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Horns Rev 3 Offshore Wind Farm

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UNDERWATER NOISE MODELLINIG

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UNDERWATER NOISE MODELLING

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SUMMARY

Subacoustech Environmental has undertaken a study on behalf of Orbicon and Haskoning UK Limited to assess the impact of underwater noise produced during pile driving operations at Horns Rev 3 Offshore Wind Farm, located off the west coast of Denmark in the North Sea. Noise due to subsea piling operations has been assessed for the installation of foundations for wind turbines at the Horns Rev 3 site.

A number of different criteria and metrics exist for the assessment of underwater noise exist, and there is little international consistency, while research is continuing rapidly in the field of underwater noise impacts on wildlife. Most research in northern European waters focuses on the harbour porpoise, which is abundant in this region. Studies by Lucke (2009) in Germany and Tougaard (2013) in Denmark have identified noise levels that can cause adverse effects and reactions in harbour porpoises. Limits on noise emissions from offshore piling have been imposed in Germany to protect marine mammals, primarily harbour porpoise, based on the studies by Lucke. Southall et al (2007) presents interim noise criteria suitable for assessing the potential impact on other marine mammals. Carlson et al (2007) and FHWG (2008) have identified interim criteria for fish. These criteria have been used in the following assessment.

The level of underwater noise from the installation of a 10 m diameter pile using a maximum hammer blow energy of 3000 kJ has been estimated using a proprietary underwater sound propagation model (INSPIRE, currently version 3.4.3) that enables the level of noise from the piling and its behaviour with range to be estimated for varying tidal conditions, water depths and piling locations. The model is based on, and validated against, an existing database of measurements of piling noise. The INSPIRE model has been used to calculate the expected noise level on 180 transects radiating outwards from piling locations at the Horns Rev 3 site and the results interpreted to yield impact range contours.

Estimates of underwater noise in terms of SEL have been made using this model to indicate the range at which the various criteria at which injury or behavioural avoidance might occur.

The wind turbines installed at the Horns Rev 3 will be located in a water depth of between 11 m and 19 m at the lowest astronomical tide (LAT), with mean high water springs (MHWS) at LAT + 1.8 m. Two piling locations were selected for modelling to account for transmission from a northerly and deeper water location, and a southerly and relatively shallow water location.

Assuming worst case piling conditions, lethal and physical traumatic (but sub-lethal) injury could occur to any animal at distances of 6 metres and 82 metres respectively.

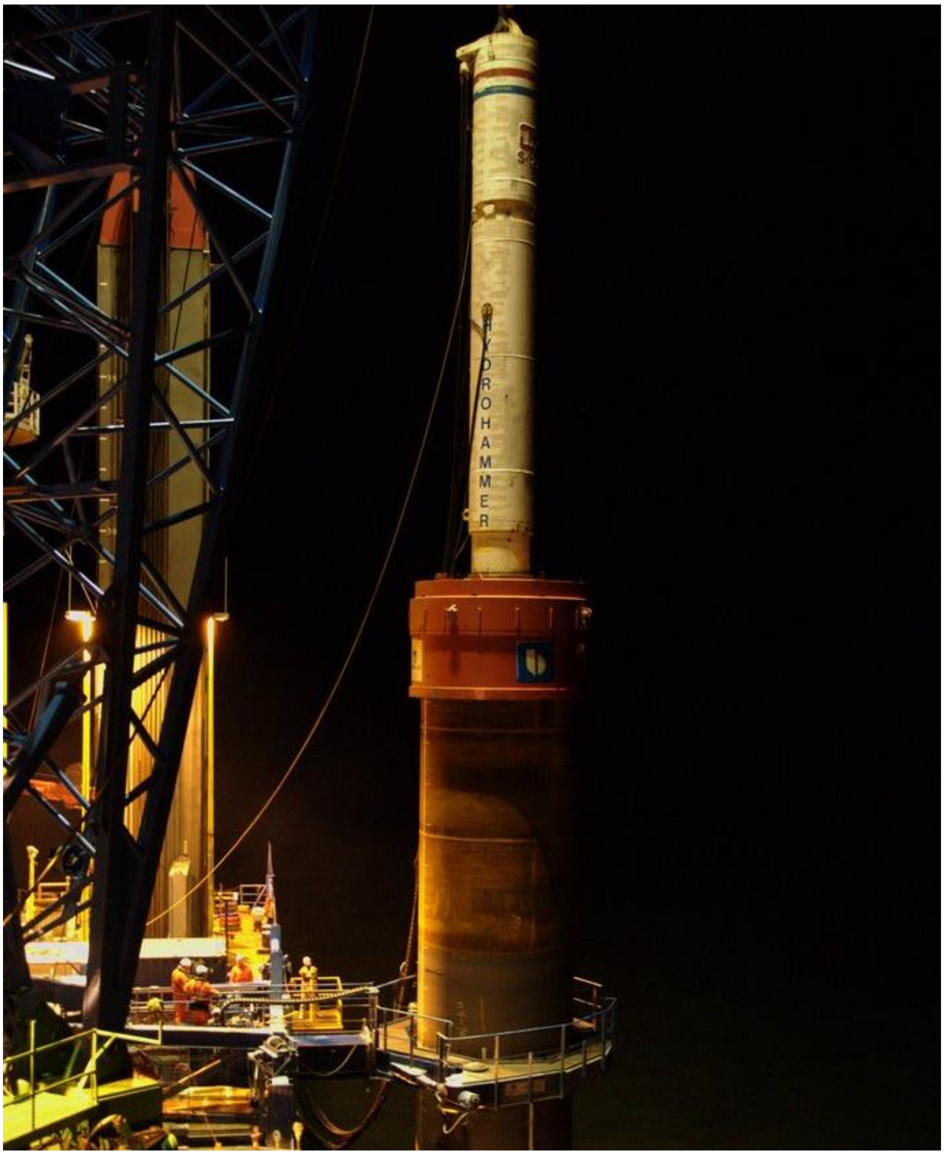
Permanent damage to harbour porpoise hearing (PTS) is predicted where an animal is present at distances of between 5.3 km and 10.4 km (180 dB SEL re 1 µPa^{2}s (unweighted)) at the start of the piling. This reduces to between 700 m and 2.1 km for pinnipeds (186 dB SEL re 1 µPa^{2}s (M_{pw})).

Temporary damage to harbour porpoise hearing (TTS) is predicted where an animal is within 4.9 km to 6.2 km (165 dB SEL re 1 µPa^{2}s (unweighted)) of the piling at the highest

blow energy. This reduces to between 1.3 m and 2.0 km for pinnipeds (171 dB SEL re 1 µPa^{2}s (M_{pw})).

Injury to fish is predicted to a maximum distance of 14.6 km (187 dB re 1 µPa^{2}s SEL criterion) over the whole piling period, which extends to 19.4 km for small fish of size less than 2 grams (183 dB re 1 µPa^{2}s SEL criterion).

A strong behavioural response may occur out to distances of up to 15.5 km in harbour porpoise using the 90 dB_{ht} criterion, or up to 21.5 km for behavioural disturbance using the 150 dB re 1 µPa^{2}s SEL criterion.



Piling

1. INTRODUCTION

1.1. Project description

The Horns Rev 3 site is located on Horns Rev, in a shallow area in the eastern North Sea, approximately 20-30 km northwest of Denmark. The water depth in the proposed area for the wind farm is between 11 and 19 metres at lowest astronomical tide (LAT), with a Mean High Water Springs (MHWS) of LAT + 1.8 m at Blåvands Huk.

As part of the construction for the Horns Rev 3 project, piles for the wind turbine foundations will be driven into the substrate by impact piling. Impact piling is a large source of noise, which is readily transmitted into the surrounding water. This noise can have potentially adverse effects on marine life and as a consequence there is a need for the assessment of its impact on marine mammals and fish present in the region. A variety of research has been done considering the effect of high noise levels on different species and the most appropriate criteria will be included in the following assessment. Bundesamt für Seeschifffahrt und Hydrographie (BSH) in Germany has applied a noise restriction of 160 dB re. 1 µPa^2s SEL (and 190 dB re. 1 µPa SPL peak) at 750 metres from the piling source in recent German wind farm consents.

The purpose of this report is to model the predicted noise levels from the installation of the turbine foundations for proposed 10 MW turbines and determine the noise levels without any noise mitigation.

1.2. Projects objectives

This report has been compiled by Subacoustech Environmental Limited to estimate the likely level of underwater noise during the installation of the substation foundations. Subacoustech Environmental has completed the following project objectives:

- A review of background information on the units for measuring and assessing under-water noise and vibration;
- A review of the current research on the impact and effect of noise on marine fauna;
- Subsea noise modelling to estimate the potential for physical injury or fatality to marine species based on predicted unweighted levels of underwater noise;
- Modelling of sound propagation in the dB_{ht}(Species) metrics for 10 m diameter piles;
- Comments on the variability of noise propagation across the transects; and
- Summary and conclusions.

This report quantifies the potential effects and impacts of the underwater noise that is likely to be generated by impact piling operations during the installation of wind turbine foundations at the Horns Rev 3 wind farm.

1.3. Impact piling

It has been proposed that impact piling is used to drive the piles into the seabed. This technique involves a large weight or “ram” being dropped or driven onto the top of the pile, driving it into the sea bed. Usually, double-acting hammers are used in which compressed air not only lifts the ram, but also imparts a downward force on the ram, exerting a larger force than would be the case if it were only dropped under the action of gravity. Percussive impact piling has been established as a high level source of underwater impulsive noise (Würsig, 2000; Caltrans, 2001; Nedwell et al, 2003b; Parvin et al, 2006; Thomsen et al, 2006; Nedwell et al 2007a).

Noise is created in air by the hammer, partly as a direct result of the impact of the hammer with the pile. Some of this airborne noise is transmitted into the water. Of more significance to the underwater noise, however, is the direct radiation of noise from the surface of the pile into the water as a consequence of the compressional, flexural or other complex structural waves that travel down the pile following the impact of the hammer on its head. As water is of similar density to steel, waves in the submerged section of the pile couple sound efficiently into the surrounding water. These waterborne waves will radiate outwards, usually providing the greatest contribution to the underwater noise.

At the end of the pile, force is exerted on the substrate not only by the mean force transmitted from the hammer by the pile, but also by the structural waves travelling down the pile which induce lateral waves in the seabed. These may travel both as compressional waves, in a similar manner to the sound in the water, or as a seismic wave, where the displacement travels as Rayleigh waves (Brekhovskikh, 1960). The waves can travel outwards through the seabed or by reflection from deeper sediments. As they propagate, sound will tend to “leak” upwards into the water, contributing to the waterborne wave. Since the speed of sound is generally greater in consolidated sediments than in water, these waves usually arrive first as a precursor to the waterborne wave.

Generally, the level of the seismic wave is typically 10 – 20 dB below the waterborne arrival, and hence it is the latter that dominates the noise. In the context of this study, it should be noted that where mitigation measures such as pile cladding are used to attenuate the waterborne noise, the seismic wave may remain and limit the effectiveness of the technique.

Cod

2. UNDERWATER NOISE

2.1. Introduction

Sound travels much faster in water (approximately 1,500 m/s) than in air (340 m/s). Since water is a relatively incompressible, dense medium, the pressures associated with underwater sound tend to be much higher than in air. As an example, background levels of sea noise of approximately 130 dB re 1 µPa for UK coastal waters are not uncommon (Nedwell et al, 2003a and 2007a). This level equates to about 100 dB re 20 µPa in the units that would be used to describe a sound level in air. Such levels in air would be considered to be hazardous. However, marine mammals and fish have evolved to live in this environment. The most sensitive thresholds are often not below 100 dB re 1 µPa and typically not below 70 dB re 1 µPa (44 dB re 20 µPa using the reference unit that would be used in air).

2.2. Units of measurement

Sound measurements underwater are usually expressed using the decibel (dB) scale, which is a logarithmic measure of sound. A logarithmic scale is used because rather than equal increments of sound having an equal increase in effect, typically a constant ratio is required for this to be the case; that is, each doubling of sound level will cause a roughly equal increase in "loudness".

Any quantity expressed in this scale is termed a "level". If the unit is sound pressure, expressed on the dB scale, it will be termed a "Sound Pressure Level". The fundamental definition of the dB scale is given by:

- Level = $10 \times \log_{10}(Q/Q_{ref})$ eqn. 2-1

where Q is the quantity being expressed on the scale, and Q_{ref} is the reference quantity.

The dB scale represents a ratio and, for instance, 6 dB really means "twice as much as…". It is, therefore, used with a reference unit, which expresses the base from which the ratio is expressed. The reference quantity is conventionally smaller than the smallest value to be expressed on the scale, so that any level quoted is positive. For instance, a reference quantity of 20 µPa is usually used for sound in air, since this is the threshold of human hearing.

A refinement is that the scale, when used with sound pressure, is applied to the pressure squared rather than the pressure. If this were not the case, if the acoustic power level of a source rose by 10 dB the Sound Pressure Level would rise by 20 dB. So that variations in the units agree, the sound pressure must be specified in units of RMS pressure squared. This is equivalent to expressing the sound as:

- Sound Pressure Level = $20 \times \log_{10} (P_{RMS}/P_{ref})$ eqn. 2-2

For underwater sound, typically a unit of one microPascal (µPa) is used as the reference unit; a Pascal is equal to the pressure exerted by one Newton over one square metre. One microPascal equals one millionth of this.

2.3. Quantities of measurement

Sound may be expressed in many different ways depending upon the particular type of noise, and the parameters of the noise that allow it to be evaluated in terms of a biological effect. These are described in more detail below.

2.3.1 Peak level

The peak level is the maximum level of the acoustic pressure, usually a positive pressure. This form of measurement is often used to characterise underwater blasts where there is a clear positive peak following the detonation of explosives. Examples of this type of measurement used to define underwater blast waves can be found in Bebb and Wright (1953, 1955), Richmond et al (1973), Yelverton et al (1973) and Yelverton and Richmond (1981). The data from these studies have been widely interpreted in a number of reviews on the impact of high level underwater noise causing fatality and injury in human divers, marine mammals and fish (see for example Rawlins, 1974; Hill, 1978; Goertner, 1982; Richardson et al, 1995; Cudahy and Parvin, 2001; Hastings and Popper, 2005). The peak sound level of a freely suspended charge of Tri-Nitro-Toluene (TNT) in water can be estimated from Arons (1954), as summarised by Urick (1983). For offshore operations such as well head severance, typical charge weights of 40 kg may be used, giving a source peak pressure of 195 MPa or 285 dB re 1 µPa @ 1m (Parvin et al, 2007). The BSH requirements include peak SPL (see below).

2.3.2 Peak to peak level

The peak to peak level is usually calculated using the maximum variation of the pressure from positive to negative within the wave. This represents the maximum change in pressure (differential pressure from positive to negative) as the transient pressure wave propagates. Where the wave is symmetrically distributed in positive and negative pressure, the peak to peak level will be twice the peak level, and hence 6 dB higher.

Peak to peak levels of noise are often used to characterise sound transients from impulsive sources such as percussive impact piling and seismic airgun sources. Measurements during offshore impact piling operations to secure tubular steel piles into the seabed have indicated peak to peak source level noise from 244 to 252 dB re 1 µPa @ 1m for piles from 4.0 to 4.7 m diameter (Parvin et al, 2006; Nedwell et al, 2007a).

2.3.3 Sound Pressure level (SPL)

The Sound Pressure Level is normally used to characterise noise and vibration of a continuous nature such as drilling, boring, continuous wave sonar, or background sea and river noise levels. To calculate the SPL, the variation in sound pressure is measured over a specific time period to determine the Root Mean Square (RMS) level of the time varying sound. The SPL can therefore be considered to be a measure of the average level of the sound over the measurement period.

As an example, small sea going vessels typically produce broadband noise-at-source SPLs from 170 – 180 dB re 1 µPa @ 1 m (Richardson et al, 1995), whereas a supertanker generates source SPLs of typically 198 dB re 1 µPa @ 1 m (Hildebrand, 2004).

However, where an SPL is used to characterise transient pressure waves such as that from seismic airguns, underwater blasting or piling, the peak or peak-to-peak pressure is usually used instead of the RMS pressure. The advantage of using the peak-to-peak pressure is that it does not require a reference to any time period. Hence, this is the most effective way to characterise transient pressure waves as SPLs and avoids inconsistencies they could occur in having to choose a time period which could dramatically alter the calculated level. It has been reported that differences of 2 to 12 dB in RMS pressure, for the same wave form, can occur due to there not being a standardised method for deriving a time period for the RMS pressure of a transient (Madsen, 2005). In the case of piling it is the peak-to-peak pressure of an individual pile strike that is taken.

2.3.4 Sound Exposure Level (SEL)

When assessing the noise from transient sources such as blast waves, impact piling or seismic airgun noise, the issue of the time period of the pressure wave (highlighted above) is often addressed by measuring the total acoustic energy (energy flux density) of the wave. This form of analysis was used by Bebb and Wright (1953, 1954a, 1954b, 1955), and later by Rawlins (1987) to explain the apparent discrepancies in the biological effect of short and long range blast waves on human divers. More recently, this form of analysis has been used to develop an interim exposure criterion for assessing the injury range for fish from impact piling operations (Hastings and Popper, 2005; Popper et al, 2006).

The Sound Exposure Level (SEL) sums the acoustic energy over a measurement period, and effectively takes account of both the SPL of the sound source and the duration the sound is present in the acoustic environment. Sound Exposure (SE) is defined by the equation:

- $$SE = \int_0^T p^2(t)\,dt$$ eqn. 2-3

where p is the acoustic pressure in Pascals, T is the duration of the sound in seconds and t is time in seconds.

The Sound Exposure is a measure of the acoustic energy and, therefore, has units of Pascal squared seconds (Pa^2s).

To express the Sound Exposure on a logarithmic scale by means of a dB, it is compared with a reference acoustic energy level of 1 µPa^2 (P^2_{ref}) and a reference time (T_{ref}).

The Sound Exposure Level (SEL) is then defined by:

$$SEL = 10\log_{10}\left(\frac{\int_0^T p^2(t)\,dt}{P_{ref}^2 T_{ref}}\right)$$ eqn. 2-4

By selecting a common reference pressure P_{ref} of 1 µPa for assessments of underwater noise, the SEL and SPL can be compared using the expression:

- $SEL = SPL + 10\log_{10}T$ .eqn. 2-5

where the SPL is a measure of the average level of the broadband noise, and the SEL sums the cumulative broadband noise energy.

Therefore, for continuous sounds of duration less than one second, the SEL will be lower than the SPL. For periods of greater than one second the SEL will be numerically greater than the SPL (i.e. for a sound of ten seconds duration the SEL will be 10 dB higher than the SPL, for a sound of 100 seconds duration the SEL will be 20 dB higher than the SPL and so on).

2.4. The dB_{ht}(Species)

Measurement of sound using electronic recording equipment provides an overall linear, or unweighted, level of that sound. The level that is obtained depends upon the recording bandwidth and sensitivity of the equipment used. This, however, does not provide an indication of the behavioural impact that the sound will have upon a particular marine receptor. This is of fundamental importance when considering the behavioural impact of underwater sound, as this is associated with the perceived loudness of the sound by the species. Therefore, the same underwater sound will affect marine species in a different manner depending upon the hearing sensitivity of that species.

Where the intention is to estimate these more subtle behavioural or audiological effects of noise, caused by “loudness”, hearing ability has to be taken into account and simple metrics based on unweighted measures are inadequate. For instance, it has been determined that in humans a metric incorporating a frequency weighting that parallels the sensitivity of the human ear is required to accurately assess the behavioural effects of noise. The most widely used metric in this case is the dB(A), which incorporates a frequency weighting (the A-weighting).

The modelled levels of noise in this study have therefore also been presented in the form of a dB_{ht}(Species) level (Nedwell et al, 2007b and Terhune, 2013). This scale incorporates the concept of “loudness” for a species. The metric incorporates hearing ability by referencing the sound to the species’ hearing threshold, and hence evaluates the level of sound a species can perceive. In Figure 2.1 the same noise spectrum is perceived at a different loudness level depending upon the particular fish or marine mammal receptor. The aspect of the noise that can be heard is represented by the ‘hatched’ region in each case. The receptors also hear different parts of the noise spectrum. In the example shown, Fish 1 has the poorest hearing (highest threshold) and only hears the noise over a limited low frequency range. Fish 2 has very much better hearing and hears the main dominant components of the noise. Although having the lowest threshold to the sound, the marine mammal only hears the very high components of the noise and so it may be perceived as relatively quiet. From this it can be seen that the perceived noise levels of sources measured in dB_{ht}(Species) are usually much lower than the unweighted levels, both because the sound will contain frequency components that the species cannot detect and also because most aquatic and marine species have high thresholds of perception (are relatively insensitive) to sound.

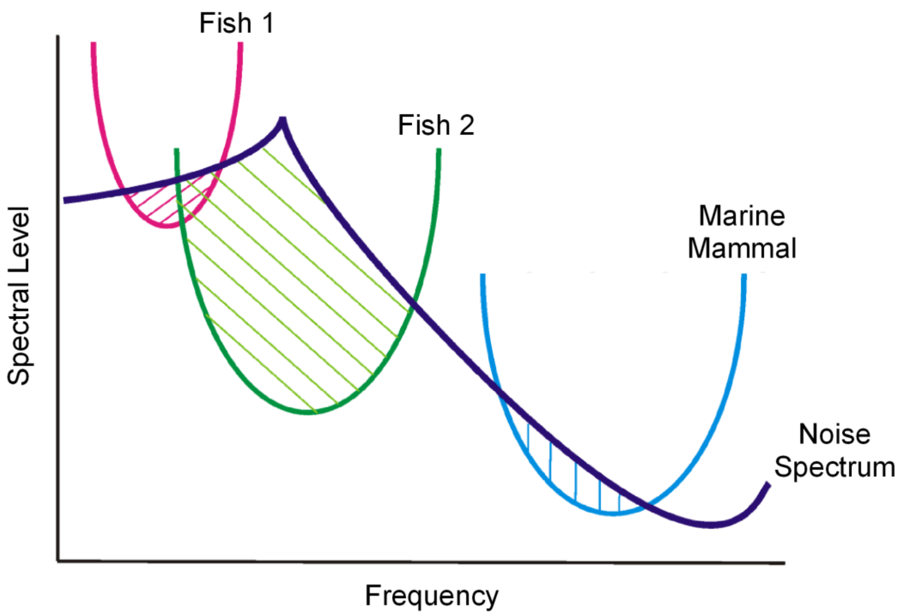


Figure 2.1 Illustration of perceived sound level (dB_{ht}) for representative fish and marine mammal species.

The dB_{ht}(Species) metric (Nedwell et al., 2007b) has been developed as a means for quantifying the potential for a behavioural impact on a species in the underwater environment. Since any given sound will be perceived differently by different species (since they have differing hearing abilities) the species name must be appended when specifying a level. For instance, the same sound might have a level of 70 dB_{ht} (*Gadus morhua*) for a cod and 40 dB_{ht} (*Salmo salar*) for a salmon, i.e. it is perceived as louder by a cod.

Currently, on the basis of a large body of measurements of fish avoidance of noise (Maes et al, 2004), and from re-analysis of marine mammal behavioural response to underwater sound, the following assessment criteria was published by the Department of Business, Enterprise and Regulatory Reform (BERR) (Nedwell et al, 2007b) to assess the potential impact of the underwater noise on marine species, Table 2.1.

Table 2.1 Assessment criteria used in this study to assess the potential impact of underwater noise on marine species.

Level in dB_{ht}(*Species*)	**Effect**
90 and above	Strong avoidance reaction by virtually all individuals
Above 110	Tolerance limit of sound; unbearably loud.
Above 130	Possibility of traumatic hearing damage from single event.

In addition, a lower level of 75 dB_{ht}(Species) has been used for analysis as a level of “significant avoidance”. At this level, it is estimated that about 50% of individuals will react to the noise, although the effect will probably be limited in duration by habituation (Thompson et al, 2013) and desire to be in an area.

2.4.1 Selection of species

In this study, a variety of fish and marine mammals with different hearing abilities have be chosen to give a good representation of how the sound from the proposed impact piling operations may affect marine receptors using the dB_{ht}(Species) metric. Peer reviewed audiograms are available for most of the species being considered and these are shown in Figure 2.2 and Figure 2.3 The exception is the sandeel, where a tentative surrogate has been used.

The marine mammal species considered in this study are:

- Harbour Porpoise (*Phocoena phocoena*), a marine mammal (toothed whale) that, based on current peer reviewed audiogram data (Kastelein et al, 2002), is the most sensitive marine mammal to high frequency underwater sound and prevalent in Danish waters; and
- Harbour (or common) Seal (*Phoca vitulina*), a pinniped that, based on current peer re-viewed audiogram data (Møhl, 1968, Kastak and Schustermann, 1998), is the most sensitive of the different seal species, or other marine mammals to mid-frequency underwater sound.

The fish species considered in this study are:

- Cod (*Gadus morhua*), (Chapman and Hawkins, 1973) a fish that is sensitive to under-water sound;
- Dab (*Limanda limanda*), a flatfish species that, based on current peer reviewed audiogram data (Chapman and Sand, 1974), is the most sensitive flatfish to underwater sound and used as a surrogate for plaice (*Pleuronectes platessa*);
- Herring (*Clupea harengus*), a fish that, based on current peer reviewed audiogram data (Enger and Andersen, 1967), is a particularly sensitive marine fish to underwater sound. It is also used as a conservative surrogate for sprat (*Sprattus sprattus*); and
- Sandeel (*Ammodytes marinus*) or sand lances lack a swim bladder and generally have poor sensitivity to sound. No audiogram is known to be available for *A. marinus* and so the Japanese sand lance *A. personatus* (Suga et al, 2005) is used as a surrogate. They are capable of hearing low frequencies typically less than about 500 Hz.

Where a surrogate has been used, the conclusions should be treated with caution.

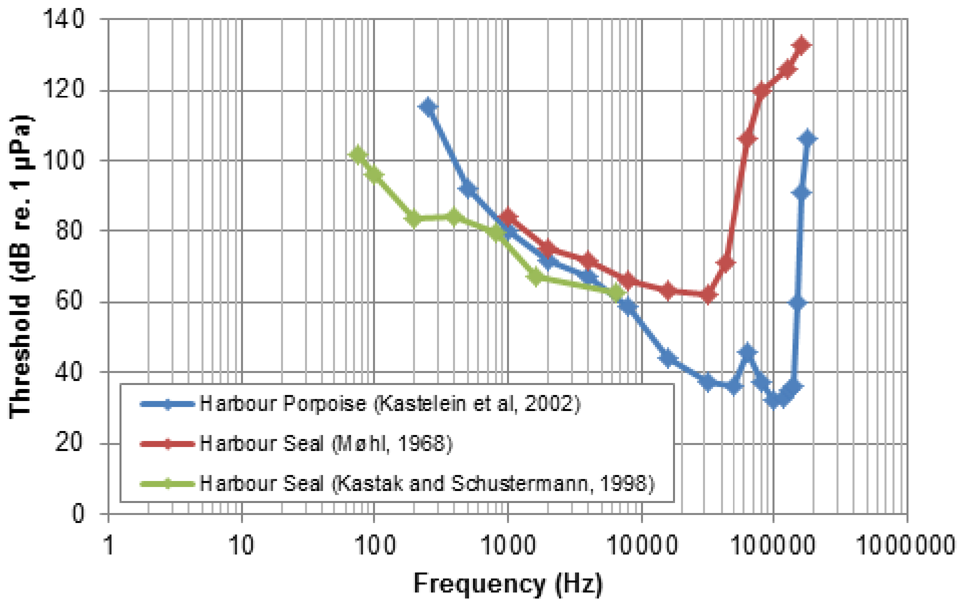


Figure 2.2 Audiograms of the species of marine mammals used in this study.

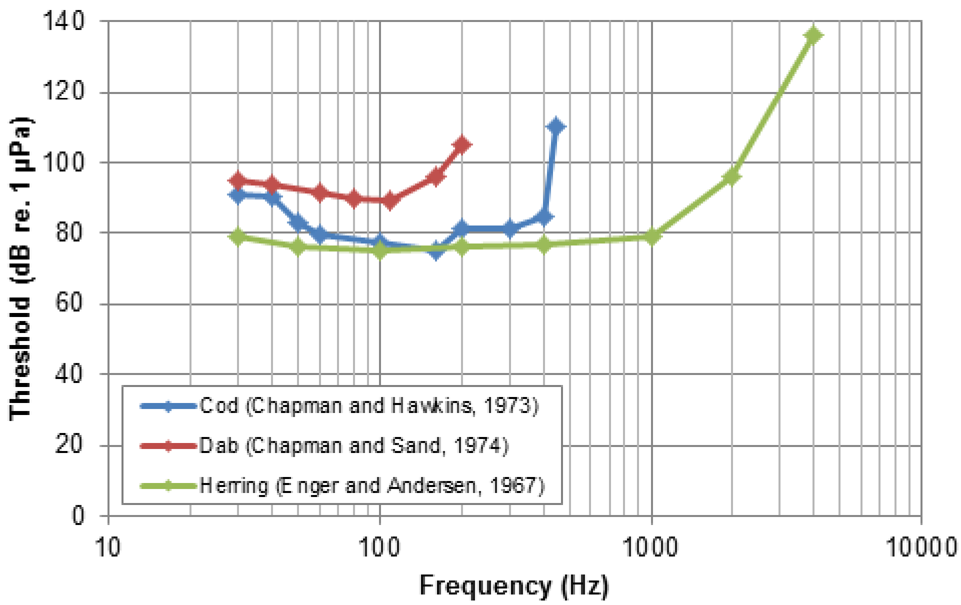


Figure 2.3 Audiograms of the species of fish used in this study.

It is important to note that the application of the dB_{ht}(Species) metric can only be as good as the audiogram for the species that it is based on. There is always variation from study to study, and tends to depend on the methodology used to derive the audiogram, for example by behavioural or auditory brainstem response techniques, and typically few individuals of a species are tested. Where there is a significant variation between the audiograms for a species available in the published data, generally the most sensitive, or most widely accepted, of the available audiograms will be used in the calculations.

2.5. The INSPIRE model

The Impulse Noise Sound Propagation and Impact Range Estimator (INSPIRE) model has been developed specifically to model the propagation of impulsive broadband underwater noise in shallow waters.

INSPIRE is a semi-empirical model designed to estimate the propagation of broadband pulses of sound, rather than single frequencies, as is usually the case for programs that have been developed as a result of military interests. These broadband pulses of sound are characteristic of piling, seismics, blasting and many other man-made noise sources.

It is relatively easy to show that the physical mechanisms that are of great importance in de-termining the propagation of single frequency sound may be of no relevance to the propaga-tion of broadband pulses, such as the noise emitted during impact piling. For instance, the surface anomaly effect ("Lloyd's Mirror"), which is of critical importance in determining single frequency propagation, has no bearing on the propagation of a broadband pulse. Thus, the physical mechanisms that determine the propagation of impulsive sounds are not the same as those that determine the propagation of single frequency pulses such as sonar.

As a result of a substantial programme of investigation of the database of recordings that Subacoustech has made, it has been determined that two key features determine the propa-gation of impulsive sound in coastal water. First, there is a geometric loss which is caused by sound spreading out over an increasingly wide wave front, and also diffracting downwards into the underlying bedrock. Second, there is a mechanism in which sounds may be considered to be "channelled" in the shallow water with a refracting surface and lossy sediment. The water may be considered to be a waveguide, with losses proportional to the degree to which sound energy is compacted into the waveguide. In shallow water, the losses are higher as the influence of energy loss in the substrate is proportionally greater. The effect of seasonal variations in temperature in northern European waters on transmission loss is small, and outweighed by other factors described here.

Subacoustech have found that these two mechanisms are completely adequate to model propagation of impulsive noise in shallow water within the limits of accuracy of the data that we possess. Thus, INSPIRE is a physical model, one in which the constants of the model have been set by comparison with actual data. The errors in modelling the propagation when it is subsequently compared with actual results largely arise from the natural range of variations in the blow energies that are used to drive the pile. If the pile encounters a hard patch of substrate, the blow energy can temporarily increase, leading to an increase in the radiated noise. Clearly, this effect cannot be pre-emptively predicted, but it can be dealt with statistically, which is why INSPIRE is set to yield a conservative value of noise.

The INSPIRE model has been specifically developed by Subacoustech to model the propagation of impulsive noise in shallow water. It uses a combined geometric and energy flow/hysteresis loss model to model propagation in shallow water. The INSPIRE model (currently version 3.4.3) has also been tested “blind” against measured impact piling noise data from several offshore construction operations, as well as a range of estuarine piling operations, and has been found to provide accurate results (Thompson et al., 2013).

The basic inputs of the INSPIRE model include;

Bathymetry and water depth above lowest astronomical tide;

- Co-ordinates of piling;
- Pile diameter;
- Blow energy;
- Piling duration;
- Strike rate;

Mitigation measures – including soft and slow starts.

The database that INSPIRE is based on consists of data taken from 10 individual sites, which includes measurements of sound propagation along 29 different transects. Pile diameters range from 500 mm to 6100 mm; specifically there are a large number of measurements for pile diameters sized 1800 mm, 4300 mm, 4700 mm and 6000 mm. Blow energies of up to 1100 kJ have been recorded, ranging from maximums of approximately 400 kJ for 1800 mm piles, 800 kJ for 4700 mm piles and between 800 and 1100 kJ for 6000 mm diameter piles. It has been validated against data from larger blow energies, and refined when necessary. Measurements have been taken in water depths anywhere between 2 or 3 m and up to 80 m. The majority of the measurements are from offshore piling, apart from piles less than 1000 mm in diameter which are coastal or riverine. All measurements in the database are taken from in and around the UK and the North Sea, with a significant number in the Thames Estuary and in the Irish Sea.

The model is able to provide a wide range of physical outputs, including the peak pressure, impulse, SEL and dB_{ht} of the noise. Transmission Losses are calculated by the model on a fully range and depth dependent basis. The INSPIRE model imports electronic bathymetry data as a primary input to determine the transmission losses along transects extending from the pile location which has been input in addition to other simple physical data.

INSPIRE has a model of mitigation built in, which allows the effect of bubble curtains, cladding, and other mitigation methods to be estimated. It should be noted that when the frequency-dependent behaviour of these methods is considered, they are often found to be less effective than if simple measures of overall sound level such as peak pressure are used.

3. IMPACT OF UNDERWATER SOUND ON MARINE SPECIES

3.1. Introduction

As part of this study, the propagation of underwater noise from the pile driving operations has been modelled in order to provide estimates of underwater sound levels as a function of range from two locations in the Horns Rev 3 site.

Transmission of sound in the underwater environment is highly variable from region to region, and can also vary considerably with the local bathymetry and physical conditions. Some frequency components of piling noise can be more rapidly attenuated than others in very shallow water regions typical of the silt and sandbank regions located around European coasts in which wind farms are often constructed.

In the conditions typical of those in which wind farms are installed (estuaries and shoals), the underwater sound may vary considerably temporally and spatially. The approach used in this and previous studies is, therefore, to base the modelling and assessment on a suitable acoustic model, which has been validated against a database of measured data in similar operations.

In this case, piles with a diameter of 10 m have been modelled, as this is the largest proposed foundation for 10 megawatt (MW) wind turbines at the Horns Rev 3 site. It has been assumed that a hammer blow energy of up to 3000 kJ will be used to install the piles, based on large piling hammers currently available. The maximum blow energy will be reach just before the monopile reach its maximum depth at the end of the piling.

One hundred and eighty transects have been modelled for each pile location using INSPIRE. These transects are equally spaced at two degree intervals (taken from grid north) for 360 degrees around the pile position and are generally taken to the extent of any impact ranges or until land is reached. The bathymetry along each of these transects has been recorded and depth profiles have been generated using digital bathymetry data and input into the INSPIRE model. In order to provide a balanced estimate of the likely impacts of underwater noise during piling at the Horns Rev 3 site in terms of water depth, the varying tidal states that may be encountered have been taken into account. Modelling has been carried out for water depth at Mean High Water Springs (MHWS) at Blåvands Huk, which 1.8 m above Lowest Astronomical Tide (LAT).

3.2. Noise modelling criteria

3.2.1 Criteria for assessing the effect of noise on marine mammals

The data currently available relating to the levels of underwater noise likely to cause physical injury or fatality are primarily based on studies of blast injury at close range to explosives with an additional small amount of information on fish kill as a result of impact piling. All the data concentrate on impulsive underwater noise sources as other sources of noise are rarely of a sufficient level to cause these effects.

Parvin et al (2007) present a comprehensive review of information on lethal and physical impacts of underwater noise on marine receptors previously studied and propose the following criteria to assess the likelihood of these effects occurring:

- Lethal effect may occur where peak to peak noise levels exceed 240 dB re 1 µPa; and
- Physical trauma may occur where peak to peak noise levels exceed 220 dB re 1 µPa.

These will be used for general criteria for all species of marine mammal and fish to define the potential for gross damage such as fatality, swim bladder rupture or tissue damage, since hearing is not involved in this process.

Increasing research has been undertaken recently to investigate the impact of noise on marine mammals. Harbour porpoises (Phocoena phocoena) are abundant in the North Sea and much of the research has been undertaken on this species. A study by Lucke et al (2009) noted the onset of a temporary threshold shift (TTS), or short term reduction in hearing capability, in a captive har bour porpoise when it was exposed to a noise level of 164 dB re 1 µPa.s SEL, or 194 dB re 1 µPa SPLpeak. Danish research by Tougaard (2013) suggests that 165 dB re 1 µPa.s SEL may be a more reasonable figure to use for the onset of TTS. In fact, Tougaard stated at the Effects of Noise on Aquatic Life conference in Budapest, 2013, that a level of 165 dB re 1 $\mu Pa^2 s$ SEL be considered a preliminary safe exposure limit for porpoises. Therefore, 165 dB re 1 µPa.s SEL will be used as the criteria for onset of TTS for harbour porpoises but should be considered precautionary.

Southall et al (2007) present another set of interim criteria for the levels of underwater noise that may lead to auditory injury to marine mammals based on the M-weighted Sound Exposure Level (SEL) and peak Sound Pressure Level (see Section 2). These criteria are presented in Table 3.1 In order to obtain the weighted sound exposure levels the data are first filtered using the proposed filter responses presented in Southall et al (2007) for either high, low or mid-frequency cetaceans or pinnipeds in water, then the sound exposure level is calculated.

Table 3.1 Proposed injury criteria for various marine mammal groups (after Southall et al, 2007).

Marine mammal group	**Sound Type**		
	Single pulses	**Multiple pulses**	**Nonpulses**
Low, Mid and High frequency cetaceans			
Sound Pressure Level	230 dB re. 1 µPa (peak)	230 dB re. 1 µPa (peak)	230 dB re. 1 µPa (peak)
Sound Exposure Level	198 dB re. 1 μPa^2-s ($M_{hf,mf,lf}$)	198 dB re. 1 μPa^2-s ($M_{hf,mf,lf}$)	215 dB re. 1 μPa^2-s ($M_{hf,mf,lf}$)
Pinnipeds (in water)			
Sound Pressure Level	218 dB re. 1 µPa (peak)	218 dB re. 1 µPa (peak)	218 dB re. 1 µPa (peak)
Sound Exposure Level	186 dB re. 1 μPa^2-s (M_{pw})	186 dB re. 1 μPa^2-s (M_{pw})	203 dB re. 1 μPa^2-s (M_{pw})

Based on the suggested groupings for marine mammals given above, the harbour porpoise is categorised as a 'high-frequency cetacean', based on its hearing capabilities. The injury criteria are based on research on other mammals species, where it was found that onset of permanent threshold shift (PTS), or an irrecoverable reduction in hearing acuity, was caused at an SEL level of 15 dB above the level that led to onset of TTS. Based on this adjustment, and utilising the latest research above, it is proposed that PTS in harbour porpoise could occur at noise levels in excess of 180 dB re 1 µPa^{2}s SEL. It is worth noting that the research leading to the 15 dB adjustment was carried out using chinchillas, and so this should be treated with caution in its application to marine mammals.

The criteria suggested by Southall et al (2007) for pinnipeds will be utilised, leading to a PTS threshold of 186 dB re 1 µPa^{2}s (M_{pw}) SEL (as in Table 3.1 above) and a TTS threshold of 171 dB re 1 µPa^{2}s (M_{pw}) SEL. This is parameter is weighted to the approximate hearing sensitivity of pinnipeds using the M-weighting suggested by Southall et al.

The noise level at which a behavioural response could be caused is somewhat lower than that which could lead to an injury to a mammal. In investigations into the reactions of marine mammals (seals and harbour porpoises) to loud introduced noise sources (Brandt et al, 2011), received noise levels of 150 dB re 1 µPa^{2}s SEL were found to be high enough to cause a behavioural disturbance. At 145 dB re 1 µPa^{2}s SEL, minor behavioural reactions might be expected. Modelling to these two thresholds has also been included in the assessment.

To summarise, the criteria to assess the potential impact for marine mammals used in this assessment are given in Table 3.2.

Table 3.2 Summary of noise criteria used for the assessment of potential impact on marine mammals.

Effect	Criteria	Weighting	Species
Lethal	240 dB re 1 µPa	Unweighted $SPL_{peak\text{-}to\text{-}peak}$	All
Physical injury	220 dB re 1 µPa	Unweighted $SPL_{peak\text{-}to\text{-}peak}$	All
PTS	186 dB re 1 µPa^{2}s (M_{pw})	Cumulative M-Weighted (pinniped) SEL	Pinniped (seal)
PTS	180 dB re 1 µPa^{2}s	Cumulative Unweighted SEL	Harbour porpoise
TTS	171 dB re 1 µPa^{2}s (M_{pw})	M-Weighted (pinniped) SEL	Pinniped (seal)
TTS	165 dB re 1 µPa^{2}s	Unweighted SEL	Harbour porpoise
Behavioural effect	150 dB re 1 µPa^{2}s	Unweighted SEL	Harbour porpoise and Pinniped (seal)
Behavioural effect	90 dB_{ht}(*Species*)	Various	Various

Effect	Criteria	Weighting	Species
Minor behavioural effect	145 dB re 1 µPa^{2}s	Unweighted SEL	Harbour porpoise and seal

3.2.2 Criteria for modelling the effect of noise on fish

The criteria used for assessing the impact of noise on fish injury is based on the work of the Fisheries Hydroacoustic Working Group in the USA. In the Agreement in Principle for Interim Criteria for Injury to Fish from Pile Driving Activities memo (2008), three criteria were assigned based on unweighted noise levels. This includes a peak sound pressure level and an accumulated sound exposure level over a period of time. An additional noise criterion is offered for fish less than 2 grams in weight, although they are otherwise generic criteria which make no distinction between species.

These criteria do not address behavioural impacts. A study undertaken by McCauley et al (2000) proposed noise levels which could cause a behavioural response in fish. However, the conclusions were based on the responses of antipodean species of caged fish to seismic airgun blasts. These results are therefore felt not to be relevant to the situation in Danish waters. The use of the dB_{ht}(Species) metric described in Section 2.4 is therefore considered the best method of describing the potential reactions of fish to introduced noise, as this can be ‘tailored’ to the specific species of fish actually present in the region.

Table 3.3 describes the full list of criteria used to assess the impact of noise introduced during the construction of Horns Rev 3 on fish.

Table 3.3 Summary of noise criteria used for the assessment of potential impact on fish.

Effect	Criteria	Weighting	Species
Lethal	240 dB re 1 µPa	Unweighted $SPL_{peak\text{-}to\text{-}peak}$	All
Physical injury	220 dB re 1 µPa	Unweighted $SPL_{peak\text{-}to\text{-}peak}$	All
Injury	206 dB re 1 µPa	Unweighted SPL_{peak}	All fish
Injury	187 dB re 1 µPa^{2}s	Cumulative Unweighted SEL	All fish
Injury	183 dB re 1 µPa^{2}s	Cumulative Unweighted SEL	Fish < 2g
Behavioural effect	90 dB_{ht}(*Species*)	Various	Various

Where the impact of noise is considered as an exposure over a period of time, it is assumed that the fish cannot flee fast enough to significantly reduce their exposure and therefore remain stationary, to provide a worst-case impact.

4. MODELLING RESULTS

4.1. Site and modelling location

Figure 4.1 below illustrates the location of the Horns Rev 3 site and the two modelling locations used for this study. The position at the northwest of the site is in deeper water (19.5 m at MHWS) than the southern position (13.8 m at MHWS), these two locations have been chosen to show the effect of piling into different depths of water, Table 4.1.

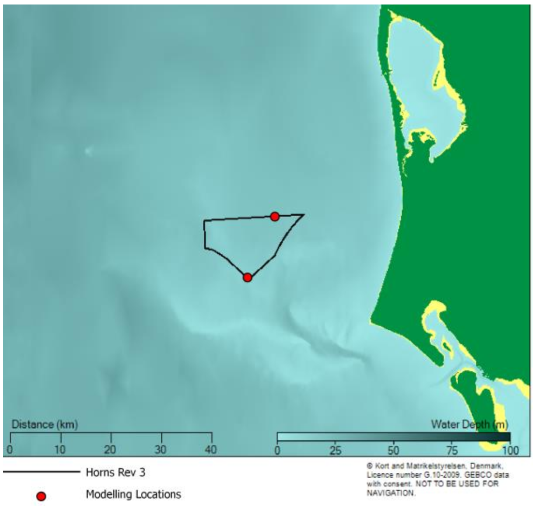


Figure 4.1 Map showing the boundary of the Horns Rev 3 site along with the two modelling locations used in this study.

Table 4.1 Co-ordinates of the two modelling locations.

	Latitude	Longitude
North East	55.7429° N	7.7746° E
South	55.6345° N	7.6893° E

4.2. Modelling of lethal effect and physical injury

Two criteria have been identified in Sections 3.2.1 and 3.2.2 to assess lethal effect and physical injury, unrelated to hearing, to all receptors using unweighted peak-to-peak sound pressure levels. These are:

- 240 dB re 1 µPa single strike unweighted peak-to-peak SPL for lethal effect, and
- 220 dB re 1 µPa single strike unweighted peak-to-peak SPL for physical traumatic injury, in excess of hearing damage.

The results of modelling a 10 m pile being installed with a maximum blow energy of 3000 kJ at Horns Rev 3 are summarised in Table 4.2 below.

Table 4.2 Maximum predicted impact ranges for lethal effect and physical traumatic injury.

	Lethal effect (240 dB re 1 µPa $SPL_{peak\text{-}to\text{-}peak}$)	**Physical Injury** (220 dB re 1 µPa $SPL_{peak\text{-}to\text{-}peak}$)
North East	6 m	6 m
South	82 m	75 m

Due to the relatively small size of these ranges, these have not been described graphically on a figure.

4.3. Modelling of PTS in marine mammals

Two criteria for assessing permanent threshold shift (PTS) in marine mammals have been identified in Sections 3.2.1 and 3.2.2. The two criteria are:

- 186 dB re 1 µPa^{2}s (M_{pw}) cumulative M-Weighted SEL for PTS in pinnipeds, and
- 180 dB re 1 µPa^{2}s cumulative unweighted SEL for PTS in harbour porpoise.

Both of these criteria take into account the cumulative received Sound Exposure Level (SEL) for a marine mammal over the entire piling operation. For this modelling it is assumed that the receptor is fleeing from the noise at a rate of 1.5 m/s.

The INSPIRE model handles fleeing animals and cumulative noise impacts over time by calculating “starting range” for receptor. For example, if an animal were to start at the 180 dB SEL contour at the commencement of piling, and flees, in a straight line away from the noise at a rate of 1.5 m/s for the duration of the operation its total received level of noise at the end of the piling would be 180 dB SEL. If an animal were to start anywhere inside the contour and flee at 1.5 m/s it would receive a level of noise in excess of 180 dB SEL at the end of piling. The INSPIRE model also assumes that if the fleeing animal meets the coast it will stop in the shallow water for the remainder of the piling.

The results of modelling a 10 m pile being installed with a maximum blow energy of 3000 kJ at Horns Rev 3 are summarised in Table 4.3and presented as contour plots in Figure 4.2 and Figure 4.3.

Table 4.3 Predicted impact ranges using the PTS criteria for marine mammals.

PTS		Pinniped (186 dB SEL re 1 µPa^{2}s (M_{pw}) (cumulative))	Harbour Porpoise (180 dB SEL re 1 µPa^{2}s (cumulative))
North East	Maximum	2.1 km	10.4 km
	Minimum	1.7 km	7.2 km
	Mean	1.9 km	8.7 km
South	Maximum	900 m	8.0 km
	Minimum	700 m	5.3 km
	Mean	800 m	6.6 km

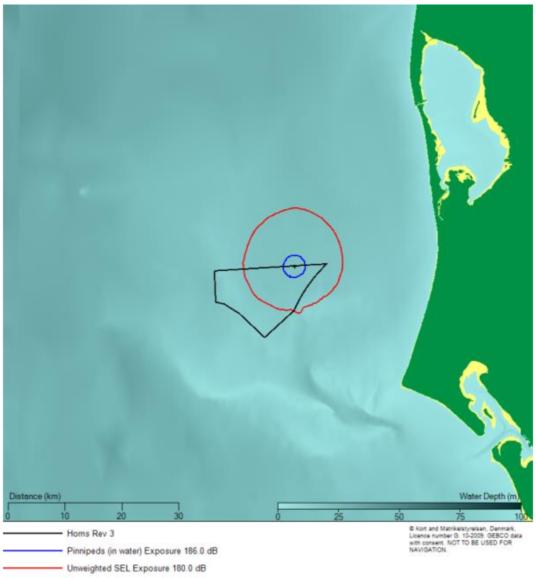


Figure 4.2 Contour plot showing the estimated impact ranges for the identified PTS criteria for marine mammals from installing a 10 m diameter pile using a maximum blow energy of 3000 kJ at the North East modelling location.

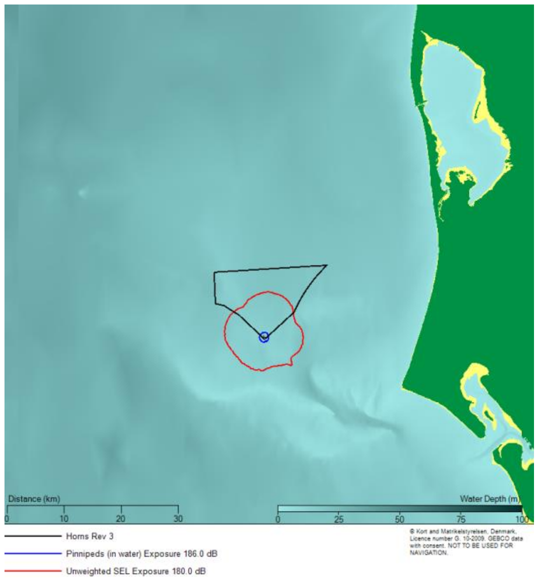


Figure 4.3 Contour plot showing the estimated impact ranges for the identified PTS criteria for marine mammals from installing a 10 m diameter pile using a maximum blow energy of 3000 kJ at the South modelling location.

4.4. Modelling of TTS in marine mammals

Four criteria for assessing temporary threshold shift (TTS) in marine mammals have been identified in sections 3.2.1 and 3.2.2 These criteria are as follows:

- 171 dB re 1 µPa^{2}s (M_{pw}) single strike M-Weighted SEL for TTS in pinnipeds,
- 165 dB re 1 µPa^{2}s single strike unweighted SEL for TTS in harbour porpoise.

The results of modelling a 10 m pile being installed with a maximum blow energy of 3000 kJ at Horns Rev 3 are summarised in Table 4.4 and presented as contour plots in Figure 4.4 and Figure 4.5.

Table 4.4 Predicted impact ranges using the TTS criteria for marine mammals.

TTS		**Pinniped (171 dB re 1 µPa^{2}s (M_{pw}))**	**Harbour Porpoise (165 dB re 1 µPa^{2}s)**
North East	Maximum	2.0 km	6.2 km
	Minimum	1.9 km	6.0 km
	Mean	1.9 km	6.1 km
South	Maximum	1.4 km	5.3 km
	Minimum	1.3 km	4.9 km
	Mean	1.3 km	5.1 km

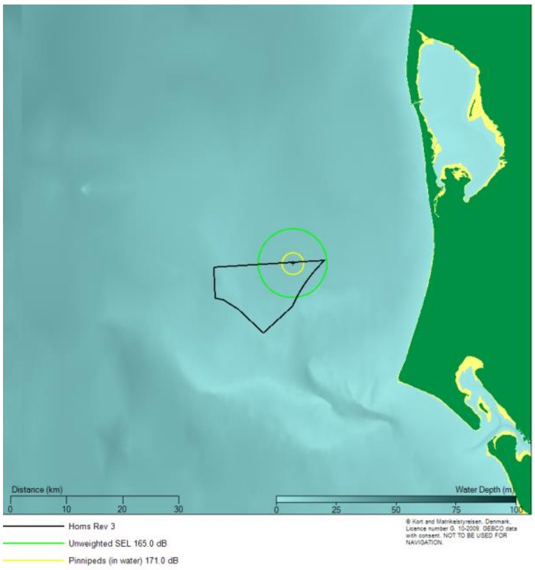


Figure 4.4 Contour plot showing the estimated impact ranges for the identified TTS criteria for marine mammals from installing a 10 m diameter pile using a maximum blow energy of 3000 kJ at the North East modelling location.

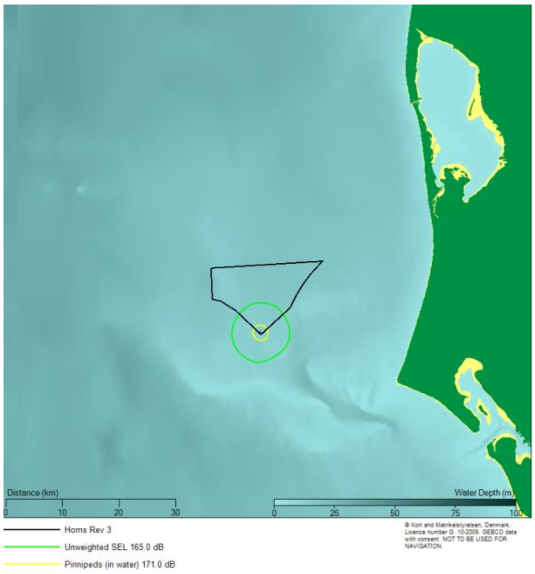


Figure 4.5 Contour plot showing the estimated impact ranges for the identified TTS criteria for marine mammals from installing a 10 m diameter pile using a maximum blow energy of 3000 kJ at the South modelling location.

4.5. Modelling of injury to fish

Three criteria for assessing injury in fish have been identified in Sections 3.2.1 and 3.2.2. The criteria are:

- 206 dB re 1 µPa single strike unweighted SPL (peak) for injury in all sizes of fish,
- 187 dB re 1 µPa^{2}s cumulative unweighted SEL for injury in all sizes of fish, and
- 183 dB re 1 µPa^{2}s cumulative unweighted SEL for injury for fish under 2 g in mass.

The second and third of these criteria take into account the cumulative received SEL for a receptor over the entire piling operation. For this modelling it is assumed that the receptor is stationary throughout the piling operation. The results of modelling a 10 m pile being installed with a maximum blow energy of 3000 kJ at Horns Rev 3 using these criteria are summarised in Table 4.5and resented as contour plots in Figure 4.6 and Figure 4.7.

Table 4.5 Predicted impact ranges using the injury criteria for fish

Injury		**All fish (206 dB re 1 µPa SPL_{peak})**	**All fish (187 dB re 1 µPa^{2}s (cumulative))**	**Fish < 2 g (183 dB re 1 µPa^{2}s (cumulative))**
North East	Maximum	250 m	14.6 km	19.4 km
	Minimum	250 m	12.0 km	15.4 km

Injury		**All fish** (206 dB re 1 µPa SPL_{peak})	**All fish** (187 dB re 1 µPa^{2}s (cumulative))	**Fish < 2 g** (183 dB re 1 µPa^{2}s (cumulative))
	Mean	250 m	13.4 km	17.3 km
South	Maximum	220 m	12.5 km	16.6 km
	Minimum	220 m	9.5 km	11.4 km
	Mean	220 m	11.2 km	14.3 km

It is worth noting that these ranges are somewhat larger than for the marine mammals despite the criteria being similar. This is mostly due to the ability of the mammals to flee relatively quickly, and thus reduce their exposure, whereas the fish must be assumed to be stationary.

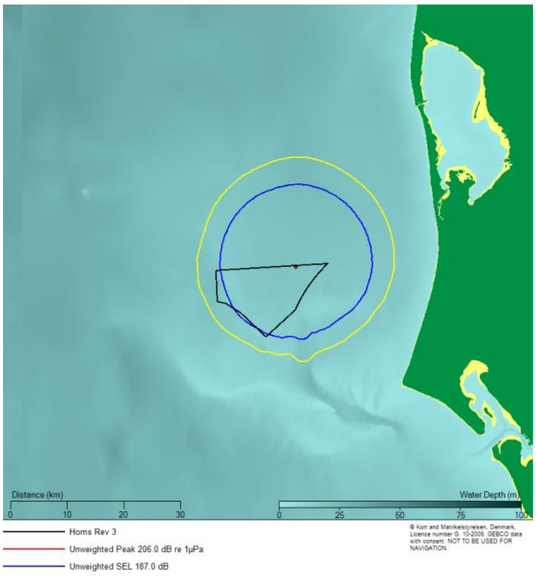


Figure 4.6 Contour plot showing the estimated impact ranges for the identified injury criteria for fish from installing a 10 m diameter pile using a maximum blow energy of 3000 kJ at the North East modelling location.

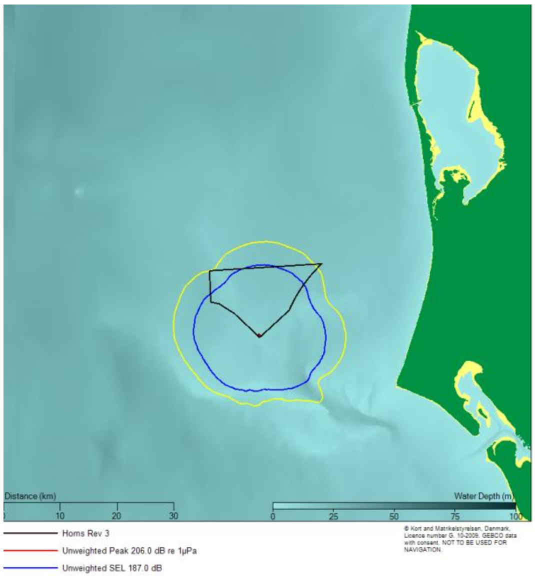


Figure 4.7 7 Contour plot showing the estimated impact ranges for the identified injury criteria for fish from installing a 10 m diameter pile using a maximum blow energy of 3000 kJ at the South modelling location

4.6. Modelling of behavioural effect in marine mammals using unweighted SELs

Two criteria have been identified for assessing the behavioural effect in marine mammals in Sections 3.2.1 and 3.2.2, both using the level from a single strike in terms of unweighted SEL. The two criteria are:

- 150 dB re 1 µPa^{2}s single strike unweighted SEL for behavioural effect in harbour porpoise and pinnipeds, and
- 145 dB re 1 µPa^{2}s single strike unweighted SEL for minor behavioural effect in harbour porpoise and pinnipeds.

The results of modelling a 10 m pile being installed with a maximum blow energy of 3000 kJ at Horns Rev 3 using these criteria are summarised in Table 4.6 and presented as contour plots in Figure 4.8 and Figure 4.9.

Table 4.6 Predicted impact ranges for behavioural effect using unweighted SELs for marine mammals

Behavioural Effect		**Harbour Porpoise and Pinniped (150 dB re 1 µPa^{2}s)**	**Harbour Porpoise and Pinniped (145 dB re 1 µPa^{2}s)**
North East	Maximum	21.5 km	28.8 km
	Minimum	16.7 km	20.3 km
	Mean	19.0 km	24.4 km
South	Maximum	18.4 km	24.5 km
	Minimum	12.3 km	15.5 km
	Mean	15.7 km	20.5 km

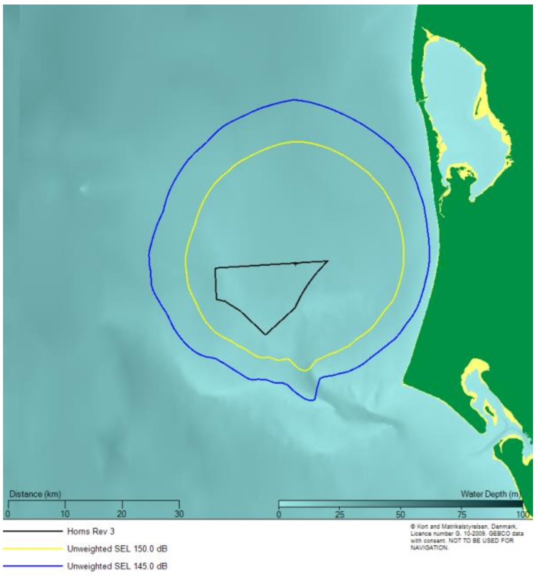


Figure 4.8 Contour plot showing the estimated impact ranges for the identified unweighted SEL behavioural effect criteria for marine mammals from installing a 10 m diameter pile using a maximum blow energy of 3000 kJ at the North East modelling location.

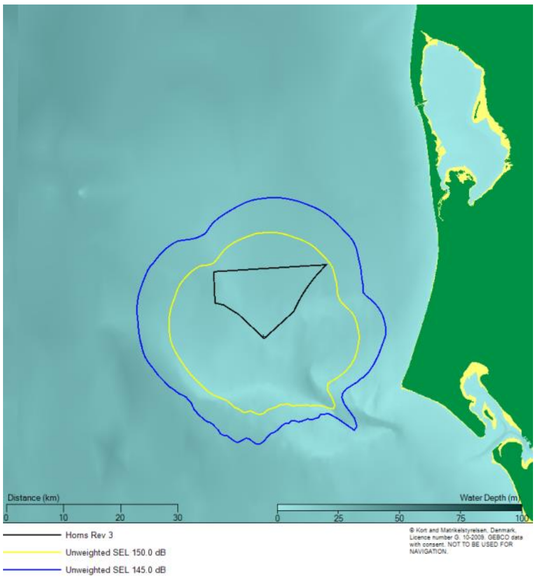


Figure 4.9 Contour plot showing the estimated impact ranges for the identified unweighted SEL behavioural effect criteria for marine mammals from installing a 10 m diameter pile using a maximum blow energy of 3000 kJ at the South modelling location.

4.7. Modelling of behavioural effect using the dB_{ht}(Species)

Table 4.7and Table 4.8 present summaries of impact ranges out to which a strong behavioural avoidance is expected to occur (90 dB_{ht}). The tables show that the largest 90 dB_{ht} impact ranges are expected out to a maximum of 24 km for herring and cod from the North East modelling location, with smaller impact ranges predicted for the other species. These results are summarised in Table 4.7 and Table 4.8 below, and illustrated as contour plots in Figure 4.10 to Figure 4.14. It should be noted that ranges for the sand lance/sandeel are very small and have therefore not be shown as figures. Additionally the modelling was undertaken assuming the maximum blow energy will be used, whereas in practice the piling is unlikely to reach this maximum or only for a short period of time.

Table 4.7 Summary of the mean ranges from the North East location out to 90 dB_{ht} where a behavioural reaction could occur in individuals from impact piling of a 10 m diameter pile using a blow energy of 3000 kJ.

North East	Range to 90 dB_{ht}(*Species*) (km)		
	Max	Min	Mean
Cod	23.7	17.4	20.3
Dab	6.9	6.5	6.8
Herring	24.7	17.7	20.5
Sand Lance	0.5	0.4	0.5
Harbour Porpoise	15.5	13.4	14.5
Harbour Seal	10.6	9.2	10.1

Table 4.8 Summary of the mean ranges from the south location out to 90 dB_{ht} where a behavioural reaction could occur in individuals from impact piling of a 10 m diameter pile using a blow energy of 3000 kJ

South	Range to 90 dB_{ht}(*Species*) (km)		
	Max	Min	Mean
Cod	17.6	11.4	14.8
Dab	5.1	4.7	4.9
Herring	18.8	12.2	15.8
Sand Lance	0.4	0.3	0.3
Harbour Porpoise	13.3	10.5	12.1
Harbour Seal	8.8	7.8	8.2

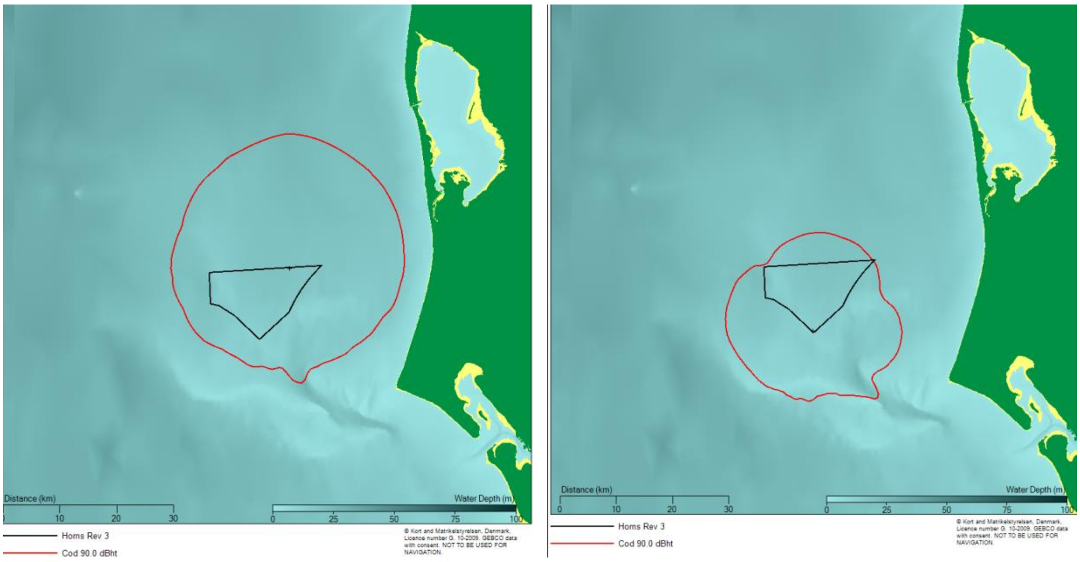


Figure 4.10 Contour plot showing the estimated levels of noise in terms of dB$_{ht}$ for cod from installing a 10 m diameter pile using a maximum blow energy of 3000 kJ at the North East (left) and South (right) modelling location.

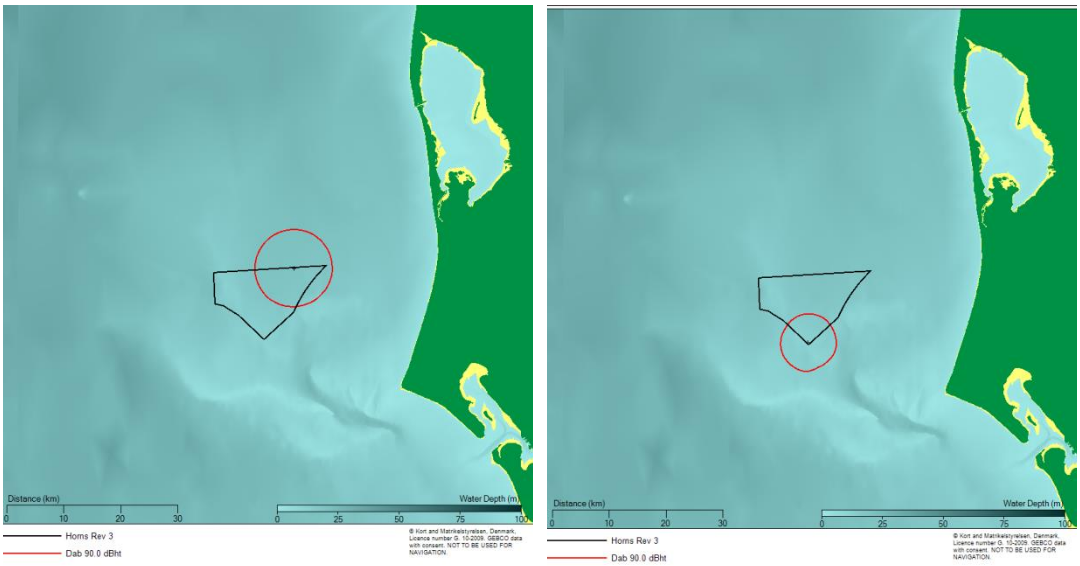


Figure 4.11 Contour plot showing the estimated levels of noise in terms of dB$_{ht}$ for dab from installing a 10 m diameter pile using a maximum blow energy of 3000 kJ at the North East (left) and South (right) modelling location.

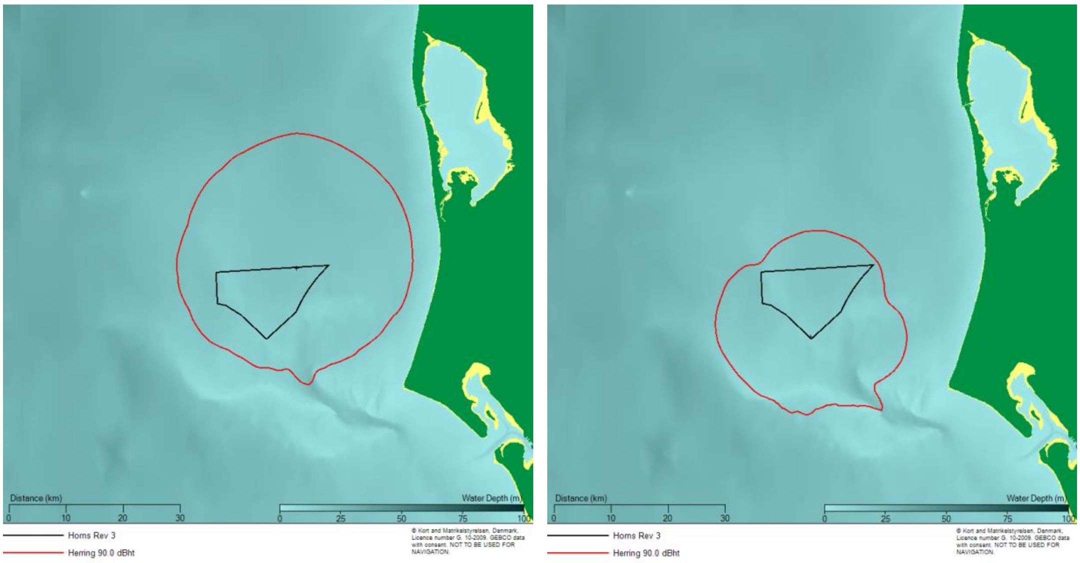


Figure 4.12 Contour plot showing the estimated levels of noise in terms of dB$_{ht}$ for herring from installing a 10 m diameter pile using a maximum blow energy of 3000 kJ at the North East (left) and South (right) modelling location.

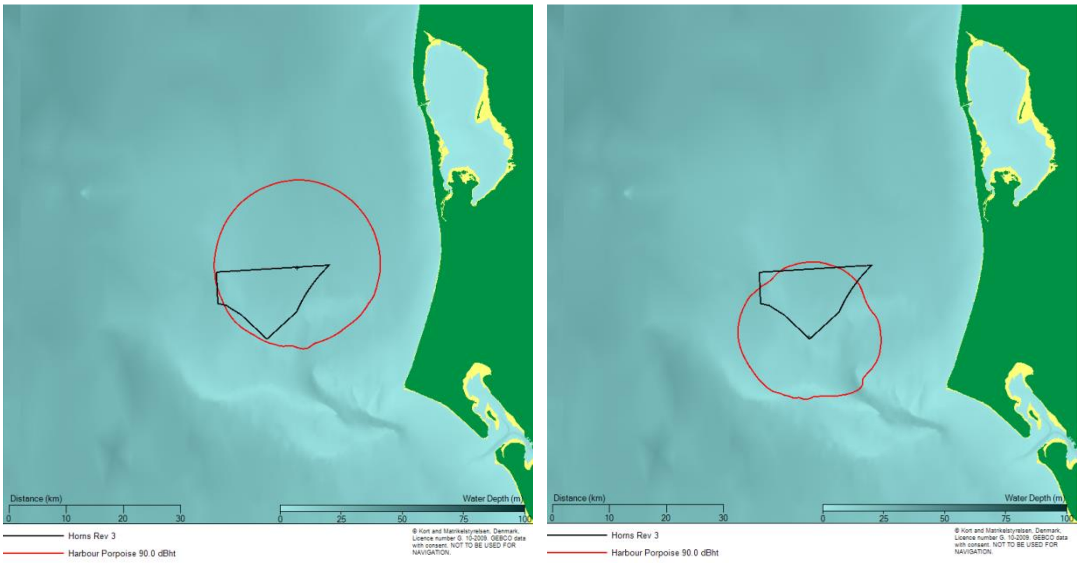


Figure 4.13 Contour plot showing the estimated levels of noise in terms of dB$_{ht}$ for harbour porpoise from installing a 10 m diameter pile using a maximum blow energy of 3000 kJ at the North East (left) and South (right) modelling location.

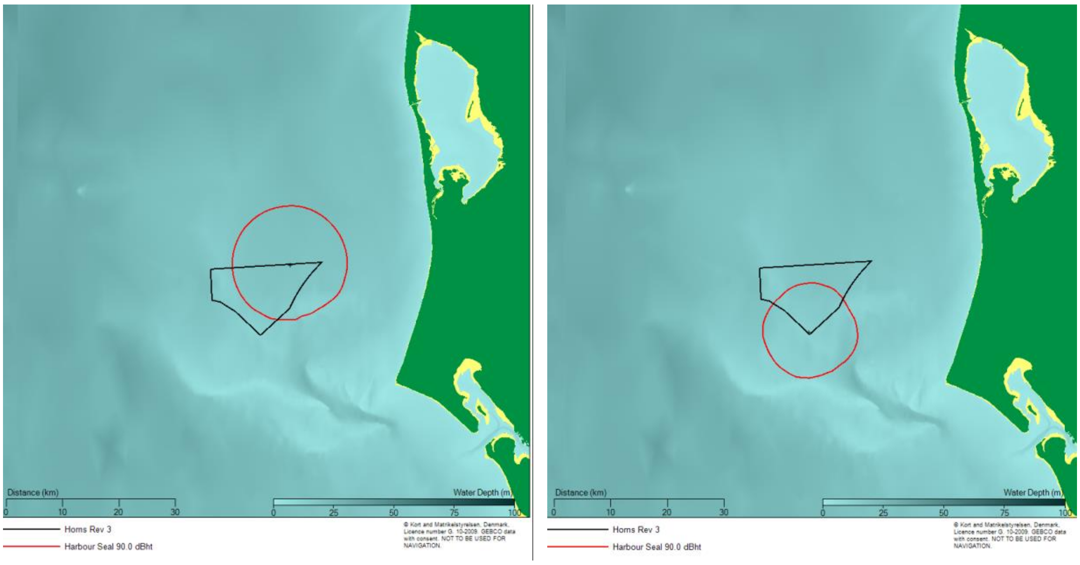


Figure 4.14 Contour plot showing the estimated levels of noise in terms of dB_{ht} for harbour seal from installing a 10 m diameter pile using a maximum blow energy of 3000 kJ at the North East (left) and South (right) modelling location.

Harbour porpoise – mother and calf © Caroline Höschle

5. SUMMARY AND CONCLUSION

Subacoustech Environmental has undertaken a study on behalf of Orbicon A/S to assess the impact of underwater piling in the North Sea in relation to the proposed construction of offshore wind turbine foundations as part of the Horns Rev 3 project.

The level of underwater noise from the installation of 10 m diameter piles with a maximum hammer blow energy of 3000 kJ has been estimated by using a proprietary underwater sound propagation model that enables the behaviour of noise with range from the piling to be estimated for varying tidal conditions, water depths and piling locations based on an existing database of measurements of piling noise.

Estimates of underwater noise in terms of sound exposure level and sound pressure level have been made to indicate the range at which each restriction might occur without mitigation. The range to which noise levels will propagate underwater in the vicinity of the piling at the Horns Rev 3 site have been calculated based on a variety of criteria.

1. Risk of lethal and physical injury, i.e. trauma to internal organs in excess of hearing damage, is calculated at ranges of less than 10 metres and less than 100 metres, respectively, for any species.
2. A noise exposure leading to a permanent threshold shift (hearing damage) in pinnipeds over the whole piling period, using the 186 dB SEL re 1 µPa^{2}s (M_{pw}) criterion could occur where an animal is present between 700 m and 2.1 km from the pile at the start of the piling operation, depending on animal and piling location. This increases to between 5.3 km and 10.4 km for harbour porpoises, based on a criterion of 180 dB SEL.
3. An instantaneous temporary threshold shift (i.e. a short-term reduction in hearing sensitivity) in pinnipeds could occur at between 1.3 km and 2.0 km from the pile, depending on the piling and animal location, based on the 171 dB SEL criteria noted in Southall et al (2007). For harbour porpoises, the distance is 4.9 km to 6.2 km based on 165 dB SEL as noted in Tougaard (2013).
4. The range where injury could occur for fish is calculated using interim criteria proposed by the FHWG in the USA. Based on the 206 dB dB re 1 µPa SPLpeak criterion, injury to fish could occur at distances up to 250 m. Using the 187 dB re 1 µPa^{2}s SEL criterion, and assuming the fish do not flee, the fish would receive the noise exposure within a distance of 9.5 km to 14.6 km from the piling, depending on the piling and the fish location. For small fish, under 2 grams, this range extends to 19.4 km at its maximum.
5. The range at which a behavioural effect could occur has been calculated for marine mammals using the 150 dB re 1 µPa^{2}s SEL noted in Brandt et al (2011). This is calculated to occur 12.3 km to 21.5 km from the piling depending on piling and animal location. A minor behavioural effect could occur at up to 28.8 km from the piling, based on 145 dB re 1 µPa^{2}s SEL from the same document.
6. Behavioural response has also been assessed using the dB_{ht}(Species). Using this metric, which is based on the specific hearing capabilities of the species under consideration, strong avoidance behaviour (90 dB_{ht}) in harbour porpoise is expected to occur out to a maximum range of 15.5 km from the piling. A strong

behavioural avoidance is expected out to a maximum range of 10.6 km for harbour seal.

7. Considering the behavioural response of fish using the dB_{ht}(Species) metric, the greatest response is expected from herring, a fish that is particularly sensitive to sound, with a strong avoidance behaviour expected between 12.2 and 24.7 km from the piling. The maximum equivalent range for cod is 23.7 km. Dab, the most sensitive flatfish, could exhibit a strong aversive reaction out to 6.9 km. The sandeel, using the sand lance as a surrogate species, is modelled to show this reaction at distances less than 500 metres.

These ranges are the greatest expected during piling and are only expected when the piling is undertaken at the maximum blow energy. This is not generally a common occur-rence, with a pile typically being driven at much lower blow energies for the majority of time.

Harbour seal inside the Horns Rev 1 Offshore Wind Farm © Graeme Pegram

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