using a 90 dB_{ht} criterion. It may be seen that impact piling dominates over other sources, even when the considerable time that a windfarm may be in operation is taken into account. Data from *SPEAR* are only intended as an indicator, and can vary with the configuration of the noise source, such as the size of the piles, type of dredging or seismic airgun source. Generally though, the effects relative to other sources will not change significantly.

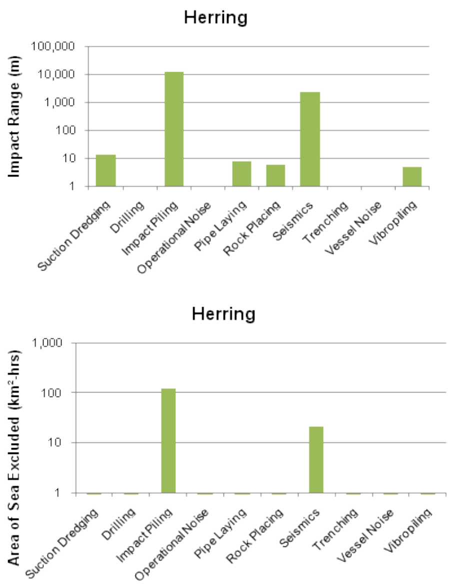

Figure 1. Avoidance range and habitat exclusion caused by typical windfarm construction activities, for the case of herring.

As an example, Figure 2 illustrates a calculation of the 90 dB_{ht} range, at which a strong avoidance reaction would be expected, for two species having greatly different hearing abilities, the herring and salmon. The contours have been produced using a purpose-written acoustic analysis programme, *INSPIRE*. This uses a combined shallow-water geometric and hysteris loss model to both predict the blow energy and predict the level of noise from piling operations. It can typically give results accurate to a dB or two, although it is generally set to yield pessimistic values to allow for cases where piles “refuse” and require exceptional energy to drive. Results are presented for the case of a 6.5 m diameter pile driven at a typical 1 MJ energy per impact. It may be seen that the area of sea impacted by the piling is very much greater for the herring than the salmon, as a consequence of the much poorer hearing ability of the latter. Although concerns are sometimes raised over the ability of piling to impede migration, it may be seen that at most it may cause salmon in the area of the piling to divert slightly in their route. By comparison, the area of sea affected for the herring is much larger, and if it coincides with a significant herring feeding or breeding area this might cause concern. In this case, resources might well be focussed on optimising the project in respect of the impact on herring.

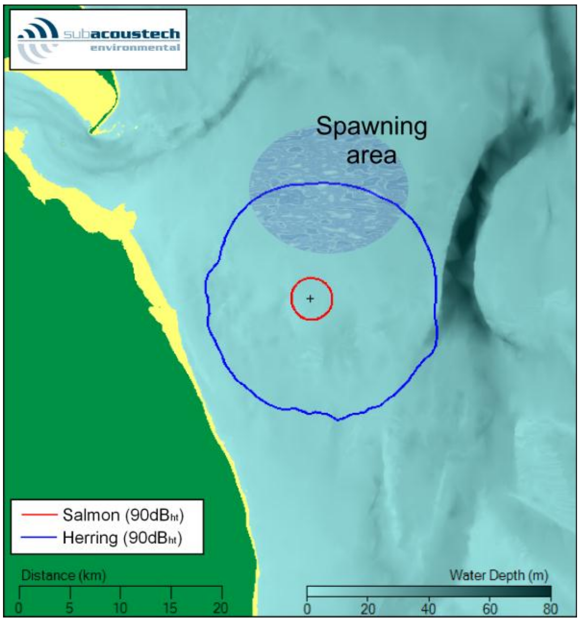

Figure 2. Salmon and Herring 90 dB_{ht} contours for a 6.5m diameter pile at 1 MJ blow force. The cross shows the position of piling.

An example of a common potential impact is illustrated in Figure 3. In this case, piling near a coast creates a zone of strong avoidance which intersects the coast. In the example shown, which is for the case of a harbour porpoise, the noise may be thought of as a “barrier” which might prevent movement along the coast. If the local population were threatened by other factors, this might well be thought of as an unacceptable impact, and a means of mitigating the impact sought. A second potential impact is also illustrated on the figure; in this case the avoidance zone for seals is shown to intersect a haul-out area. Again, depending on the status of the population and whether there are other areas in the vicinity that might offer an alternative, this might be considered unacceptable.

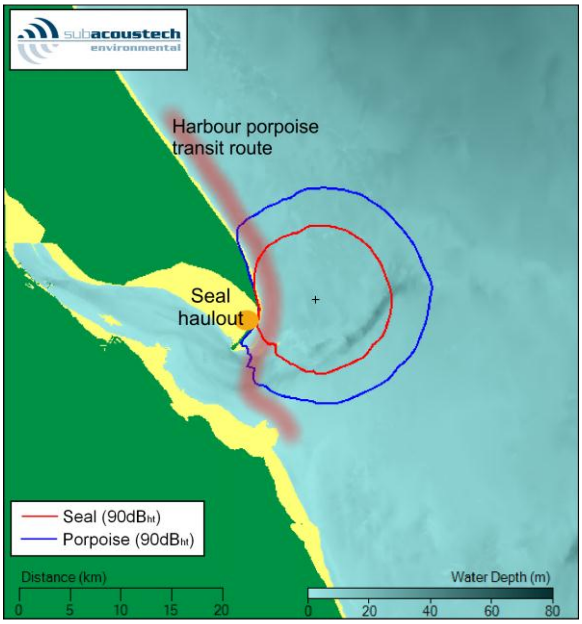

Figure 3. Seal and Porpoise 90 dB_{ht} contours for a 6.5 m diameter pile at 1 MJ blow force

There are ways in which the natural features of propagation may be used to minimise impact. Figure 4 illustrates the difference that results from differences in water depth. The noise from piles in shallow water is more rapidly attenuated than that of piles driven in deep water, and hence the area impacted may be much smaller for piles in shallow water. It may be possible to minimise risk by scheduling activities with the lowest likely impact at a period in which the potential for impact is largest, for instance the driving of piles in shallower water during spawning or migration.

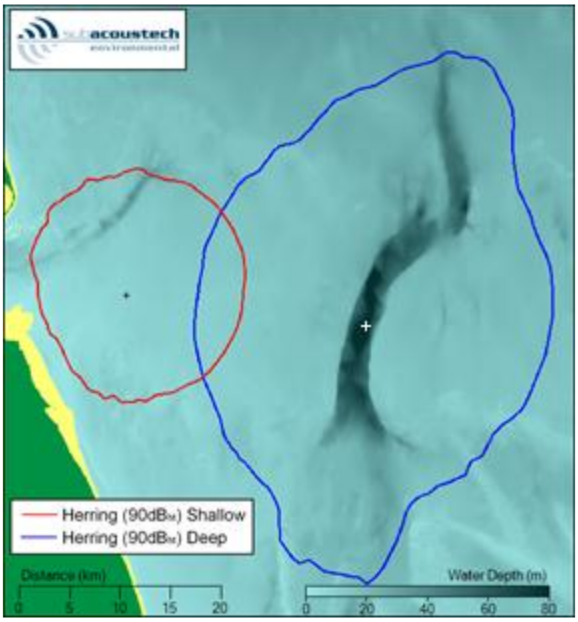

Figure 4. Herring 90 dB_{ht} contours for the same 6.5 m diameter pile driven at 1 MJ blow force in deep and shallow water. The crosses show the alternative positions of piling.

Figure 5 illustrates a similar result, for a 7 m diameter pile driven at 1.1 MJ, a 4 m pile driven at 600 kJ, and a 2 m pile driven at 300 kJ. There is a significant reduction in the area impacted by the piling for smaller piles. The contours enclose an area of about 500 km^2, 300 km^2, and 130 km^2 respectively. Therefore, it might be possible to use a jacket pile of three small piles to support a turbine, rather than one large monopole. However, it should be noted that while the range of effect decreases, this will significantly extend the period of piling, and hence the habitat exclusion (i.e. the area times the time) may actually increase, reducing the overall environmental benefit.

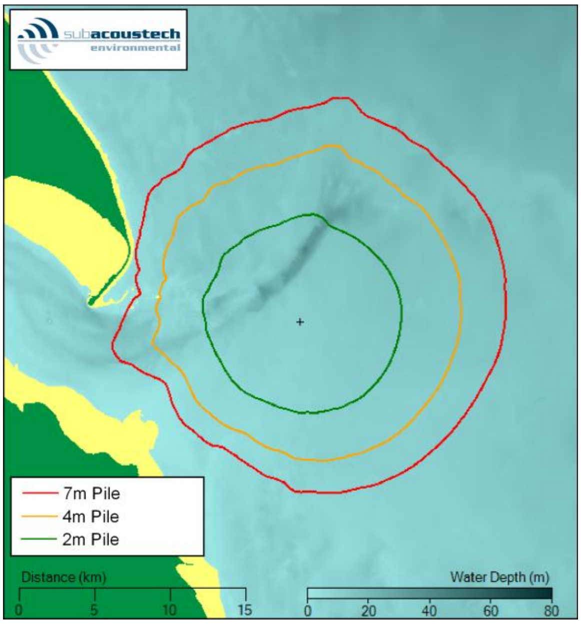

Figure 5. Effects of pile size: 90 dB_{ht} contours for a 7 m diameter pile at 1.1 MJ blow force, a 4 m pile at 600 kJ, and a 2 m pile at 300 kJ.

Figure 6 illustrates an estimate of hearing damage range for a seal using the SEL criterion of Southall. The calculation is, in this case, slightly more difficult as it requires an assumption as to the movement of the animal while the noise dose accumulates. In this case, it has been assumed that the animal flees radially away from the piling. Three cases are considered, which alter the noise dose that the animal receives. If the animal remains in one position, it will receive the highest noise dose and hence the contour separating safe and hazardous exposures is the furthest from the piling. In the case where it is assumed that the animal flees, a degree of self-mitigation to the effects of noise results and the range at which the animal can start in order to just receive the criterion dose of noise is consequently nearer to the source. The faster it is assumed the animal will flee, the closer it can theoretically be to the piling to avoid a significant dose, as may be seen for the two assumptions of fleeing at 1 m/s and 2 m/s.

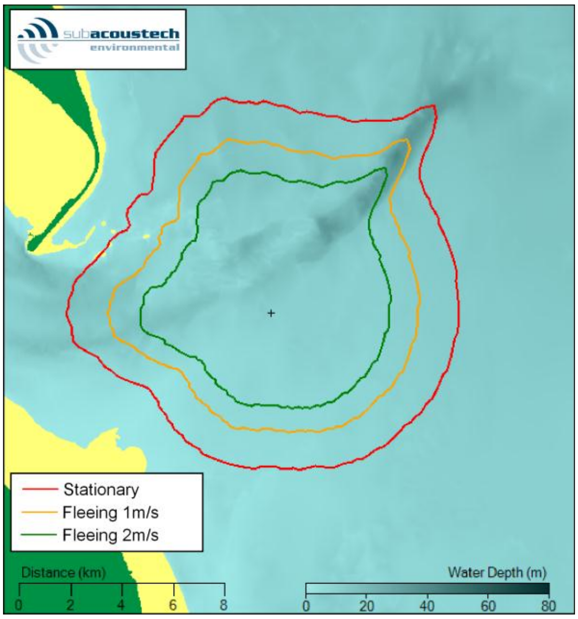

Figure 6. Starting range from a 6.5 m diameter pile driven at 1 MJ for a pinniped to receive a maximum SEL of 186 dB re. 1 µPa²/s for a stationary animal, and at fleeing speeds of 1 and 2 m/s.

SUMMARY

It may be seen that careful and objective estimates of the noise level created during windfarm construction are essential if the project is to be optimised from an environmental standpoint, while not constraining the construction programme and cost unduly. Using modelling tools, in conjunction with biologists, engineers and project managers, at an early stage, is essential in order to iterate towards an optimal design, plan the project and avoid delays to the project caused by environmental concerns. Intuitive or subjective decisions can be wrong, are difficult to justify retrospectively and can have severe financial and environmental consequences. Simple questions, answered at an early stage using the best available approach, can greatly aid the many engineering decisions that have to be taken at an early stage in any offshore windfarm project.

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