A case study on the effects of underwater noise during the construction of large offshore wind farms

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ABSTRACT

The installation of wind farms is considered a key step towards the provision of sustainable energy supply in the UK. Offshore wind farms offer a great potential in terms of availability of resources in terms of space and energy with the minimum of impact on human activity. A growing body of evidence, however, suggests that the construction and operation of wind farms are likely to pose a risk to offshore wildlife. As such, these wind farms must undergo detailed environmental impact assessment prior to installation to determine their impact on marine fauna. In this paper, we discuss the construction of a large UK wind farm, for which a comprehensive noise study was produced reviewing its impacts and the calculation of their severity. The impacts on underwater wildlife considered included lethality and physical injury, auditory effects and behavioural avoidance response. The use of an underwater broadband noise propagation model which has been implemented as software, and which has been validated for shallow water is described. The range of effects of unweighted, dB_{ht}(*Species*) and M-weighted Sound Exposure Level were calculated for a variety of appropriate species with this software. This software tool was used interactively by the engineers, regulators and marine specialists, and it offered the constructor the ability to assess and minimise the development's potential for environmental impact from an early point. This allowed the developer an accurate impression of the likelihood of gaining consent for the project and provided a direction for the best way to minimise or mitigate the introduced noise.

INTRODUCTION

That underwater noise can have a significant impact on marine life is now well known and accepted; indeed the impacts may well be greater than the impact of land-based airborne noise. Military and civil noise sources have long been blamed for causing adverse impacts on marine species (Frantzis, 1997 and Hastings and Popper, 2005). The stranding of animals on the beaches brings home the potential effects of human activities underwater to the general public - and to environmental authorities.

A large proportion of the major offshore development in the UK and European waters is for wind power (DECC 2009). Thousands of large wind turbine generators are proposed to be installed this decade and the construction process in particular has the potential to cause a significant noise impact in the underwater environment. The installation of the foundations, with designs for steel piles of eight metres in diameter or more being considered, typically involves massive piling rigs which drive the foundations into the seabed with energies measured in megajoules. This translates to the introduction of very large sound pressures, much of which is transmitted straight into the water column. The scale of the development around the UK means that not only is there the potential for more than one piling rig to be used on a single wind farm but there are often multiple wind farms within the acoustic vicinity. The potential for cumulative effects, where these multiple noise sources can combine to produce higher noise levels or greater areas exposed is significant.

The potential injury or disturbance to marine fauna has the potential to be in conflict with The Conservation of Habitats and Species Regulations 2010 or the Offshore Marine Conservation (Natural Habitats etc.) Regulations 2007, as amended 2009 and 2010, in UK waters. In Australia, the Environment Protection and Biodiversity Conservation Act is key, and it prohibits interfering with protected marine species. New major offshore works require the impact on marine life to be taken into account as part of the Environmental Impact Assessment and underwater noise is one of the main stressors on the wildlife.

Wind farms in the Firth of Forth, north-east Scotland are a very good example of a circumstance requiring such an assessment. The Firth of Forth Offshore Wind Farm itself is a large area split up into seven phases. There are also two smaller wind farms planned, Inch Cape and Neart na Gaoithe (NNG), which are slightly closer to land and whose construction may well overlap in time with the early phases of the main Firth of Forth field. The development of each of these fields has the potential for significant noise impacts, and by virtue of their geographical vicinity and temporal overlap of construction, may well combine to create cumulative effects.

This paper will discuss our methodology for assessment of the impact of noise on underwater species, look at the potential challenges that can occur on a relatively complex situation and consider the potential options for noise mitigation at the design stage.

UNDERWATER NOISE

Due to the incompressible nature of water, sound is transmitted much more readily than in the air and thus any sound from a high power underwater source will tend to travel much further underwater. Sound underwater is denoted in decibels with reference to 1 µPa as opposed to the 20 µPa used in air. Underwater ambient noise levels of the order of 100 to 130 dB re 1 µPa (unweighted) are not unusual around the UK waters (Bailey *et al.* 2010).

The basic descriptors in use are generally as per those on land: peak, peak-to-peak, sound pressure level (SPL) and sound exposure level (SEL) are all common, although the common land-based environmental descriptors such as L_{eq}, L_{10} and L_{90} are not typically used. The A-weighting which is ubiquitous in airborne noise measurements also does not generally exist; human hearing underwater does not follow the usual airborne curves, and a human presence is relatively rare. Broadband underwater noise is typically described in terms of unweighted decibels rather than as, for example, an A-weighted decibel, and where a noise relates to a specific marine species, metrics are available that can be used which relate to the audiological capabilities of that species, where such data is available.

MARINE EFFECTS

The construction of a wind farm will involve many noise generating sources, for example the additional vessels to transport components as well as dredging and trenching on the seabed. By far the greatest single source of noise over the whole lifecycle of the turbines is as a consequence of the installation of their foundations.

Although there are many turbine installation methodologies, by far the most common is the use of pile-driven steel foundations. These steel tubes range from diameters of less than two metres to upwards of seven metres. In order to fix them the required 30 metres or more into the seabed, the piles will be driven by percussive (impact) piling techniques or, in some cases, a combination of percussive piling and drilling where ground conditions require it. Percussive piling can generate extremely high source levels and this has the potential to affect marine species in the vicinity of the work.

It is worth noting that marine species can include humans, although humans as a receptor are not often included in the assessment as they are rarely present. However, if work is undertaken in a region popular with underwater pursuits such as diving (either recreational or commercial) then humans can be just as significantly affected as any other marine species.

Range of effects

The effects of noise tend to fall into one of three main categories:

- Physical injury in which physical damage is experienced. Typically this affects air containing vessels in a body such as lungs or a swim bladder. For very high pressures death can result;
- Audiological injury for which long term damage can occur to the hearing of species; and
- Behavioural effects, where an animal may avoid or flee an area if it finds the noise level in that area ‘uncomfortably’ high. This has the potential to cause environmental effects where it interrupts feeding or breeding areas, blocks migration routes or otherwise disturbs protected species.

The injury or lethality effects are physical processes and largely independent of species. Unweighted sound pressure is used to assess this, with levels of 240 dB re 1 µPa for lethality and 220 dB re 1 µPa for physical injury (Parvin *et al*, 2007a, Yelverton *et al*, 1973, Richardson *et al*, 1995). Audiological injury and behavioural avoidance are more dependent on a species’ auditory capabilities and as such species more sensitive to sound will be more greatly affected than a less sensitive one. Two primary sets of criteria are used to assess these impacts in the UK sector: the dB_{ht}(*Species*) (Nedwell *et al*. 2007b) and the SEL (Southall *et al*. 2007).

The dB_{ht}(*Species*) metric is based on the audiogram for the species in question, working in a similar way to the dB(A) works for humans. The dB_{ht}(*Species*) value is a weighted integral over frequency of the difference between the received level and the absolute hearing threshold at that frequency for the species in question. A link has been demonstrated between dB_{ht}(*Species*) and a species’ reactions, with 90 dB_{ht}(*Species*) appearing to lead to a majority of a species avoiding or fleeing from an area (Nedwell 2007). Furthermore a 75 dB_{ht}(*Species*) level tends to lead to ‘significant’ avoidance, where many of a species will avoid an area, but the avoidance is limited by habituation or context (such as for feeding, spawning or migration). Thompson *et al* (in prep.) has undertaken a recent study of the apparent displacement of harbour porpoises against known noise levels, which appears to support the dB_{ht} avoidance criteria. This approach has been extensively used in the assessment of wind farms around the UK since it gives a consistent and increasingly accepted behavioural criterion for both fish and marine mammals. It is not known how widespread its use is outside of the UK sector. A more detailed description of this metric and how it can be used to model behaviour is provide in an accompanying paper in this conference (Nedwell *et al* 2012).

The Southall auditory injury criteria (Southall et al, 2007) are based on a form of instantaneous sound pressure level (SPL) and a sound exposure level (SEL) based on longer exposures to calculate the possibility of sudden impulsive injury or dangerous noise exposure to a marine mammal species over a period of time. A number of different species groups are represented by an “M-weighting,” which categorises an approximate auditory capability of various species: low-frequency cetaceans (e.g. humpback whale), mid-frequency cetaceans (e.g. bottlenose dolphin), high-frequency cetaceans (e.g. harbour porpoise) and pinnipeds (i.e. seals).

It is worth noting that neither of the dB_{ht}(*Species*) or M-weighted SEL assessment methodologies can be described as comprehensive or definitive. With respect to the dB_{ht}, relatively few species have peer-reviewed audiograms available, and where they are they will tend to be limited to data on only a few animals. The testing will generally provide only a hearing threshold and how an animal’s hearing capabilities change at higher noise levels are far less known. Where no audiogram is available the method relies on the use of surrogate species with morphological or taxonomic similarities. Although results so far are indicative that many species are affected more strongly at an increasing noise level that appears to fit the dB_{ht} model, a substantial amount of further research is required to increase the confidence in the criteria used.

With respect to the M-weighted SEL, the criteria were only intended as initial recommendations although have been taken up as firm criteria by regulators in many parts of the world. They are limited to mammals and they collect a many species into large groups, which cannot account for the substantial variation in audiological capability between species within the groups. This also leads to the assumption of an effectively ‘unweighted’ audiological capability between the frequency boundaries, with more detail being impossible with such a broad grouping. This would be expected to lead to the estimation of higher perceived levels for a given species within a group. As with the dB_{ht}, the potential variation in hearing in a species at different noise levels, considered in humans with the A- and C-weighting curves, is not taken into account.

The use of these two methodologies is now an accepted practice based on limited existing knowledge by regulators in the UK sector, and commonly an underwater noise impact assessment is requested to include unweighted noise levels for lethality and physical injury, M-weighted SEL for audiological injury and dB_{ht}(*Species*) for behavioural effects.

Criteria for the effects of non-transient sound exposure on fish are currently in development (Carlson *et al*, 2007, Halvorsen *et al*, 2012). Although they were not used for this assessment, the authors have been requested to investigate an implementation of the criteria recommended in upcoming developments and these are expected to take a place in future underwater environmental impact assessments.

ASSESSMENT

Our assessment of the environmental impact of a wind farm starts with the calculation of the range of effects. For impact piling, the top of a metal 'pile' tube is struck by a hydraulic ram, which transmits its energy down through the cylinder and out as broadband sound energy into the air, water column and seabed. Following many marine surveys during piling operations we have found that the primary factors affecting the source noise level are the 'blow energy' used to drive the pile into the seabed and the diameter of the pile itself, which to some extent is a factor in the blow energy required and also affects the frequency content of the transmitted noise. The transmission and attenuation through the water is to the greatest extent a factor of the water depth, with shallower water providing more attenuation than deeper water, although other factors such as water temperature, salinity, seabed type and current have an effect on the overall level of attenuation. In the assessment, the temporal aspects such as the change in water temperature throughout the year have had to be averaged out. The long term nature of the wind farm planning process makes it almost impossible to know exactly what time of year the actual construction will take place when the information is required for the early environmental assessment.

The extent of the range of effects of the noise transmission through the water column is calculated using our Impulse Noise Sound Propagation Impact Range Estimator (INSPIRE) modelling software. The INSPIRE software has been developed by reference to many tens of actual acoustic measurements taken around the coast of the UK. The model has shown to give excellent results for the propagation of impulsive broadband noise in shallow waters (i.e. sea depth under approximately 80 metres). It has been used for the assessment of noise on many of the wind farms which have been, or are in the process of being, developed.

At the early stages it is of benefit to the developers to keep their options open. Engineering designs are likely to be some way off being completed and so we suggest looking at the potential impacts of 'worst case' and 'most likely' options for the piling. The worst case typically involves the largest foundation size and the greatest blow energy: if it is found that this does not have a major impact on any significant areas of environmental sensitivity then all of the options remain on the table for the developers. At the same time, modelling the 'most likely' engineering parameters available at that stage gives a more accurate representation of the effects of the forthcoming work. Ultimately we expect to identify a 'realistic worst case', which gives the greatest scope for options for the developer without calculating an excessive and unlikely impact range.

The first stage in considering the noise impact of the Firth of Forth wind farm construction was the impact of a single turbine foundation in the Firth of Forth Phase Alpha. For the 'worst case' situation the engineering team suggested a 3.0 m diameter turbine foundation (based on preliminary data). The upper limit for energy of the piling rig to be used to drive the foundation was 2185 kJ. The basic parameters of the 'most likely' foundation were a 2 m diameter steel pile driven with a piling rig operating at a maximum blow energy of just over 1700 kJ. There was a 'ramp up' process on the piling, where the pile is hit more gently at first and the power is steadily increased towards the maximum. This has the benefit of creating lower noise levels at first, which gives species in the vicinity a little time to flee from the immediate area before the highest and most potentially dangerous sound levels are introduced.

A number of species of both fish and marine mammals are of concern in the Firth of Forth, and were included in the assessment. For fish, dab, herring, salmon, sand lance and trout were considered. For marine mammals, the effects on bottlenose dolphin, harbour porpoise, harbour seal and minke whale were predicted. One species of fish and one species of marine mammal have been selected for this paper.

The outputs from modelling this position are shown below, using the harbour seal (*Phoca vitulina*) as an example of a marine mammal species. The harbour seal was selected as a species for investigation here as it has a good sensitivity to sound, and both dB_{ht}(*Species*) and M-weighted SEL are straightforward to calculate for the species (defined Southall criteria and known audiograms).

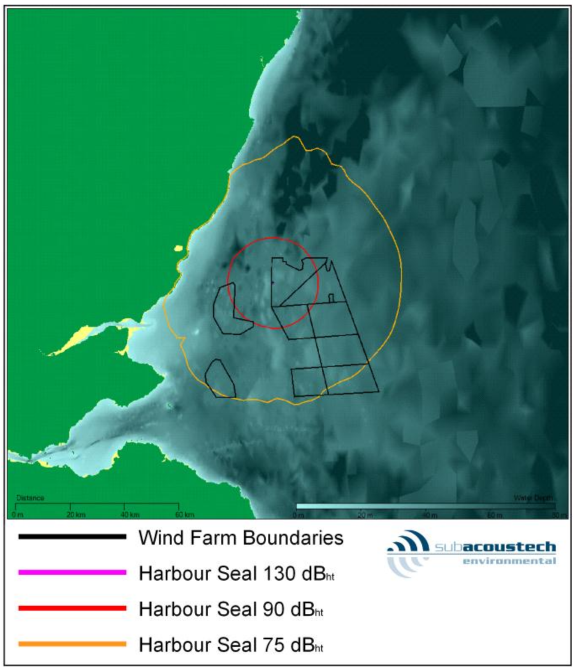

Figure 1. dB_{ht}(*Phoca vitulina*) contours for harbour seal during typical piling event. (130 dB_{ht} contour just visible.)

Figure 1 shows the location of the Firth of Forth, in north-east Scotland. Darker shades of blue describe deeper water and most water is less than 50 metres in depth. The black outlines are the wind farms, with the large area to the east showing the multiple phases of the large Firth of Forth development and the two smaller farms to the west showing the NNG and Inch Cape wind farms.

The coloured lines show equal sound level contours, with the inner red line showing 90 dB_{ht}, or the 'strong avoidance' contour, and the outer yellow line showing the 75 dB_{ht} or 'significant avoidance' contour. For comparison purposes, equivalent contours for the salmon (*Salmo salar*) are given in Figure 2.

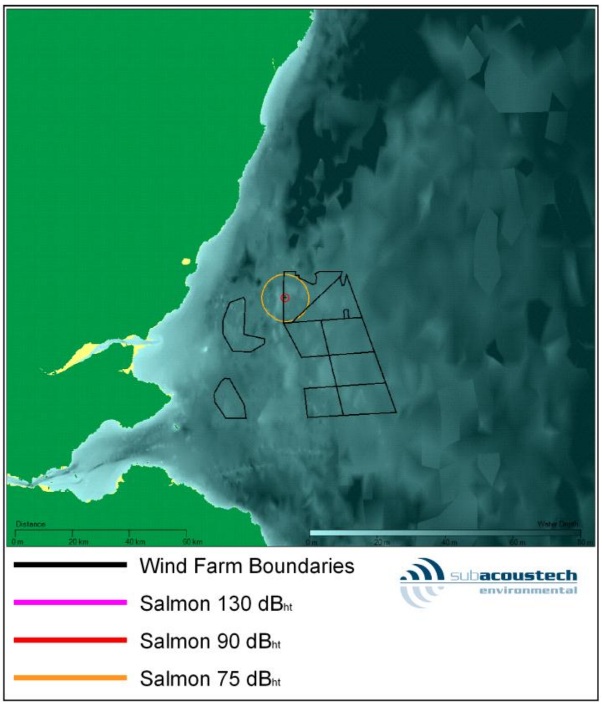

Figure 2. dB_{ht}(*Salmo salar*) contours for salmon during typical piling event (130 dB_{ht} contour too small to show)

It is clear, if somewhat self-evident, that the sensitivity of a species' hearing has a significant effect on the impact of sound on them. However it can be seen that where there may well be a significant effect on harbour seals in the Firth of Forth, salmon would be, relatively speaking, affected to a small degree. The magnitude of risk to salmonids, along with other insensitive fish species such as bass and trout, would therefore be relatively low, unless the location within the contours was of special significance, such as for feeding or breeding.

Visible on Figure 1and Figure 2 above are two or three contours: 90 dB_{ht} and 75 dB_{ht} on both, and 130 dB_{ht} on the harbour seal plot. The 130 dB_{ht} contour (representative of a level at which audiological damage is likely to occur) is small enough not to be visible at this scale for the salmon as a consequence of the salmon's relatively low sensitivity. However, on the harbour seal plot, these animals are calculated to be at risk of hearing damage out to a range of approximately 600 m. The range of avoidance behaviours, or 90 dB_{ht} and lower, is calculated to extend to the coastline which leads to a greater risk of cutting off migration or other travel links and the large area risks disturbing large populations.

It is worth drawing attention to the sensitivity of the salmon. It has been noted (Hawkins 1981, Hastings and Popper 2005) that hearing "generalist" fish species, such as salmon (*Salmo salar*) and the flatfish dab (*Limanda limanda*) primarily detect the particle motion component of the sound field rather than the sound pressure. As such, strictly an assessment based on their sensitivity in terms of sound pressure may not accurately define their behaviour. However, in the far-field in open water sound pressure and particle velocity will be proportional to one another and the sound pressure and particle velocity audiograms will be directly comparable (Fisher, 1992). Additionally, to date, no criteria are available that define a potential hazard to species in terms of particle velocity and so there is no practical way to assess the risk directly in these terms.

The accumulated exposure to sound for marine mammals has been assessed using the criteria proposed by Southall *et al* (2007), using M-Weighted SELs. This has been done by calculating a starting range for each marine mammal group, whereby the receptor would be able to escape the affected area without receiving the specified level of sound where auditory injury is expected to occur.

Figure 3 shows the range to which a harbour seal would be at risk of hearing damage from exposure for the duration of piling, which is typically few hours for the pile described herein. A 'multiple pulse' calculation was undertaken for the pile installation, taking into account the whole duration of predicted pile installation and number of times the pile was struck.

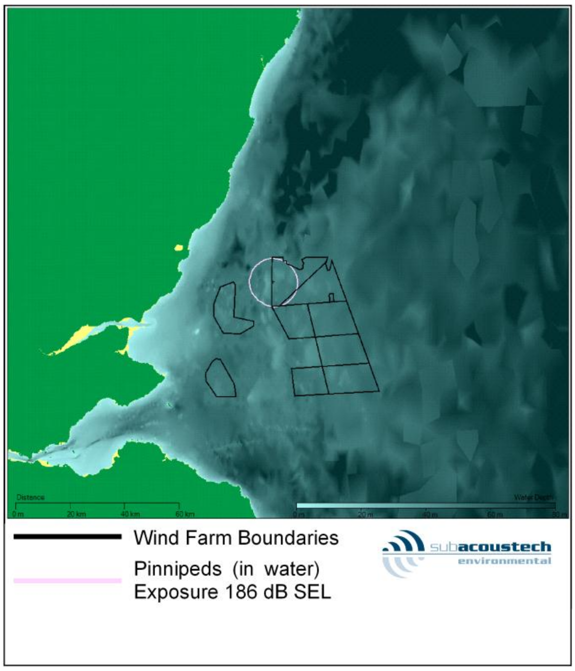

Figure 3. Contours showing the extent of the Southall criteria as applied pinnipeds for pile-driving events.

A substantial and detailed 'ramp up' period was planned for the piling event. An initial 'soft start' was proposed at 15% of maximum piling efficiency, and the blow energy was increased incrementally after that up over the pile duration. The strike rate (number of strikes per second or seconds per strike) is also key to include in calculations for the most realistic calculation model of a fleeing animal (see below) as the faster the strike rate, the greater the exposure an animal will have while it is fleeing. A strike rate of approximately one strike every second and a half was used in these calculations.

For this part of the modelling we use the so called 'fleeing-animal model' in which it is assumed that as soon as piling begins the seal will start fleeing away from the noise source, and so this contour represents the closest position that a seal could start fleeing from before it receives a potentially dangerous noise dose. The average radius of the contour is 8.8 km. Although this approach lays itself open to various questions such as 'what is the correct speed to model for the animal?' (we have used 1.5 ms^{-1}), 'will the animal move directly and radially away from the noise source?' etc., it has proved itself very useful in providing realistic estimates for areas of effect. The model will always reduce the range of consequence relative to the unrealistic situation of an animal which remains fixed and unresponsive for the duration of the piling.

Cumulative Effects

The problem of modelling and assessment becomes compounded when we consider multiple pile locations. The assessment must consider the possibility that the piling could occur at all three wind farms simultaneously. All three wind farm developers proposed different piling parameters, and so the three models were overlaid and the results displayed in Figure 4 which shows the behavioural avoidance ranges for all developments for seals.

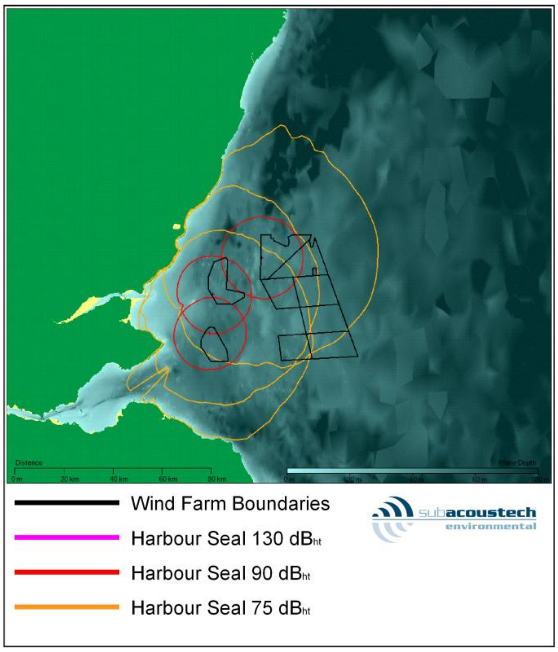

Figure 4. dB_{ht}(*Species*) contours for simultaneous piling at three different sites.

It can be seen that the combined impact now effectively blocks a very large area of coastline, potentially posing a significant obstacle to fauna in the region. There are two points worth noting: firstly that only the yellow contours – 75 dB_{ht} – reach the shore. This is outside of the range of strong avoidance within the red contours. This would suggest that, although the noise would be potentially disturbing for the seals, if there was a strong desire to be in the area then it may be tolerable.

The second point is that for this calculation there is no addition of the noise levels from the multiple sources. The dB_{ht} as a metric assesses the energy received by an animal on a blow-by-blow basis. In a realistic scenario with a number of piles occurring in the same area the likelihood that more than one peak would occur exactly simultaneously is very unlikely.

When considering the effects of multiple piles on a daily exposure to an animal however, the repeated strikes accumulate and the results of Figure 5 are obtained.

Figure 5 shows that, based on the Southall *et al.* SEL criteria, seals would be at risk of auditory damage over a substantial region. This would have a potentially significant effect on the ecology of the area and a significant hindrance to the consentability of a scheme with respect to the regulators. It is then critical to identify the specific regions of sensitivity for the species in question, as an area of sea measuring in hundreds of square kilometres insonified to a potentially dangerous level is of a low significance if none of the species of concern are there, or expected to be there at the time of piling.

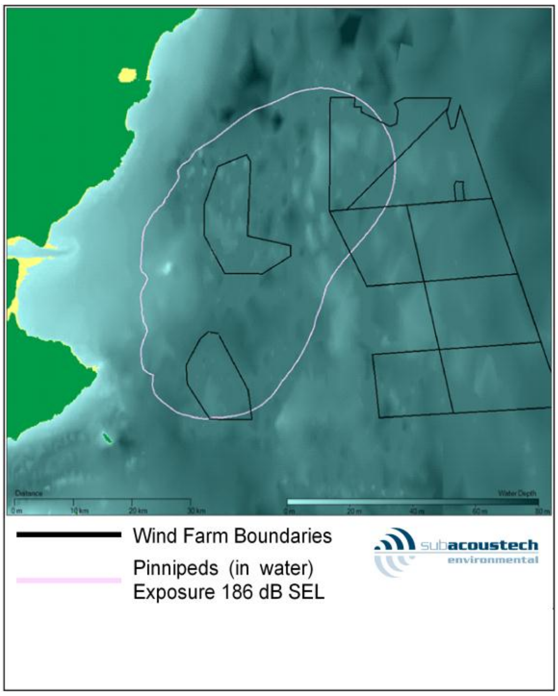

Figure 5. Southall criteria for the combined and cumulative effects of Figure 4. (Notice figure zoomed in relative to previous representations.)

Early identification of potential obstacles such as those described in the previous paragraph is crucial to avoid costly delays to a project and as much opportunity to design in mitigation to reduce the scheme's potential environmental impact. The plots shown above are the result of a redesign, changing the size of the piles following even greater ranges with the larger specifications. Initially, large monopiles with large energies were considered, as this would be likely to reduce the length of time that it would take to install a turbine foundation. However, the range of effect would be considerably larger than with the smaller specification, which requires less energy to drive into the seabed, and consequently less overall noise. Ultimately the decision is made following consultation with fish and marine mammal specialists.

Reducing an adverse impact in design is usually more effective than having to employ some form of mitigation further down the line. As with many situations we deal with, it is ultimately a complicated trade-off between the cost of the project, and the ability for it to be completed from an engineering perspective as well as its potential impact on the environment. At the time of writing, the results given and engineering parameters used are still under development and consultation and are subject to further change.

CONCLUSION

The construction of offshore wind farms is a significant source of underwater noise and the scale of their deployment in the UK has the potential to cause effects ranging from disturbance to injury for many species of marine fauna. The potential impacts of the introduction of such developments offshore on the natural environment are becoming increasingly well studied and the ability to predict these effects in advance is becoming more sophisticated.

The number of turbines planned to be installed and the time it will take to do this runs the risk of making large areas of water uninhabitable for considerable periods, and the long term impacts, such as how long it will take for animals to return to the area, or indeed whether or not they will, are not clear. It is therefore crucial to identify the scale of these effects as early as possible so that mitigation to minimise them can be built into the design.

The wind farms planned to be installed in the Firth of Forth are currently undergoing an Environmental Impact Assessment and consideration of the impacts of noise during the construction of the turbine foundations features heavily in the considerations. No definitive criteria exist in national standards or statutory regulations for the assessment of marine mammals and fish, so the potential adverse effects on these species have been calculated using criteria based on unweighted noise levels, M-weighted SELs and the dB_{ht}(*Species*) methodology.

The number of wind farms proposed within a region and the likelihood that more than one turbine foundation could be installed simultaneously compounds the potential risk and is likely to increase the range and magnitude of the environmental effects. When taking into account the effects of exposure on marine mammals in the area, we have found that, although the larger monopiles proposed will have a greater impact in terms of the distance affected, the fact that only a single pile might need to be installed for each turbine could reduce the overall length of time an area will be insonified, when compared to the alternative of a jacket with three or four smaller piles required. Experience has shown that the most efficient and best way to assess such complicated multi-parameter problems is by close collaboration between acousticians, engineers and marine biologist as early in the planning process as possible.

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