DOGGER BANK
TEESSIDE A & B

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UNDERWATER NOISE MODELLING TO SUPPORT THE DOGGER BANK WIND FARM ENVIRONMENTAL IMPACT ASSESSMENT FOR DOGGER BANK TEESSIDE A AND DOGGER BANKTEESSIDE B

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Underwater Noise Modelling to Support the Dogger Bank Wind Farm Environmental Impact Assessment for Dogger Bank Teesside A and Dogger Bank Teesside B

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EXECUTIVE SUMMARY

This report presents the underwater noise assessment undertaken by the National Physical Laboratory and Loughborough University to estimate the likely underwater noise levels generated by pile driving of wind turbine foundations for the Dogger Bank Teesside A and Dogger Bank Teesside B projects, and assess the likely impact of subsea noise from construction, operation and decommissioning phases of the wind farm projects in support of the Environmental Impact Assessment.

Underwater sound emissions were modelled for a number of single sound sources (piles) within Dogger Bank Teesside A and Dogger Bank Teesside B. In addition, multiple concurrently operating sound sources were also modelled. These included sounds from multiple impact piling locations that either (i) all originated from within Dogger Bank Teesside A or Dogger Bank Teesside B or (ii) occurred concurrently with impact piling at Dogger Bank Teesside A and Dogger Bank Teesside B, but originated either in the wider Dogger Bank Zone or outside of the Zone e.g. from adjacent wind farms. Modelling was also performed to estimate the noise emissions for the operational phase of the wind farm. All modelling was selected to represent a range of propagation scenarios, and is intended to help identify the realistic worst case scenarios for the specific hearing sensitive receptors. For the construction phase, the modelled source was based on the use of various hammer blow energies considered for pile driving at Dogger Bank Teesside A and Dogger Bank Teesside B, and includes 3,000kJ, 2,300kJ, 1,900kJ and 300kJ (soft-start) hammer blow energies. It should be noted that the maximum hammer blow energy will not be realised at the onset of piling. Instead, piling will commence at a fraction of the maximum hammer blow energy (often around 20%) and ramp up to the full hammer energy over the period of the ‘soft-start’. It is also possible that the full hammer blow energy may not be realised at all sites or for all foundation locations.

The propagation model used was based on an energy flux approach, which calculates the sound energy transmitted through the water column. Results are presented as sound exposure level (SEL) and peak pressure received level outputs as a function of range from each modelled pile location, whilst accounting for seabed properties and varying bathymetry. The modelling indicates that there is considerable variation in noise propagation across Dogger Bank Teesside A and Dogger Bank Teesside B due to variations in bathymetry. The most efficient sound propagation conditions occur from the north, east and west of Dogger Bank Teesside A, and from the north of Dogger Bank Teesside B.

For both fish and marine mammals, injury and behavioural impact criteria have been applied to the outputs of the underwater noise modelling to predict the potential impact ranges during wind farm construction at Dogger Bank Teesside A and Dogger Bank Teesside B. It has been estimated that mortality of marine mammals or fish would be unlikely to occur except in very close proximity to the pile. Whilst it is possible that fish larvae mortality may occur, it is not possible to establish, due to absence of data regarding fish larval mortality from underwater noise, if mortality will occur, or indeed at what range from the pile. There is, however, indicative evidence that there will be no statistically significant effect on survival rates beyond a few kilometres assuming zero to very low tidal currents around Dogger Bank when fish larvae might be considered static.

Adopting the Joint Nature Conservation Committee (JNCC) guidance and assumptions (JNCC, 2010a), that the animal will flee the sound and the 500m mitigation zone monitored during the pre-piling watch is effective, it can be estimated that potential for instantaneous onset of injury (auditory, specifically PTS onset) for marine mammals will be mitigated by the 500m mitigation zone for hammer energies at least up to about 1900kJ. The potential for instantaneous onset of auditory injury (onset of PTS) could further be alleviated by extending the mitigation zone to 700m from the pile or by ensuring the hammer energy does not exceed 1900kJ within the first seven minutes of piling. Assuming that the animal swims away from the sound source at a relatively slow, cruising speed of 0.5m/s in a straight line, it would transit the distance between 500 and 700m in less than seven minutes from the first strike. In reality, an animal in close proximity to a high level sound source is likely to swim away faster (e.g. Brandt *et al.;* 2013a; 2013b).

Based on the available criteria and sound propagation modelling outputs the instantaneous onset of auditory injury (PTS onset from exposure to a single piling pulse) for marine mammals would be unlikely to occur beyond around 200m from the pile during full piling with maximum hammer blow energy of 3,000kJ, with the exception of harbour porpoise, where this range extends up to about 700m from the pile. As noted above, ramp up of the hammer energy during soft-start will reduce the risk of onset of instantaneous auditory injury to marine mammals and the gradual increase in hammer energy should enable harbour porpoise to move beyond the 700m range before the hammer reaches its maximum energy at 3,000kJ. Potential for onset of instantaneous injury from a pile driven with an initial soft-start hammer blow energy at 300kJ, for example, would be less than 100m for all marine mammals at Dogger Bank Teesside A and Dogger Bank Teesside B. Moreover, the maximum hammer strike energy is unlikely to be achieved during the soft-start and even at slow, cruising speed of 0.5m/s, the animal will transit the distance between the 500m mitigation zone and the 700m maximum injury impact range in much less than the shortest soft-start duration recommended by the JNCC in their 2010 guidelines for minimising the risk of piling on marine mammals. Prolonged exposure to the noise (SEL dose) may increase the risk of hearing damage at larger ranges. The range over which instantaneous injury (auditory and non-auditory) may occur to fish was estimated to be less than 200m from the pile for Dogger Bank Teesside A and less than 250m from a pile for Dogger Bank Teesside B. The SEL dose may increase the range at which hearing damage may occur, although it is thought likely that fish in very close proximity to the pile would move away from the pile during installation, which would decrease their SEL dose. The impact ranges summarised above for fish were estimated for the maximum 3,000kJ hammer blow energy, with lower hammer energies resulting in smaller ranges.

Using the currently available information in the literature and assuming a hammer blow energy of 3,000kJ, it has been estimated that pinnipeds may suffer temporary threshold shift (TTS) of hearing sensitivity and exhibit a fleeing response to the underwater noise from the foundation installation at ranges of up to about 1.7km for Dogger Bank Teesside A and Dogger Bank Teesside B. Equivalent responses in harbour porpoise were estimated at ranges of up to 4km to 5.5km from the pile for Dogger Bank Teesside A and Dogger Bank Teesside B. Low- (i.e. mysticetes) and mid-frequency (some odontocetes, primarily dolphins) cetaceans are not expected to suffer a TTS or exhibit a fleeing response at ranges exceeding about 400m and 200m from the pile, respectively. Another form of behavioural response considered in this assessment is avoidance, which is regarded as a more modest averse behavioural response compared to fleeing. For mid-frequency cetaceans, the evidence, suggests that they are likely to avoid ranges up to around 2.5km from the pile for Dogger

Bank Teesside A and Dogger Bank Teesside B. Low-frequency cetaceans are thought likely to avoid radii around the foundation from around 13.5km to 18km for Dogger Bank Teesside A and 13.5km to 19km for Dogger Bank Teesside B. This will depend on the activity of the animal, the location of the foundation within the site and the bearing away from the foundation, with the maximum avoidance range occurring a few tens of km to the north, east and west of the Dogger Bank Teesside A boundary and mainly to the north of the Dogger Bank Teesside B boundary. For harbour porpoise, the possible avoidance area around the foundation was estimated to be 22km to 33km for Dogger Bank Teesside A and between 22km and 33.5km for Dogger Bank Teesside B, depending on the location of the foundation within the site and the surrounding bathymetry. The estimated avoidance zone for the harbour porpoise is in places greater than the approximate 20km range observed in a recent study in Denmark. However, these ranges depend on hammer blow energy and the location of the pile, and its surrounding environment. It is also important to note that; possible avoidance does not necessarily equate to a 100% reduction in abundance; the estimated impact zones, particularly relating to the lower thresholds occurring at greater distance, are not uniform around the pile; and the impact ranges vary between pile locations. The larger impact ranges mostly occur from pile locations towards the north of the Dogger Bank Teesside A & B projects due to the down-sloping seabed. Observational field data have previously shown a reduction in acoustic detections, from harbour porpoise, at ranges up to around 20km from the pile with an increase in animal abundance observed with increasing time following piling and with increasing distance from the pile (Brandt *et al.* 2011). It is also worth noting that many of the avoidance ranges estimated in this assessment are based on average noise levels within the water column, and approximate sound levels around the mid-water column. Variations in sound levels through the water column as a function of depth are described further in Section 4.5. It is possible that marine mammals may occupy the surface layer during the piling activity where the noise levels are lower, or leave the area whilst swimming near the surface resulting in a reduced exposure compared to that expected closer to the mid-water column.

The area around the foundation which pelagic fish may avoid was estimated to vary from 10km to 21km for Dogger Bank Teesside A and Dogger Bank Teesside B. Fish closer to the sea bed may avoid an area of 7.5km to 17km for Dogger Bank Teesside A and between 8km and 17.5km for Dogger Bank Teesside B, depending on the location of the foundation within the site, the surrounding bathymetry, the type of fish, its sex, age and condition, as well as other stressors to which the fish is or has been exposed. The response of the fish may also depend on the underlying biological drivers for the fish to be in the area (e.g. feeding or spawning).

Modelling of the operational noise indicates the noise levels are such that they would not be expected to result in behavioural disturbance, although the potential increase in ambient noise within the boundaries of the site may influence behavioural patterns of species present which are sensitive to increasing ambient noise levels. Noise from the operational wind turbines is not expected to noticeably increase ambient noise beyond a few kilometres from the boundary of the wind farm.

The cumulative effect relating to underwater noise was considered for projects that have the potential for spatial and/or temporal overlap of noise impacts with construction at Dogger Bank Teesside A & B. Whilst temporal overlap of construction at a number of neighbouring sites will result in elevated noise levels across a relatively large part of the central North Sea, it is likely that potential for overlap of the behavioural disturbance impact zones resulting from Dogger Bank Teesside A and Dogger Bank Teesside B only exists for the neighbouring

Dogger Bank projects, Cygnus, Hornsea Project One and Two, H2-20 and Nord-Ost Passat. It should be noted that the extent of the potential behavioural impact zone depends on the receptor in question, and the model assumed uniform seabed properties throughout the modelled area of the North Sea, which may not necessarily be representative of actual conditions for surrounding developments. In addition, the hammer strike energy adopted for this illustrative assessment followed a simplistic assumption that the maximum rated hammer energy currently available (Menck, 2013) would be utilised at all wind farm projects considered, which follows an over precautionary approach in absence of more realistic data from all of the surrounding projects.

GLOSSARY AND LIST OF ABBREVIATIONS

ADD Acoustic Deterrent Device

AHD Acoustic Harassment Devices

AMD Acoustic Mitigation Device

Cefas UK Centre for Environment, Fisheries and Aquaculture Science, an Executive Agency of Defra (Department for Environment, Food and Rural Affairs)

dB Decibel; a logarithmic unit expressing the ratio of a quantity, a_1, relative to a reference value, a_0, according to the formula: $10 \cdot \log_{10}(a_1/a_0)$

DAOPA Dredging Application, Option and Prospecting Area

ES Environmental Statement

Jacket Foundation Type of wind turbine foundation pinned to the seabed with four piles; generally smaller in size compared to a monopile

JNCC Joint Nature Conservation Committee

LU Loughborough University

MMO Marine Management Organisation

MSFD Marine Strategy Framework Directive

Monopile Type of wind turbine foundation that consists of a cylindrical concaved pile that is driven into seabed, often by impact piling

Monopole (in relation to foundation types) See Monopile

Monopole (in relation to acoustic source characteristics) A point acoustic source which has an omni-directional acoustic output

NSIP Nationally Significant Infrastructure Projects

NMS Noise Mitigation Screen, A commercial mitigation sleeve developed by IHC Merwede

NPL National Physical Laboratory

NPS National Policy Statement

TTS Temporary Threshold Shift or recoverable auditory fatigue

PAM Passive Acoustic Monitoring

PE Parabolic Equation, used as part of an ocean sound propagation model

$P_{pk\text{-}pk}$, Peak-to-peak pressure level, the difference between the peak positive pressure and the peak negative pressure of the pulse

PPL Peak Pressure Level

PL Propagation Loss in water, Reduction of sound level with range, expressed in decibels - same as Transmission Loss. Unit: dB

PTS Permanent Threshold Shift or auditory damage in the form of hearing sensitivity reduction

RAM Range-dependent Acoustic Model, an ocean sound propagation model

RL Received Level, Acoustic sound pressure level at the receiver position

RMS Root mean squared (rms)

SL Source Level, a measure of the acoustic output of a source. Unit: dB re 1 $\mu Pa^2 \cdot m^2$ The Source Level is sometimes stated as a spectral level (as a function of frequency – e.g. in third-octave bands) or as a broadband level (summed over all the frequencies of radiation)

SEL Sound Exposure Level, a measure of the received acoustic energy at the receptor.

Unit: dB re 1 μPa^2·s

SEL dose The overall summed sound energy, which considers the combined effect of each piling pulse

SPL Sound Pressure Level. Unit: dB re 1 μPa or dB re 1 μPa^2

TL Transmission Loss, Acoustic Propagation Loss in the water, reduction of sound energy level with range, expressed in decibels (dB)

TOB Third Octave Band, frequency band consisting of one-third of an octave, an octave representing a doubling of frequency

UK United Kingdom

CONTENTS

1. BACKGROUND INFORMATION

1. This document is a technical report detailing the underwater noise assessment for the construction, operational and decommissioning phases of two offshore wind farms (referred to as Dogger Bank Teesside A and Dogger Bank Teesside B), which together comprise the Dogger Bank Teesside A & B application. These are the second two wind farm projects within the Dogger Bank Round 3 Offshore Wind Farm Zone (Dogger Bank Zone), each with a generating capacity of up to 1.2GW. **Figure 1.1** shows their locations.

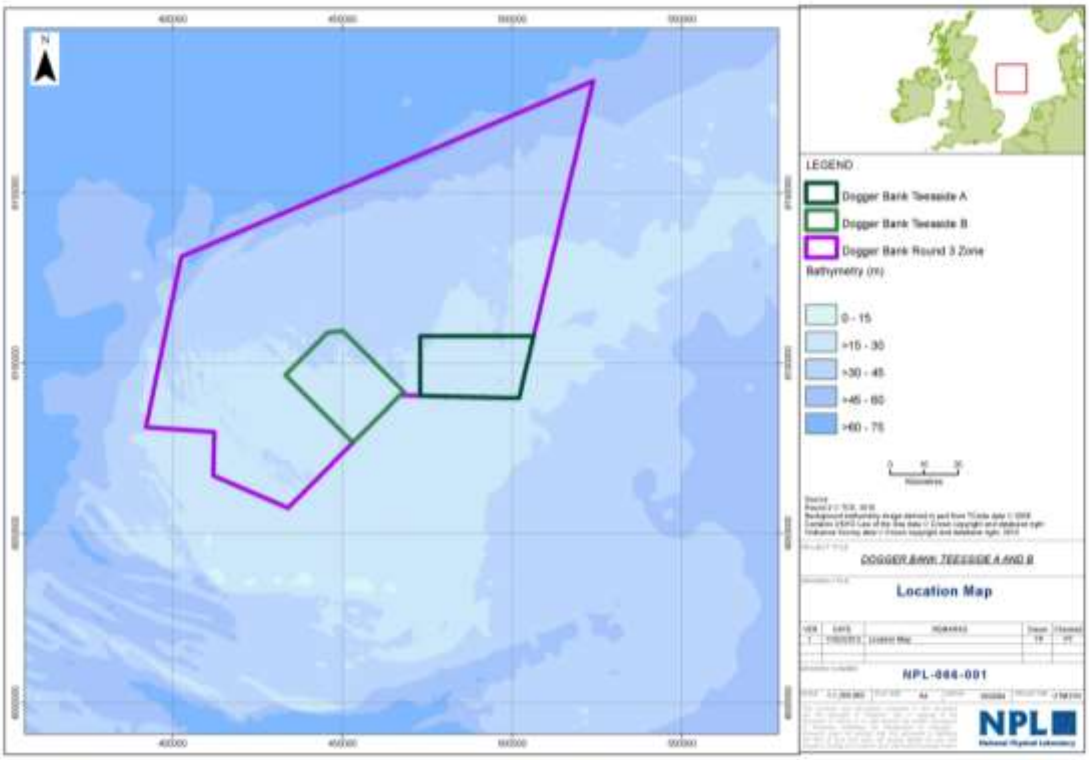


Figure 1.1: Map showing location of Dogger Bank Teesside A and Dogger Bank Teesside B offshore wind farms within the Dogger Bank Zone. The background bathymetry image indicates local variations in depth. Inset at the top right shows the wider area around the Dogger Bank Zone.

2. This report estimates the underwater acoustic emissions associated with Dogger Bank Teesside A & B and assesses the potential for the associated noise sources to impact marine fauna. The National Physical Laboratory (NPL), with its partner Loughborough University (LU), has been contracted by Forewind Limited to undertake this assessment to inform the Environmental Statement (ES) for Dogger Bank Teesside A & B.

3. The methodology of this assessment, described in Sections 4 and 5 is designed to predict the likely underwater noise levels generated by the Dogger Bank Teesside A and Dogger Bank Teesside B wind farm projects in order to inform of the possible impact of radiated underwater noise on sensitive marine fauna. Consideration is given to the impact of the construction, operation and decommissioning phases and the cumulative effects with other relevant offshore developments that may overlap temporally with activities at Dogger Bank Teesside A and Dogger Bank Teesside B.

4. The assessment was undertaken in the context of guidance documents and directives relating to underwater noise (JNCC2010a and 2010b; National Policy Statement (NPS) EN-1 July 2011; NPS EN- 3 July 2011; Marine Strategy Framework Directive (MSFD) 2008/56/EC (European Commission, 2008), Descriptor No. 11 (see Van der Graaf *et al*. 2012)) and is such that legislative requirements relating to the impact on marine fauna (e.g. Wildlife and Countryside Act 1981, The Conservation of Habitats and Species Regulations 2010) can be addressed in the respective Chapters of the ES. Specific consideration has been given to the relevant NPS', the principal decision making documents for Nationally Significant Infrastructure Projects (NSIP). The NPS relevant to the underwater noise assessment for these projects include;
   - Overarching NPS for Energy (EN-1) (July 2011); and
   - NPS for Renewable Energy Infrastructure (EN-3) (July 2011).

5. NPS' were considered (i) in terms of assessing the potential impact of noise on marine receptors (marine mammals and fish) during each phase of the development (i.e. construction, operation and decommissioning), (ii) when predicting noise levels in relation to impact criteria, potential for a cumulative overlap with other developments and when considering mitigation measures, (iii) in the process of collating information on the specific aspects of the development including baseline noise information and (iv) during operational considerations (e.g. hammer energy, foundation type). JNCC (2010a) protocol for minimising the risk of injury to marine mammals from piling noise was used to inform the best practice mitigation approach.

6. A thorough literature review was conducted to obtain and summarise the most relevant, up-to-date and internationally accepted impact criteria from peer reviewed literature in order to assess the impact on marine mammals and fish. For marine mammals, the work of Southall *et al.* (2007) and Lucke *et al.* (2009) was adopted and supported by empirical field work by Brandt *et al.* (2011) and Tougaard *et al.* (2009). Fish criteria were adopted from Popper *et al.* (2006) and Carlson *et al.* (2007) in terms of injury, while behavioural criteria were devised following the work of McCauley *et al.* (2000) and Pearson *et al.* (1992). Consideration has also been given to recent work by Halvorsen *et al.* (2012) on fish injury and Mueller-Blenkle *et al.* (2010) on fish behaviour resulting from sound exposure. The risk posed to fish larvae has also been considered based on the finding of a recent study by Bolle *et al.* (2011; 2012).

7. In line with the JNCC guidance, the criteria adopted for this assessment take into account the latest scientific evidence, and may result in different estimated impact ranges when compared to previous UK wind farm developments. It should also be acknowledged that there are still considerable knowledge gaps in understanding the effects of underwater sound on marine fauna and impact criteria should therefore be expected to evolve as new scientific evidence becomes available. Further explanation and detail on the criteria used here is given in Section 5 and Appendix B.

2. INTRODUCTION TO UNDERWATER ACOUSTICS

2.1 Basic acoustics concepts

8. This section outlines some of the relevant concepts in underwater acoustics to help non-specialist readers to best understand the results presented in this report. Further detail is provided in Appendix A of this report.

9. Underwater sound is a pressure wave travelling through the water, which can travel much greater distances than sound in air. It is the low absorption in water (Kinsler *et al.* 1982 and Kaye and Laby, 2004) that allows sound to travel large distances in the ocean, particularly low frequency sound.

10. An important characteristic of sound is the acoustic frequency, described as the number of oscillations per second, the unit of frequency being the hertz (Hz). The amplitude of the sound typically varies with the acoustic frequency. When displaying the measured sound levels, it is common to see the frequency range divided up into one-third octave bands (TOB), where each band is one third of an octave, an octave representing a doubling of frequency.

11. The sound field is typically described in terms of the sound pressure, where the unit of pressure is the pascal (Pa) or newton per square metre ($N \cdot m^{-2}$). However, by convention sound pressure levels are expressed in decibels (dB) relative to a reference pressure, which is 1 μPa for underwater sound. Metrics most commonly used to describe the underwater sound in impact piling in the UK include <u>peak-to-peak pressure level (</u>$P_{pk\text{-}pk}$) and <u>Sound Exposure Level (SEL)</u>. $P_{pk\text{-}pk}$ is a measure of maximum pressure change of a signal (i.e. the difference between the peak positive pressure and the peak negative pressure of the pulse) and is usually expressed in dB re 1 μPa. The Sound Exposure Level is a measure of the pulse energy content and is calculated from the integral of the squared sound pressure over the duration of the pulse (Madsen, 2005; Ainslie, 2011). It is also used to express the overall exposure (SEL dose), which in this case is done by summation of sound exposure levels of the entire piling event. The SEL can also be expressed in dB notation referenced to 1 $\mu Pa^2 \cdot s$.

12. It should be noted that the metric used for continuous type sounds is different to those used for impulsive sounds like piling. For continuous noise such as vessel noise or turbine operational noise, the Sound Pressure Level (SPL) metric would normally be used which by convention describes root mean square (RMS) level over a one second interval referenced to an RMS pressure of 1 μPa.

13. Definitions for all the metrics described are provided in full in Appendix A.

14. <u>Source Level (SL)</u> is a metric used in underwater acoustics to describe the source output amplitude. The decibel units for this quantity may be written as dB re 1 μPa·m, however, the unit is much more commonly seen expressed as dB re 1 μPa at 1m in spite of being a unit. It should be noted that Source Level is an idealised acoustic far-field parameter and is not necessarily equal to the acoustic pressure or received level measured at a distance of 1 metre from the source.

15. Propagation Loss (PL) or Transmission Loss (TL) is the term used to describe the reduction of the sound level as a function of distance from an acoustic source. The mechanisms by which the sound intensity reduces are primarily geometrical spreading, sound absorption in the water and losses into the seabed or other boundaries. In shallow water, particularly with varying bathymetry, this can be quite complicated due to multiple interactions with the surface and seabed. The depth can also restrict the propagation of lower frequencies in shallow water. It is normal for propagation/transmission loss to be stated as a positive number in dB representing the loss for the total range between the reference distance (1m for Source Level) and the receiver location. The quantity is a function of frequency, and depends, for example, on seabed type, bathymetry, surface roughness, sound speed profile.

16. The received level (RL) is the acoustic pressure measured by a hydrophone at some distance away from a sound source. It is also considered to be the sound pressure which arrives at any acoustic receiver which is exposed to a sound. The received level might be expressed in a number of ways, for example as a sound pressure level (dB re 1 μPa) or a sound exposure level (dB re 1 $\mu Pa^2 \cdot s$). When predicting received levels from estimated source levels for zones of impact, the received level is simply determined by subtracting the transmission loss in dB from the source level in dB, RL = SL – TL, where the TL is estimated using a transmission loss model. When the source level is estimated from measured received levels then the source level is simply found by addition of received level and transmission loss, SL = RL + TL. To calculate TL accurately requires an accurate numerical model for the propagation of the sound and its interaction with the seabed and sea surface. Sometimes, the TL is empirically estimated from the measured received level data as a function of range. Ideally the TL should still be estimated by fitting an appropriate transmission loss model capable of accurately modelling propagation for a complex environment.

17. An important point to note is that the source levels for marine piling reported in previous wind farm studies have almost exclusively been obtained by extrapolation back to the source using simple spreading formulae. This means that these reported values are not true Source Levels and are generally not consistent with the accepted definition of Source Level by Urick (1983) and others (Ainslie 2011). To distinguish between formats, data derived from simple spreading formulae are referred to as "Effective" Source Level.

18. Typically, the characteristics of an acoustic pulse propagating in shallow water do not only depend on range from the source. The transmission of sound may show a strong dependence on frequency due to the modal nature of the propagation in the shallow-water channel and the frequency-dependent absorption in the water and in the sediment. These phenomena will cause the time waveform to distort during propagation away from the source, typically causing a dilation of the acoustic pulse (an increase in pulse duration), and a reduction in high frequency content.

19. Ambient noise originates from a range of noise sources, both natural and anthropogenic and spans a large frequency range from below 1Hz, to well over 100kHz. It is most commonly expressed as spectral density levels in third octave bands, in units of dB re 1 $\mu Pa^2/Hz$, where the values have been divided by the bandwidths of each third octave band. This is different from third octave band power spectra (dB re 1 μPa^2), more appropriate for radiated noise, where the total energy in the signal is of interest. In general, ambient noise measurements in the UK coastal waters indicate that maximum

third octave band spectral noise density levels are typically between around 95 and 120dB re 1 μPa^2/Hz with these peak band levels occurring between frequencies of a few tens of hertz to a few hundred hertz, depending on location and time (Nedwell *et al.* 2007a; Theobald *et al.* 2010; Robinson *et al.* 2011).

3. BASELINE AMBIENT NOISE

20. A review of relevant subsea ambient noise studies has been undertaken to assess the likely level of ambient noise in and around the Dogger Bank Zone.

21. Underwater ambient noise levels are subject to substantial variability depending on a number of natural and anthropogenic factors. Natural factors such as sea-state, rain, surf noise in coastal waters, movement of seabed material and marine animal vocalisations all influence ambient noise levels. These often lead to a diurnal and seasonal variation in the natural ambient noise level in the oceans or regional seas and can cause significant location dependency. The contributions of anthropogenic noise sources to the ambient level are difficult to quantify, although recent studies have indicated that there has been a trend of increasing deep-ocean ambient noise as a result of shipping (McDonald *et al.* 2008; Andrew *et al.* 2011). In the North Sea for example, the contribution of shipping noise to ambient levels has been shown to be significant (Ainslie *et al.* 2009). The ambient noise level is also highly likely to depend on the distance to shipping lanes, fishing areas, dredging areas or other areas where potential noise sources are operating.

22. Previous ambient noise measurements undertaken in UK coastal waters (Nedwell *et al.* 2007a; Theobald *et al.* 2010; Robinson *et al.* 2011) indicate that maximum third-octave band spectral noise levels are generally between around 95 and 120dB re 1 $\mu Pa^2/Hz$ with these peak band levels occurring between frequencies of a few tens of hertz to a few hundred hertz, depending on location and time. This is fairly typical of coastal underwater noise, with higher noise levels at frequencies below a few hundred hertz and falling off at higher frequencies.

23. Another type of ambient noise evaluation in the UK entailed assessment of likely ambient noise contributions. This formed a part in the Strategic Environmental Assessment (SEA), however, the assessment was only undertaken for SEA area 6, which includes parts of the western UK coast (Harland *et al.* 2005). Area 3, which encompasses the Dogger Bank Zone, was not included.

24. Natural environmental contributors to the ambient noise level in and around Dogger Bank Teesside A & B, and the Dogger Bank Zone in general, will likely be from the wind (sea-state), with contributions from rain and biological noise. Noise generated by the interaction of wind with the sea surface is likely to be the dominant natural contributor to ambient noise at the Dogger Bank Zone, and will range from a few hertz to a few tens of kilohertz. This sea-state related ambient noise, reported by Wenz (1962), is thought to be the result of bubble oscillations and impact from breaking waves at the sea surface (Medwin and Beaky 1989; Medwin and Daniel 1990). The relationship of ambient noise with sea-state is shown in **Figure 3.1**, in addition to lower frequency noise levels which might be expected in shallow water. Rain can also contribute to ambient noise at several tens of kilohertz in the immediate area through bubble oscillation although this is not expected to be a dominant component of the overall ambient noise. Biological contribution to ambient noise can be significant depending on the location and time. These sounds can include a variety of marine mammal vocalisations spanning from a few hertz to several tens of kilohertz and include lower frequency sounds made by fish (Richardson *et al.* 1995; Amorim 2006).

25. The primary anthropogenic contributors to the ambient noise level in the North Sea include shipping (e.g. fishing, cargo, cruise ship, ferries, aggregate extraction) and oil and gas related activities. In general, shipping density local to Dogger Bank Teesside A and Dogger Bank Teesside B is lower than closer in-shore or in some of the surrounding areas, including areas to the south of the Dogger Bank Zone. Fishing and commercial shipping appear to be the main vessel related activities, although passenger cruise vessels also sometimes transect the Dogger Bank Zone (DECC 2009; Chapter 16 Appendix A Navigational Risk Assessment'). Some of the vessels operating in and around Dogger Bank Teesside A and Dogger Bank Teesside B, depending on vessel speed, size, type, age and condition etc., may generate significant noise levels, with the literature indicating maximum third-octave band source levels of over 200dB re 1 μPa·m (Malme *et al.* 1989) for a large tanker, over 186dB re 1 μPa·m for a cargo vessel (Arveson and Vedittis 2000) and over 170dB re 1 μPa·m for a passenger ferry (Malme *et al.* 1989) (for the third-octave band where the source level is maximum). These will result in noise levels above ambient levels out to distances of several kilometres and, to an extent, local ship traffic will influence the ambient noise. However, these will be localised, short term changes. The more constant contributor to noise within Dogger Bank Teesside A and Dogger Bank Teesside B will be distant shipping. This will likely result in ambient noise levels between frequencies of tens of hertz to a few hundred hertz within the Dogger Bank Teesside projects, similar to those estimated in **Figure 3.1** that represent distant heavy shipping.

26. Dredging vessels can also be a source of noise, which may be noisier at higher frequencies than commercial vessels operating in the shipping lanes (Robinson *et al.* 2011). There are no licenced or active dredging areas within or around the Dogger Bank Zone, although two Dredging Application, Option and Prospecting Areas (DAOPAs) exist; one (Area 466/1) within the Dogger Bank Zone (western edge) and another (Area 485 /1 &2) to the south-west of the Dogger Bank Zone (The Crown Estate, 2013). Neither of these DAOPAs falls within Dogger Bank Teesside A or B. It is assumed that Area 485/1&2, Area 466/1, and the Norwegian and the Dutch dredging projects (Ramsundet, Horvnes and Cleaver Bank, respectively) are too far away to have the potential to contribute to an increase in ambient noise at Dogger Bank Teesside A & B.

27. The waters surrounding Dogger Bank Teesside A & B support a concentration of oil and gas fields, mainly to the north, south and south-east of the Dogger Bank Zone (DECC 2013a), which if operational, may radiate low frequency machinery noise and general broadband noise into the water. Some UK gas fields (e.g. Cavendish, Munro, Tyne) appear to be currently producing (DECC 2013b) and could influence the long-term local ambient noise. Seismic surveying and possible construction activity at other near-by sites may result in noise levels similar to those resulting from wind farm construction discussed in this report. Well head decommissioning, using explosives, may also generate high levels of impulsive noise. These activity types would be over short temporal scales, and in the case of seismic surveying utilise a mobile source and would generally not persistently contribute to ambient noise in any one location. The potential for cumulative impacts between Dogger Bank Teesside A and Dogger Bank Teesside B and other developments is discussed in Section 6.4.

28. Tidal changes in shallower areas (<20m) of Dogger Bank Teesside A and Dogger Bank Teesside B may result in ambient noise variations due to changes in the propagation environment, which changes with depth. Sand banks at low tide can elevate

propagation loss of lower frequency sounds in particular, resulting in a reduction in ambient noise levels detected in the surrounding area.

29. **Figure 3.2** shows a sample of measured ambient noise data from around the UK, with the measurements in the English Channel being in close proximity to commercial shipping lanes, while measurements off the east coast were made in a relatively quieter area. These references are for areas other than Dogger Bank Teesside A & B; however, there is no evidence to suggest that ambient noise levels anywhere in the Dogger Bank Zone should be substantially different to UK coastal areas. It is anticipated they will resemble the middle range of the data spread measured for UK waters, particularly at frequency ranges between a few tens of hertz and a few hundred hertz, due to relatively low local shipping activity.

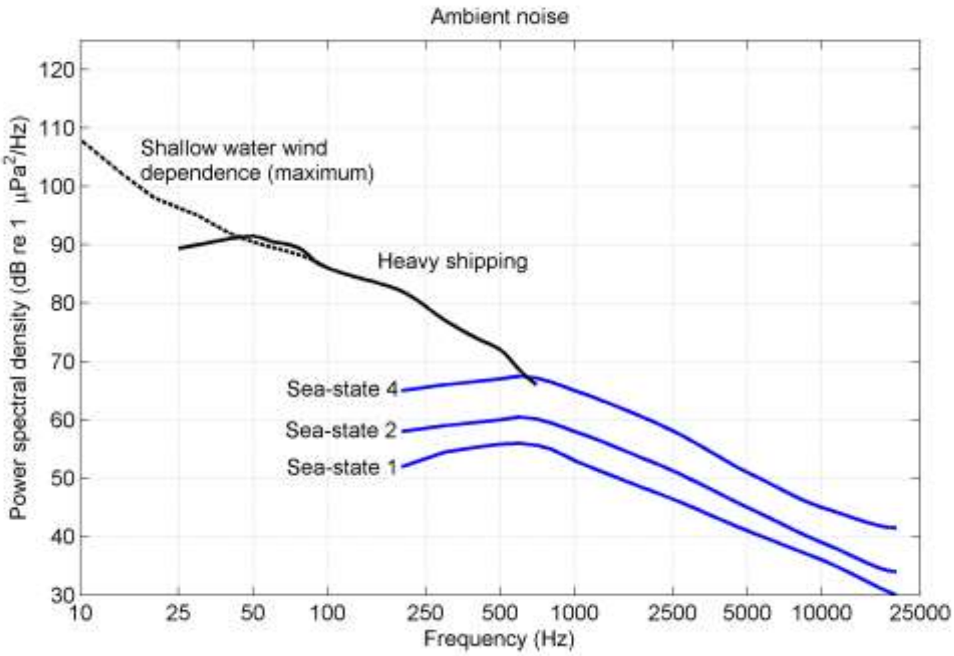
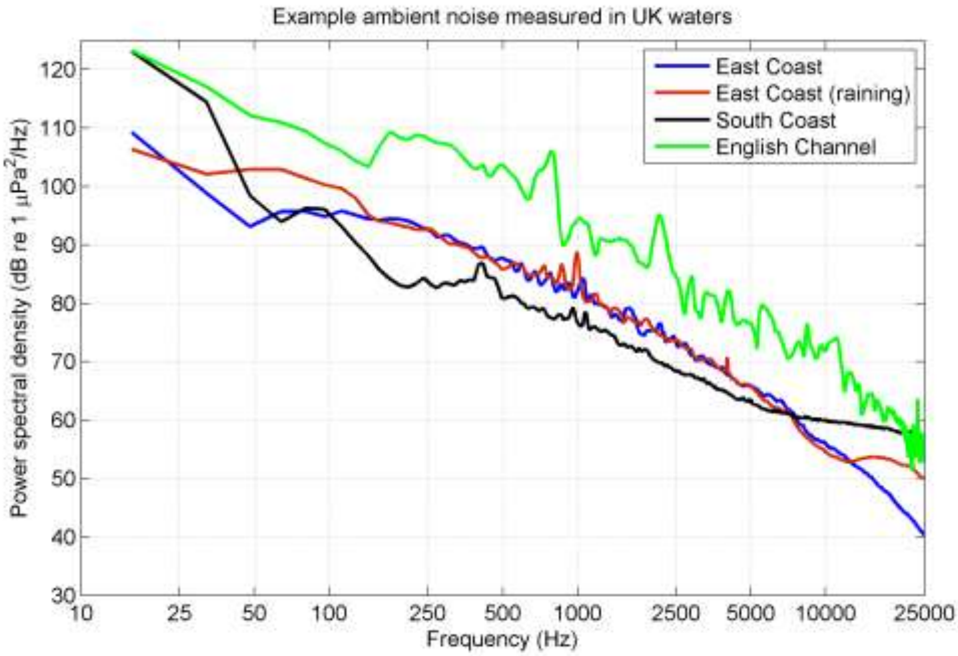


Figure 3.1 Ambient underwater noise curves showing dependence with shipping and sea-state/wind (Reproduced from Richardson *et al*. 1995 and Wenz 1962).



Source: – data owned by The Marine Aggregate Levy Sustainability Fund (MALSF) - Marine Environment Protection Fund (MEPF) and held by The National Physical Laboratory (Figure reproduced from Robinson *et al.* 2011).

Figure 3.2 Ambient underwater noise data measured around the UK.

4. UNDERWATER NOISE PROPAGATION MODELLING

30. This section describes modelling that has been utilised to predict the likley underwater noise levels, with the view of determining the potential for impact for marine life. A number of noise sources will be present during wind farm construction, with impact piling representing the worst case. The modelling described below has been applied to impact piling and the same approach adopted for operational noise modelling.

4.1 Noise propagation model

31. The noise propagation modelling employed for this study has been undertaken by the National Physical Laboratory, based on an energy flux solution by Weston (1976), which is capable of propagation over large distances whilst accounting for range-dependent bathymetry and frequency-dependent absorption. The energy flux model has been implemented, with the frequency-dependent absorption formula of Thorpe (1967), with the effect of surface scattering included (Coates 1988), and with averaged seabed properties over the region (Hamilton 1980 and Lurton 2003), using the General Bathymetric Chart of the Oceans (GEBCO) Digital Atlas bathymetry data over an area of approximately 180km by 180km, assuming highest astronomical tide. Shorter range, higher resolution, modelling runs for establishing injury ranges used lowest astronomical tide. It should be noted that for the water depths and seabed properties around Dogger Bank Teesside A and Dogger Bank Teesside B, lowest astronomical tide only results in the higher sound levels within the first few hundred metres of the source. Beyond this range, the highest sound levels are expected to occur at highest astronomical tide. The Weston energy-flux model assumes a homogenous sound speed profile, which is often the case in coastal waters due to tidal mixing. The Weston energy-flux model has been benchmarked, with good agreement, against other transmission loss models published in the literature, including the Range-dependent Acoustic Model (RAM) implementation of the parabolic equation (PE) solution (Collins 1993) based on AcTUP V2.2L, an image source model (Urick 1983), a wavenumber integration transmission loss model (OASES), and a normal mode model (Kraken).

32. The energy flux model has been used to propagate an SEL Source Level to establish the SEL received level as a function of range. To derive a Source Level for use in the model, the SEL source spectral level was specified in third-octave bands using a spectral source level shape taken from Ainslie *et al.* (2010) and was scaled with hammer energy, as described in Appendix A, and calibrated against previous impact piling noise measurement data for similar water depths. This approach was adopted to remove the dependence on an extrapolated effective source level from measured data, which is subject to substantial uncertainty. The peak pressure level of the sound pulse generated by the impact piling will decay at a slightly higher rate compared to the energy in the pulse (the SEL is proportional to pulse energy) due to temporal dilation of the pulse that results from multiple reflections from the seabed and the sea surface as the sound pulse propagates. To allow the peak pressure level to be propagated as a function of range, an extra loss term was applied to the energy flux model to account for this more rapid peak pressure level decay. This loss term was established using the OASES wavenumber integration transmission loss model to establish the difference in transmission loss between the pulse energy and the peak pulse pressure for a single flat bathymetry transect with a depth of 20m. This additional loss term was validated against previous underwater noise measurement data from impact piling of the peak pressure level and pulse SEL metrics.

33. The modelling methodology adopted provides received level output as a function of range for both SEL and peak pressure level parameters.

34. Several locations have been modelled, including (i) locations within and along the project boundaries and (ii) selected locations considered for the cumulative assessment with other projects and offshore developments (Section 4.4 and Section 6.4).

4.2 Modelling sound propagation

4.2.1 Modelled pile locations

35. In terms of the potential impact that underwater noise from wind turbine installation may have on marine fauna, impact piling can be considered to be the worst case compared to installation of gravity base or other forms of foundation that do not give rise to high noise levels. Furthermore, larger foundations such as monopoles generally require a higher hammer energy and are therefore expected to result in underwater noise levels which are higher than those associated with the installation of foundations requiring a smaller hammer such as jacket foundations. Based on the presumed hammer energies considered for the Dogger Bank Teesside A & B wind farm projects (**Table 4.3**) driving of monopole foundations was considered as the likely worst case in terms of potential impacts on marine fauna resulting from underwater noise.

36. To establish the sound propagation expected during individual piling events (Single pile modelling), positions were selected within each project such that they encompassed a range of sound propagation conditions. This included positions in shallow to deep water locations, with up-sloping and down-sloping bathymetry profiles. A selection of locations along the boundary were considered when estimating the wind farm construction noise footprint (Footprint) described in Section 4.3 and to demonstrate the effect of concurrent use of piling vessels (Multi-piling) in proximity to each other. The positions of all modelled locations are listed in **Table 4.1** and **Table 4.2**, for Dogger Bank Teesside A and Dogger Bank Teesside B, respectively and shown in **Figure 4.1**.

Table 4.1 – Summary of modelled positions at Dogger Bank Teesside A.

Location ID	Latitude (Decimal Degrees, N)	Longitude (Decimal Degrees, W)	Approximate Depth (m)*	Single Pile	Footprint	Multi-piling
1	55.11789	2.57523	30	YES	YES	
2	55.11859	3.09889	26	YES	YES	YES
3	55.05832	3.07415	24	YES	YES	
4	55.00974	3.05427	22	YES	YES	
5	54.95484	3.03186	21	YES	YES	YES
6	54.96011	2.57690	25	YES	YES	
7	55.11824	2.83706	27	YES	YES	
8	55.11807	2.70615	25	YES	YES	
9	55.11842	2.96798	29	YES	YES	
10	54.95747	2.80438	20	YES	YES	
11	54.95616	2.91812	24	YES	YES	
12	54.95879	2.69064	22	YES	YES	
13	55.01270	2.57634	27	YES	YES	
14	55.06530	2.57579	29	YES	YES	
15	55.06530	2.70670	24	YES		
16	55.06530	2.83762	25	YES		
17	55.06530	2.96853	28	YES		
18	55.01270	2.70726	23	YES		
19	55.01270	2.83817	23	YES		
20	55.01270	2.96909	26	YES		
21	55.11842	3.07489	27			YES

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Table 4.2 – Summary of modelled positions at Dogger Bank Teesside B.

Location ID	Latitude (Decimal Degrees, N)	Longitude (Decimal Degrees, W)	Approximate Depth (m)*	Single Pile	Footprint	Multi-piling
1	54.83864	2.277829	20	YES	YES	YES
2	54.83862	2.263356	22	YES	YES	
3	55.01111	1.954539	24	YES	YES	YES
4	55.12443	2.145724	32	YES	YES	
5	55.13002	2.217796	31	YES	YES	YES
6	54.9707	2.501887	28	YES	YES	
7	55.04888	2.018267	26	YES	YES	
8	55.08666	2.081996	31	YES	YES	
9	54.92486	2.108947	24	YES	YES	
10	54.88174	2.186151	24	YES	YES	
11	54.96798	2.031743	25	YES	YES	
12	55.05036	2.359842	31	YES	YES	
13	55.09019	2.288819	32	YES	YES	
14	55.01053	2.430865	30	YES	YES	
15	54.88266	2.352515	20	YES	YES	
16	54.92668	2.427201	21	YES	YES	
17	55.08642	2.183719	31	YES		
18	55.04796	2.136705	30	YES		
19	55.05258	2.246852	30	YES		
20	55.00009	2.217708	27	YES		
21	55.00009	2.100346	27	YES		
22	54.99859	2.342155	28	YES		
23	54.95235	2.340855	28	YES		
24	54.95235	2.189947	26	YES		
25	54.90448	2.264100	24	YES		
26	55.1275	2.193996	33			YES
27	54.85217	2.277829	23			YES

***Source: Round 3 © TCE, 2010 Background bathymetry image derived in part from TCarta data © 2009 Contains UKHO Law of the Sea data © Crown copyright and database right Ordnance Survey data © Crown copyright and database right, 2010**

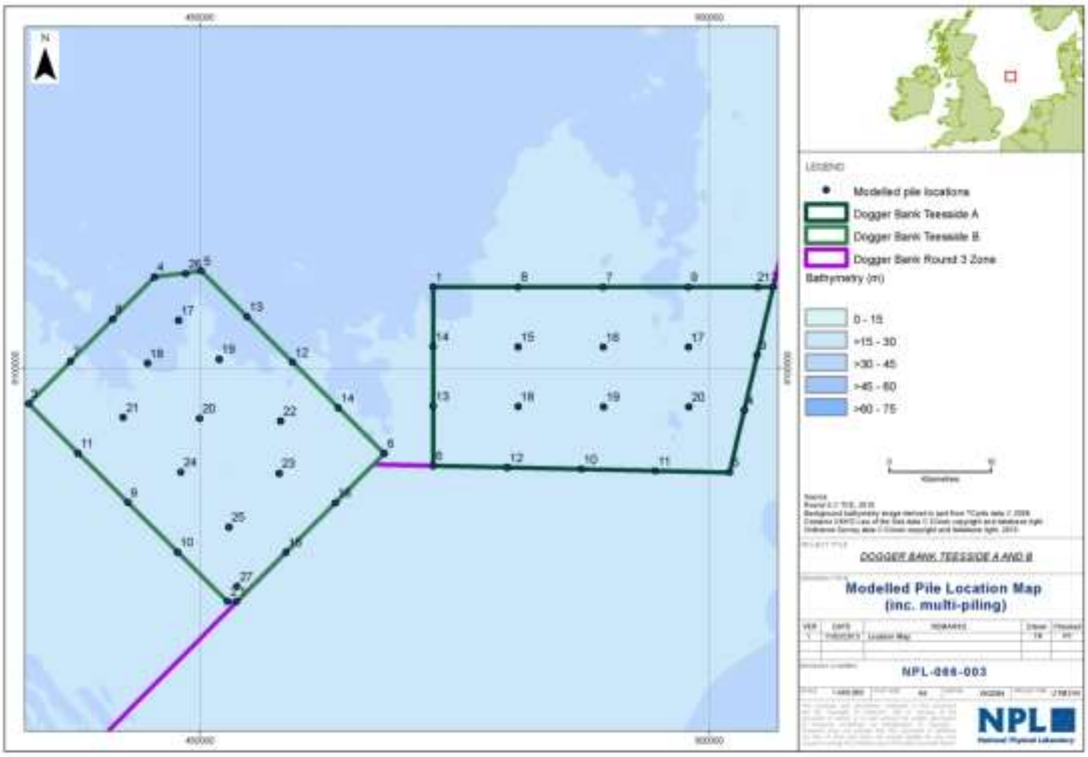


Figure 4.1 - Map showing the positions selected for underwater sound propagation modelling for impact piling at Dogger Bank Teesside A and Dogger Bank Teesside B offshore wind farms. Numbers correspond to Dogger Bank Teesside A and Dogger Bank Teesside B Location ID numbers in Table 4.1 and 4.2, respectively. The background bathymetry indicates local variations in depth. Inset at the top right indicates the general Dogger Bank location in the North Sea.

4.2.2 Modelling sound propagation for estimated impact ranges

37. For each individually modelled piling event a sound propagation map was obtained showing the noise level as a two-dimensional function of range. The impact piling underwater noise modelling has been carried out using an energy source level which scales linearly with the hammer energy. In SEL units expressed in decibels, this means a 3dB increase for a doubling in hammer energy. The dimensions of the pile alone are not expected to have a significant effect on the noise energy output, for example, the noise resulting from a monopole using a given hammer energy would be expected to be the same as that from a smaller diameter pin-pile using the same hammer energy. A range of hammer energies have been modelled from soft-start up to the maximum hammer energy expected for each turbine size and foundation type. For the purpose of this assessment, the maximum hammer energies are presented as they have the potential to result in longest impact ranges. The maximum hammer energy and respective initial soft-start energy assumed in each case are summarised in **Table 4.3**.

Table 4.3 – Summary of the maximum hammer energy proposed for construction across the Dogger Bank Teesside A & B projects, for each turbine size and foundation type.

Turbine size	Foundation type and required maximum hammer energy (Initial soft-start hammer energy)	
	Monopole	Jacket/Multipole
6MW	3,000kJ (300kJ)	2,300kJ (230kJ)
10+MW	3,000kJ (300kJ)	2,300kJ (230kJ)

38. The 300kJ hammer blow energy was taken to be representative of the maximum likely energy for the onset of soft-start and is expected to ramp up to a maximum hammer blow energy over a period of 30 minutes. The 3,000kJ hammer energy represents the absolute maximum hammer blow energy which could be used for monopole foundations. Even for this scenario, it should be noted that 3,000kJ would be the maximum size of hammer used and not necessarily the strike hammer energy used. Experience from previous wind farm construction shows that the maximum hammer energy is rarely achieved during a piling sequence and then only for a short duration (e.g. Bailey *et al.* 2010; Robinson *et al.* 2011*)*.

39. The plots in **Figures 4.2** and **4.3** show example propagation modelling outputs for the minimum and maximum hammer energies considered for Dogger Bank Teesside A and Dogger Bank Teesside B, respectively.

40. The images illustrate some degree of variation in the sound propagation expected for the different bathymetric profiles around Dogger Bank Teesside A and Dogger Bank Teesside B. In general, it can be seen that a flat and an up-sloping seabed encountered mainly in the southerly parts of the Dogger Bank Teesside A & B projects results in a more rapid reduction of the noise levels with range when compared with a down-sloping bathymetry present mainly northward. For the water depths and seabed properties around the Dogger Bank area, a down-sloping seabed results in less loss into the seabed as the sound wave travels through the water column and therefore results in the longest propagation ranges. This is common for a shallow water environment with a reflective seabed. **Figures 4.2** and **4.3** also illustrate the dependence of the received level at a given range on the hammer strike energy.

41. Generally, noise levels observed across the Dogger Bank Teesside A and Dogger Bank Teesside B projects are comparable, largely because the general propagation environment is similar. For both Dogger Bank Teesside A and Dogger Bank Teesside B projects, the largest propagation distances were observed in a northerly direction from each project, from the northerly pile locations. The primary reason for this is the generally down-sloping bathymetry to the north of both Dogger Bank Teesside A and Dogger Bank Teesside B projects.

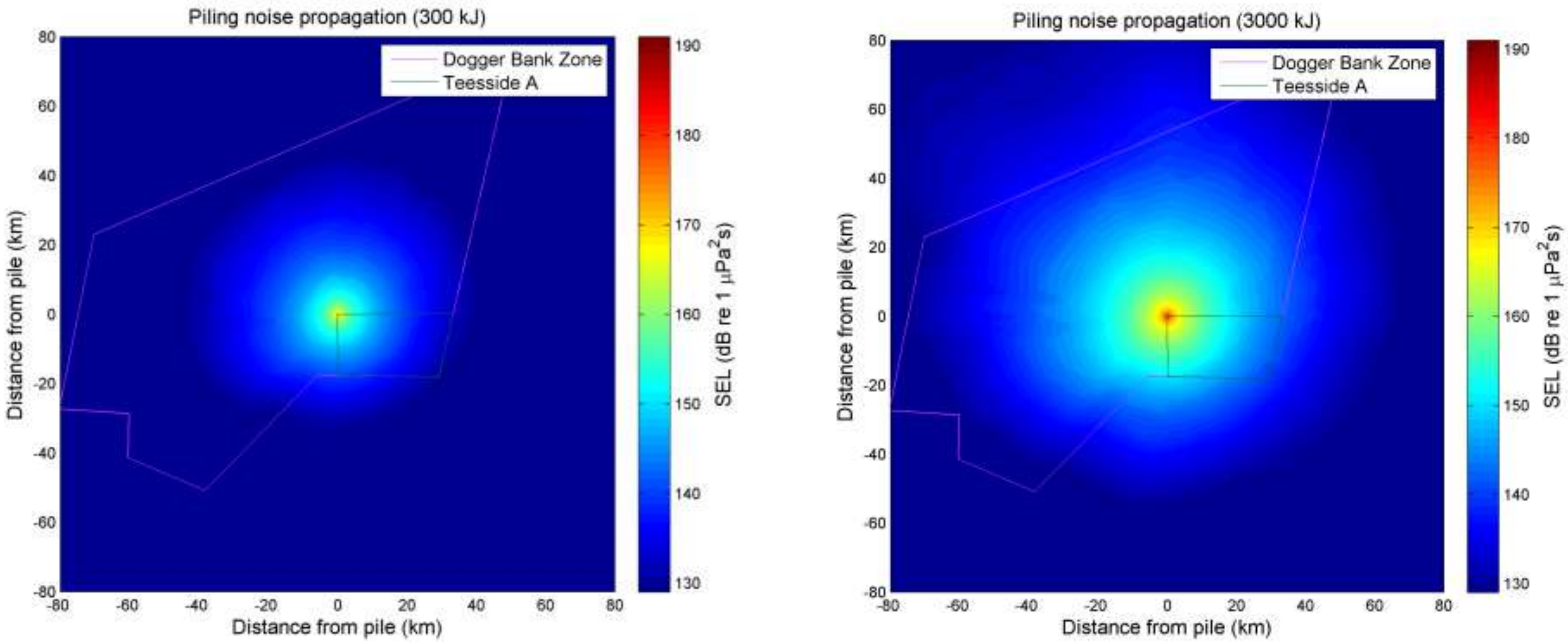


Figure 4.2 – Impact piling noise propagation maps at Dogger Bank Teesside A for a 300kJ hammer blow energy (left) and 3,000kJ hammer blow energy (right). The modelled positions correspond to location ID 1 in Table 4.1.

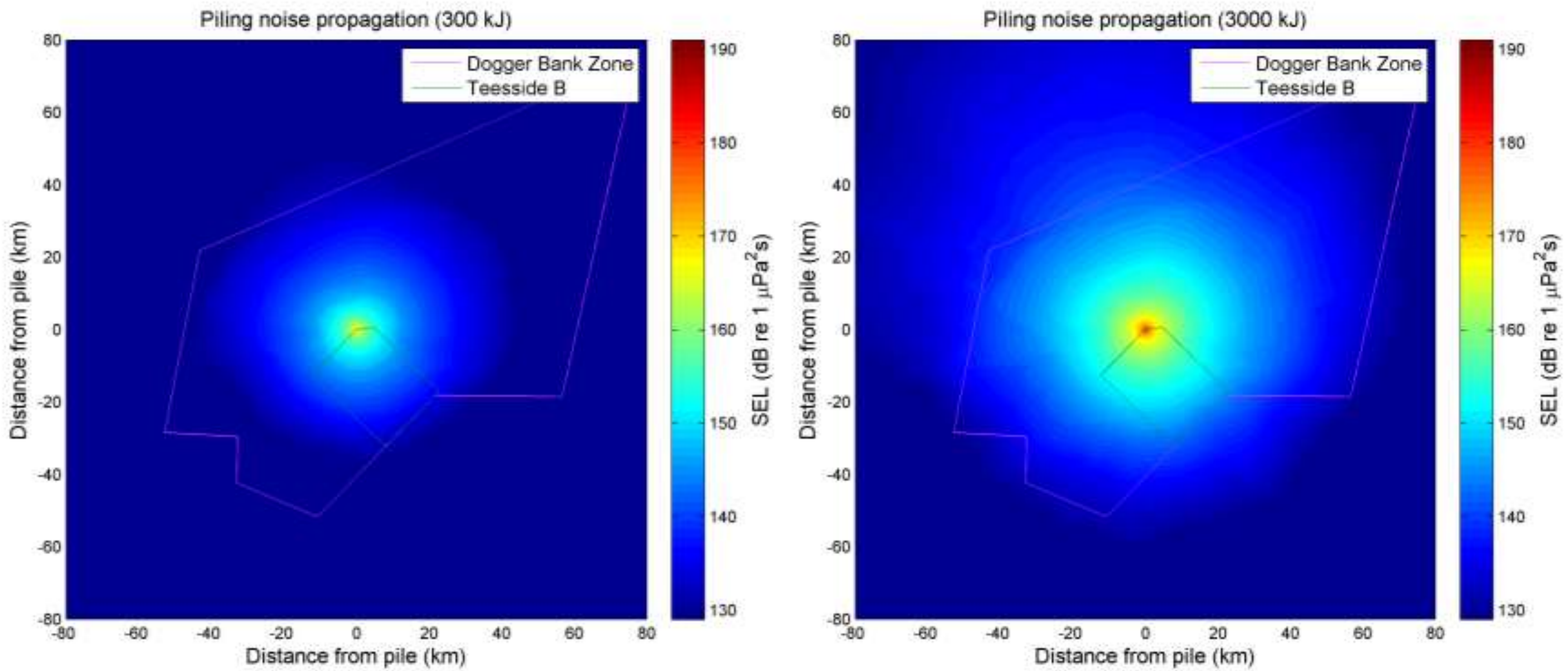


Figure 4.3 – Impact piling noise propagation maps at Dogger Bank Teesside B for a 300kJ hammer blow energy (left) and 3,000kJ hammer blow energy (right). The modelled positions correspond to location ID 4 in Table 4.1.

4.3 Modelling the wind farm construction noise footprint

42. Impact piling is a transient activity which is only likely to occur concurrently at a small number of locations within a wind farm project, where the exact locations at any given time and timing of the construction activities are unknown. To illustrate the total spatial extent of the potential impact ranges resulting from the underwater noise during the construction phase, the sound propagation was modelled at various locations along the project boundaries of Dogger Bank Teesside A and Dogger Bank Teesside B (**Tables 4.1 and 4.2**). The maximum noise level received at every location around each project was then calculated to show the construction noise footprint associated with each project. The noise footprint can be considered to be the noise level at a given range, or the maximum ranges for a given impact threshold which might occur for each project, regardless of the location or number of piling vessels operating within the project boundary. The construction noise footprints are illustrated in **Figures 6.5, 6.7, 6.9, 6.12** and **6.13** for harbour porpoise *Phocoena phocoena*, low- and mid-frequency cetaceans and fish. To illustrate the extent of potential impact in support of the receptor driven assessments (Chapter 13 Fish and Shellfish Ecology and Chapter 14 Marine Mammals) modelled footprints for the Dogger Bank Creyke Beck A & B and Dogger Bank Teesside C & D offshore wind farms were also obtained.

4.4 Modelling the effect of multiple piling vessels

43. The use of multiple piling vessels will potentially increase the area of the sea where the noise from piling is present at levels which might result in an impact. To assess the effect of multiple piling vessels, the energy flux model described in Section 4.1 has been used to model multiple sources. As it is highly unlikely that the sound pulses would interfere constructively, the sound levels would not be expected to increase as a result of summation. Whilst constructive sound interactions would not be expected, the increase in impacted area when using multiple piling vessels would depend on the separation between the piling vessels i.e. whether the impact zones from each vessel overlap or not. It is assumed that a maximum of two piling vessels per project and a maximum of 12 piling vessels may be deployed during the construction of the first six Dogger Bank projects (Dogger Bank Creyke Beck A & B, Dogger Bank Teesside A & B, Dogger Bank Teesside C &D). To illustrate the potential effect of vessel separation distance on the possible area of impact, the following two piling scenarios were considered, both assuming a maximum of two piling vessels operating in each of the six Dogger Bank projects, with a total of 12 piling vessels used within the Dogger Bank Zone;

- a 1,500m separation between the two vessels in each project; and
- a relatively large separation between the two vessels in each project (kilometres).

44. A vessel separation distance of 1,500m was chosen as this was considered the likely closest possible distance between piling vessels, i.e. limited by the planned minimum turbine spacing of 750m and a 500m safety zone around each piling vessel.

45. Whilst a number of different vessel configurations may be employed for the actual concurrent piling operations within the Dogger Bank Zone during the Dogger Bank Teesside A&B construction, the exemplar locations selected for the modelling shown here help illustrate the potential general effect of the vessel separation distance (1,500m vs larger distance) on the possible area of impact for marine receptors. The results of this modelling and the inferences for impact on marine fauna are discussed further in Section 6.1.3.

4.5 Modelling sound pressure as a function of water depth

46. For the propagation conditions around Dogger Bank, for certain frequencies at least, the noise levels at larger ranges from the source (more than a kilometre or so) resulting from impact piling are expected to be lower near the seabed than they are around mid-water depth. Due to the pressure release effect of the surface, the noise levels towards the water surface will also be lower than deeper down in the water column.

47. The energy flux model described in Section 4.1 considers only the sound energy propagating through the water column and so does not provide vertical profile data. As described above, this would not be the case in reality, where it would be expected that the sound pressure in the propagating wave would be reduced near the seabed (and near the surface). This is important when considering seabed dwelling species and species near the surface.

48. To investigate this effect a more comprehensive propagation model (computationally more intensive) was used in addition to the energy flux model. Underwater sound propagation was modelled along a select number of transects, approximately 100km in length radiating out from a pile location eastward and westward. An example location was chosen to illustrate a range of variable bathymetric profiles and is shown in **Figure 4.1**. This location corresponds to pile ID1 in **Table 4.1**.

49. The model used was the AcTUP V2.2L version of RAM (described in Section 4.1) with the actual implementation based on RAMGeo. This has previously been benchmarked, with good agreement, against the more computationally intensive RAMSGeo implementation which allows for shear wave propagation in the substrate.

50. The results of the RAM modelling are shown in **Figure 4.4** for two transects diverging from pile ID1, assuming a sandy seabed. The modelling shows two important points:

- The broadband (between 40Hz and 1kHz) noise level, as a result of complex interaction of the sound wave with the seabed, can be around 1 to 8dB lower near the seabed, compared to around mid-water column, at ranges exceeding the first few kilometres. The effect is potentially weakest where the seabed is rapidly up-sloping. The implication of this is that fish which dwell on or near the seabed (hereafter demersal fish) may be exposed to sound pressures which are potentially lower than those predicted in the energy flux model described in Section 4.1. Flat fish which might be expected to be sensitive to particle velocity would also likely be exposed to lower particle velocity components near the seabed than those present towards the mid-water column depth. However, it should be noted that these are broadband levels and this generalisation will not be true at all frequencies. Also, the model does not account for the vibration travelling along the seabed, which may generate a surface wave in the sediment with a velocity or displacement component to which flat fish may be sensitive (Hawkins, 2009; Hazelwood and Macey, 2012); and
- The noise level close to the sea surface is tens of dB lower compared to the mid-water noise levels at distances exceeding only a few hundred metres from the pile. This would result in a reduced exposure of any animal travelling through the water close to the surface, which would likely reduce the area of avoidance from the pile. It would also result in a substantially reduced SEL dose for any animals which might swim away, near the surface, from the sound source.

51. It should also be noted that sound entering the sediment from the water is attenuated more rapidly than the sound which propagates through the water column.

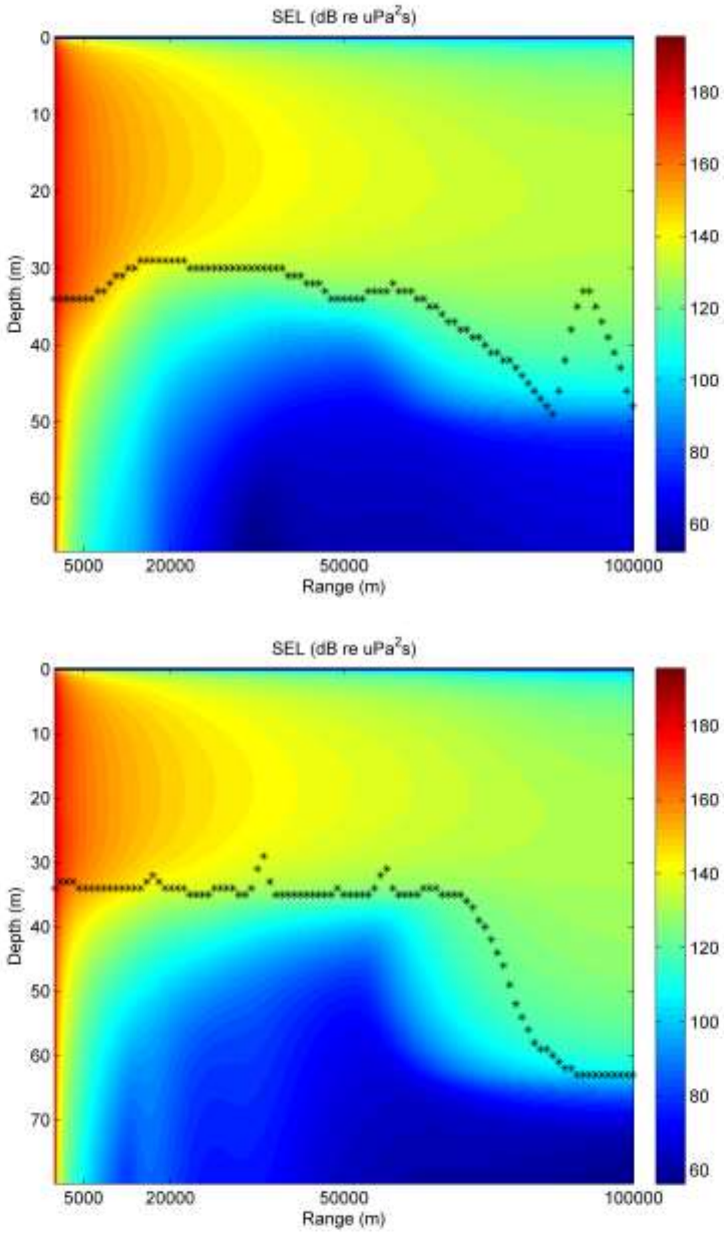


Figure 4.4 - Propagation, as a function of depth and range, along two ~100km long transects radiating out to the east (top), west (bottom) from a pile location along the northern boundary of Dogger Bank Teesside A (ID 1 in Table 4.1), assuming a sandy seabed (the bathymetry is indicated by the black asterisk symbols) and 3,000kJ hammer blow energy.

4.6 Sound Exposure Level (SEL) dose modelling

52. The effect of continued exposure during a piling sequence (i.e. exposure to more than one sound pulse) is likely to cause auditory damage at ranges greater than those for instantaneous injury from a single pulse. This results from the combined effect of each piling pulse which can be summed up as sound energy to provide the SEL dose (Theobald *et al.* 2009; Lepper *et al.* 2011). This is analogous to how noise exposure is assessed for humans, which considers exposure to noise over a working day in accordance with the Control of Noise at Work Regulations, 2004.

53. The SEL dose has been modelled for high-frequency (HF), mid-frequency (MF), low-frequency (LF) cetaceans and pinnipeds in water (PW) functional hearing groups defined by Southall *et al.* (2007).

54. Three piling sequence lengths have been considered, all based on the use of a 3,000kJ hammer, the maximum hammer blow energy expected. The piling sequence details are summarised in **Table 4.4** and are designed to represent both a typical piling sequence previously reported for UK offshore wind farms and the maximum number of hammer strikes envisaged for a given pile foundation type at Dogger Bank Teesside A & B offshore wind farms (12,600 hammer strikes). In the UK, 2,000 to 5,000 hammer blows have been typical for a pile installation, at a rate of 30 to 60 blows per minute, with Bailey *et al.* (2010) reporting up to 7,000 for each pile for the Beatrice Demonstrator quad jacket foundation (Nedwell *et al.* 2007a; Nedwell *et al.* 2009; Nedwell *et al.* 2010; Robinson *et al.* 2009a and Theobald *et al.* 2010). The three scenarios summarised in **Table 4.4** consider a total of 2,000, 5,000 and 12,600 hammer strikes per pile.

55. The modelling was carried out for single modelled pile locations with transmission losses representative of the larger propagation ranges for Dogger Bank Teesside A and Dogger Bank Teesside B. This included the northerly transect radiating from pile location ID1 (**Table 4.1**) for Dogger Bank Teesside A and from pile location ID4 (**Table 4.2**) for Dogger Bank Teesside B. Underwater sound propagation at these two locations has been illustrated in **Figures 4.2** and **4.3**.

56. The effect of SEL dose has been predicted by summing up the SEL received levels of the entire piling sequence assuming a fleeing animal. The model predicts the SEL dose for an animal that moves away from the source once piling starts and continues to move away throughout the piling sequence.

57. Reported swim speeds of free-ranging harbour porpoise span between less than 1m/s and about 6.2m/s (e.g. Otani *et al.* 2000; Cullick *et al.* 2001), although no data exist for harbour porpoise swimming in response to marine impact piling. Swim speeds less than about 1m/s have previously been reported as slow, cruising swim speeds (Otani *et al.* 2000; Akamatsu *et al.* 2007) and swimming at average rates of about 1.7 to 3.1m/s has been observed for harbour porpoise displaying an avoidance response to a sealscarer that had been activated (Brandt *et al.* 2013a; 2013b). In absence of specific swim rates in response to impact piling, this assessment adopted 1.5m/s as a presumed slow fleeing response from loud sounds for harbour porpoise. Although larger marine mammals can swim at higher rates, precautionary swim speed 1.5m/s was also adopted for other

marine mammals, excluding baleen whales, where a swim speed of 3.25m/s, reported for minke whale (Blix and Folkow, 1995) was deemed to be more representative.

Table 4.4 – Pile driving parameters assumed for calculating SEL dose resulting from prolonged exposure.

Parameter	Sequence 1	Sequence 2	Sequence 3
Hammer blow energy (soft-start)	300kJ	300kJ	300kJ
Inter-strike interval (soft-start)	3s	3s	3s
Number of strikes (soft-start)	600	600	600
Hammer blow energy (full piling)	3,000kJ	3,000kJ	3,000kJ
Inter-strike interval (full piling)	1.5s	1.5s	1.5s
Number of strikes (full piling)	1,400	4,400	12,000
Total number of strikes (soft-start and full piling)	2,000	5,000	12,600
Total duration (min)	65	140	330

5. ASSESSING THE IMPACT OF UNDERWATER NOISE ON MARINE FAUNA FROM MARINE IMPACT PILING

58. When considering the impact of noise on sensitive marine species the noise exposure process may be divided into several components:
- Noise emission from sources (requiring the characterisation of those sources in terms of parameters specific to the source);
- The sound transmission process (which will depend on boundary conditions and environmental conditions);
- The ambient noise level; and
- The hearing sensitivity and behavioural context of the subject or receiver at the location where the sound is detected.

59. This section presents the various internationally accepted impact criteria used in this assessment. More information on potential effects of underwater noise on marine receptors and a detailed description on the impact criteria used here are given in Appendix B.

5.1 Summary of criteria adopted for subsea noise impact assessment for the Dogger Bank site

60. The adopted **injury criteria** as described in Appendix B are taken from Southall *et al.* (2007) for marine mammals, with a modified threshold for harbour porpoises taken from Lucke *et al.* (2009). These indicate onset of auditory injury (i.e. PTS onset). Popper *et al.* (2006) and Carlson *et al.* (2007) injury criteria have been applied for fish for peak pressure level and Halvorson *et al.* (2011) can be considered for SEL dose. The injury criteria thresholds are summarised in **Table 5.1**. For the assessment at Dogger Bank Teesside A & B the SEL thresholds have been used for marine mammals as they will result in longer ranges. For fish the Peak Pressure Level has been used for instantaneous injury. As outlined in Southall *et al.* (2007), weighting is only applied to the SEL values.

Table 5.1 - Summary of injury criteria for marine mammals and fish.

	Dual injury criteria (PTS)	
Species	**Peak Pressure Level (dB re 1 μPa)**	**SEL (dB re 1 μPa^2·s)**
Harbour porpoise	*200*	*179* (single strike)
Mid and Low- frequency cetacean	*230*	*198* (*M_{mf}* or *M_{lf} weighted)*
Pinniped	*218*	*186* *(M_{pw} weighted)*
Fish	*206*	*211* *(cumulative)*

61. The **behavioural criteria for marine mammals** described in Appendix B are taken from Southall *et al.* (2007), with a modified threshold for harbour porpoises taken from Lucke *et al.* (2009). The thresholds are summarised in **Table 5.2** below with SEL thresholds applied to estimate potential impact ranges.

Table 5.2 - Summary of behavioural criteria for marine mammals.

	Dual behavioural response criteria for marine mammals	
Species	**Peak Pressure Level (dB re 1 μPa)**	**SEL (dB re 1 $\mu Pa^2 \cdot s$)**
Harbour porpoise ***- TTS/Fleeing response***	*194*	*164*
Harbour porpoise ***- Potential avoidance of area***	*168*	*145*
Mid & Low- frequency cetacean ***- TTS/ Fleeing response***	*224*	*183* (M_{mf} or M_{lf} weighted)
Mid frequency cetacean ***- Potential avoidance of area***	*N/A*	*160 – 170**
Low-frequency cetacean ***- Potential avoidance of area***	*N/A*	*142 – 152**
Pinniped ***- TTS/ Fleeing response/avoidance***	*212*	*171* (M_{pw} weighted)

**Derived from Southall et al. (2007) severity scaling behavioural response and converted to SEL (of the pulse) from RMS (over the duration of the pulse) by subtracting 10dB for mid-frequency cetaceans and 8dB for low-frequency cetaceans (based on the longer ranges for low-frequency cetaceans).*

62. The adopted **behavioural criteria for fish** described in Appendix B are taken from McCauley *et al.* (2000) and Pearson *et al.* (1992). The proposed thresholds are summarised in **Table 5.3** below. See Appendix B for a full description of the criteria outlined in **Table 5.3**.

Table 5.3 - Summary of behavioural criteria for generic fish species.

	Behavioural response criteria for generic fish species
Potential response	**Peak Pressure Level (dB re 1 μPa)**
Possible moderate to strong *avoidance*	*168 - 173**
***Startle response* or C-turn reaction**	*200**

**These levels have been establish from a seismic airgun and should therefore only be applied for impulsive sound source and for fish that are sensitive to sound below around 500*Hz.

63. By applying these criteria to the modelled noise levels obtained as described in Section 4, ranges or zones over which marine mammals and fish might be impacted during the foundation installation can be estimated. Section 6 predicts indicative impact zones for the installation of wind turbine foundations using a range of hammer energies from 300kJ representing the highest expected hammer blow energy at the onset of the soft-start (see **Table 4.3**), up to a maximum of 3,000kJ which is considered the maximum required for monopole foundation.

6. Predicted Impact of Subsea Noise for Dogger Bank Teesside A and Dogger Bank Teesside B

64. This section presents the potential impact of underwater noise on marine fauna at the Dogger Bank Teesside A & B offshore wind farms and is based on applying impact criteria to the modelled received levels.

6.1 Construction phase

65. Underwater noise from impact piling is known to result in significant peak pressure levels and sound exposure levels and will be distinguishable above ambient noise over distances of several tens of kilometres from the source (Nedwell *et al.* 2007; Bailey *et al. 2010*). Foundation types which rely on impact piling are considered the worst case in terms of the resulting underwater noise.

66. Using the modelled noise levels presented in Section 4 and the impact criteria for marine mammals and fish outlined in Section 5, it is possible to establish ranges or zones over which marine mammals and fish might be impacted by marine impact piling during the construction phase of Dogger Bank Teesside A and Dogger Bank Teesside B.

67. As discussed in Section 4.2 a range of hammer energies were considered to represent the different development scenarios for turbine size and foundation type. The anticipated start and maximum hammer blow energy are summarised in **Table 4.3**. Hammer energy of 2,300kJ was used to represent possible maximum hammer strike energy for multipole foundations such as jackets for a 6MW wind turbine. Hammer energy of 2,300kJ was used to represent possible maximum hammer strike energy for a multipole foundation and hammer energy of 3,000kJ was used to represent possible maximum hammer strike energy for a monopole foundation wind turbine. A 300kJ hammer blow energy was used to represent the highest expected soft-start hammer energy at the onset of piling.

6.1.1 Marine Mammals

6.1.1.1 Injury

68. The marine mammal injury criteria adopted for this assessment are outlined in Section 5 and described in detail in Appendix B. The auditory injury impact ranges predicted for mid-frequency and low-frequency cetaceans are based on the PTS onset levels proposed by U.S. National Marine Fisheries Service (NMFS) Marine Mammal Injury Criteria Group (Southall *et al.* 2007), which are based on data from a beluga *Delphinapterus leucas* (Finneran *et al.* 2002a). These may not be applicable to harbour porpoise and so harbour porpoise injury ranges estimated here are based on PTS threshold values obtained from data reported by Lucke *et al.* (2009). The auditory injury ranges for pinnipeds are based on the injury criteria by Southall *et al.* (2007) and are derived from TTS data for a harbour seal *Phoca vitulina* (Kastak *et al.* 2005) by applying the relationship between the relative TTS-onset in cetaceans and pinnipeds, and scaling up to PTS. It should be noted that prolonged exposure to repeated hammer strikes would increase the range over which the onset of PTS might occur. This is considered further in Section 6.1.1.2.

69. Ranges for potential instantaneous onset of auditory injury for marine mammals, indicated in **Tables 6.1** to **6.8**, are expected to be in the range of up to few hundred metres and are based on the onset of a PTS in hearing. Based on the injury criteria by Southall *et al.* (2007), these ranges for Dogger Bank Teesside A span from less than 200m for pinnipeds in water, mid-frequency cetaceans and low-frequency cetaceans to less than 700m for harbour porpoise. The harbour porpoise criterion is based on a TTS to PTS extrapolation of data published by Lucke *et al.* (2009), with the TTS to PTS extrapolation following the methodology outlined by Southall *et al.* (2007). The use of a soft-start, initiating with the hammer at 300kJ will reduce the ranges for potential onset of auditory injury to less than 100m for the considered marine mammal groups, including harbour porpoise (see **Tables 6.1** to **6.4**). Similar results were also obtained for modelling at Dogger Bank Teesside B (see **Tables 6.5** to **6.8**).

70. There are no known cases where marine mammal mortality has occurred as a direct result of noise exposure from wind farm construction or other acoustic sources of similar characteristics and source level. The predicted noise levels in close proximity to the pile are comparable to those estimated for auditory injury. Mortality would only be expected at noise levels substantially above those necessary to cause the onset of auditory injury. The pile driving installation is thus unlikely to result in radiated noise levels beyond a few metres which are sufficient to cause instantaneous mortality in marine mammals (Richardson *et al.* 1995 (converted from Yelverton *et al.* (1975) for marine mammals)).

6.1.1.2 Prolonged Exposure (SEL dose)

71. As described in Section 4.6 the SEL dose has been predicted by summing up the pulse SEL over an entire piling sequence assuming the animal will swim away once piling commences. The four functional hearing groups outlined by Southall *et al.* (2007) have been modelled and include: high-frequency (HF), mid-frequency (MF), low-frequency (LF) cetaceans and pinnipeds in water (PW).

72. The assumed piling sequence parameters used are summarised in **Table 4.4** and the modelled location and transects are described in Section 4.4. The location and transect were chosen to represent favourable propagation conditions and approximate the worst case.

73. The model is very precautionary in that it does not account for any time that a receptor may spend at the surface, or the reduced sound exposure levels near the surface where the animal would not be exposed to such levels, and also does not account for any temporal hearing recovery. As such, the exposure predicted in the model is likely to be an overestimate of the exposure that a receptor might be subjected to. It is assumed that the animal swims away directly from the sound source which would be likely at closer ranges where the animal would be expected to show a strong avoidance reaction. However, this may not be an accurate description of the behaviour of an animal at greater distances, although harbour porpoise abundance has been shown to reduce out to ranges of up to about 20km from the pile (Tougaard *et al.* 2009 and Brandt *et al.* 2011), indicating that they do indeed move away from the sound source. Pinnipeds, however, are only expected to exhibit a strong avoidance response at ranges of less than 2km from the pile (see **Tables 6.4** and **6.8**), although their ability to come to the surface would reduce the effects of prolonged noise exposure and allow some relaxation of TTS.

74. The calculated SEL dose for each of the three piling sequence scenarios modelled are shown in **Figures 6.1** and **6.2** for the exemplar worst case propagation transects for Dogger Bank Teesside A and Dogger Bank Teesside B, respectively, assuming a maximum hammer strike energy of 3,000kJ. This represents a noise exposure, to which a receptor might be exposed, that is higher than the noise exposure expected across most of the Dogger Bank Teesside locations. The results shown for Dogger Bank Teesside A and Dogger Bank Teesside B are for northerly pile locations and northward propagation transects where the noise generally propagates more efficiently compared to other areas across Dogger Bank Teesside A & B.

75. The use of a 3,000kJ hammer represents the absolute worst case hammer used and not necessarily the actual hammer blow energy used to insert the pile. Experience from previous wind farm construction shows that the maximum rated hammer energy is rarely achieved during a piling sequence and only for short durations if it is. Furthermore, the simulated soft-start used in the model will likely result in a higher cumulate SEL dose than a typical soft-start procedure which usually contains several short pauses in piling for alignment measurements, which would allow a fleeing animal to reduce its exposure to the sound and would further allow hearing sensitivity recovery to occur. This is particularly relevant at close ranges where the SEL dose increases more rapidly than at greater ranges from the pile where the received levels are lower.

76. The modelled sequence is considered as the potential worst case piling scenario for a given pile in each of the wind farms. The precautionary 12,600 hammer strikes assumed for the worst case is much more than typically seen for previous wind farm developments in the UK.

77. **Figures 6.1** and **6.2** also show piling durations of 2,000 and 5,000 hammer strikes, which represent the lower and upper end of what has typically been seen during the construction in many previous UK wind farms (Nedwell *et al.* 2007a; Nedwell *et al.* 2009; Nedwell *et al.* 2010; Robinson *et al.* 2009a and Theobald *et al.* 2010). Although, it should be noted that most data exist for earlier developments, and larger piles in more challenging offshore environments may require a higher number of pile strikes. In the end, however, the more pertinent uncertainties regarding the receptors' response to underwater piling noise pose the biggest limitation.

78. Whilst it is not possible, due to knowledge gaps in hearing recovery, equal energy assumptions for impulsive sounds and animal behaviour when fleeing a loud sound (i.e. where in the water column they swim and how often they break surface) to accurately assess the actual range at which an animal might exhibit a PTS effect, it is clear that increased sound exposure as a result of prolonged exposure does increase the risk of a receptor suffering some level of hearing damage. The modelling also highlights the importance of an effective mitigation zone around the piling vessel as increasing the distance at which the animal is when it starts to swim away at the onset of piling decreases the risk of it suffering hearing damage. The use of Acoustic Mitigation Devices (AMDs) could be considered as an effective way of increasing the effectiveness of the mitigation zone (e.g. Brandt *et al.* 2013a, 2013b). This is further discussed in Appendix C.

79. Information which does exist on the behaviour of pinnipeds, estimates that they can spend up to around 15% of their time on the surface during foraging (Stewart 2009) and

that they increase the time they spend with the upper part of their heads above water when exposed to intense sound (Kastelein *et al.* 2011).

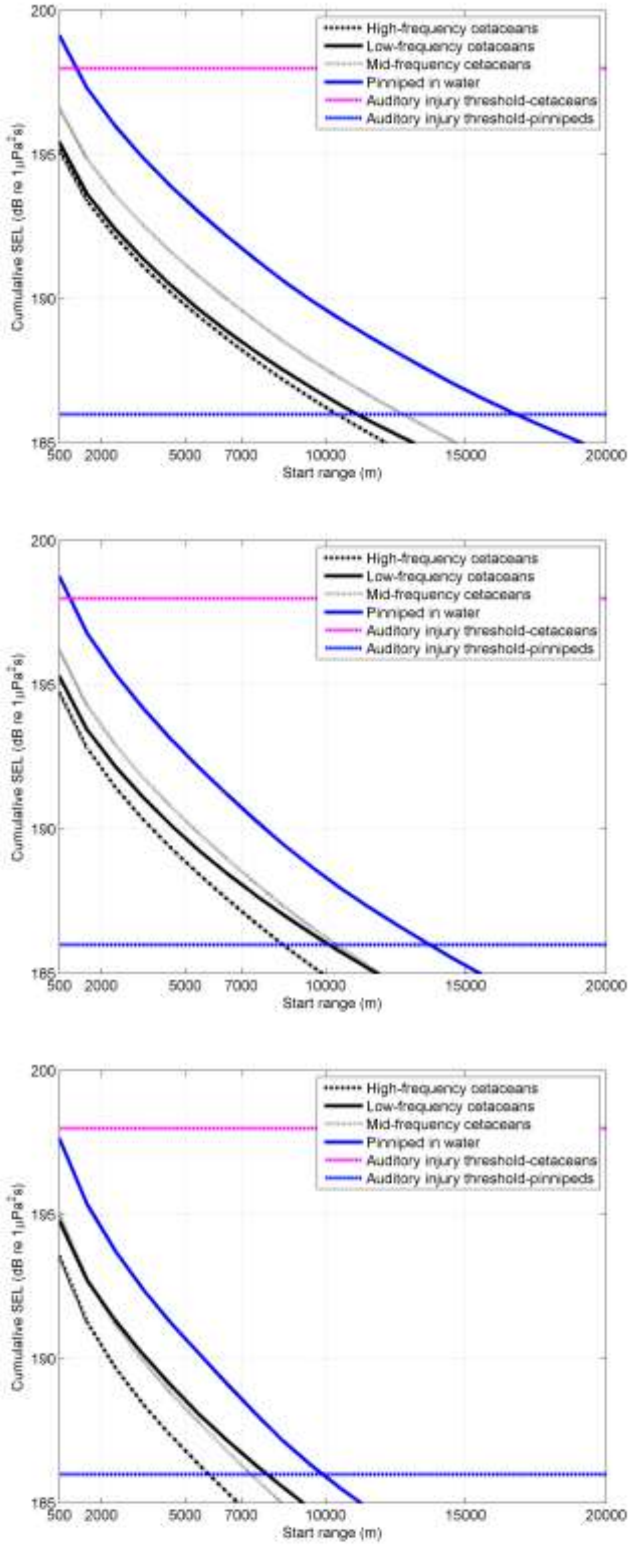


Figure 6.1 - Required start range for the marine mammal functional hearing groups (Southall *et al.* 2007) from the pile when piling starts, such that the animal is not over exposed and does not suffer auditory injury (PTS onset) for monopole parameters described in Table 4.4. The modelled results are for Dogger Bank Teesside A assuming 12,600 pile strikes (top), 5,000 pile strikes (middle), and 2,000 pile strikes (bottom) and animal swim speeds at 1.5m/s, but for the low frequency cetacean where a swim rate of 3.25m/s was used.

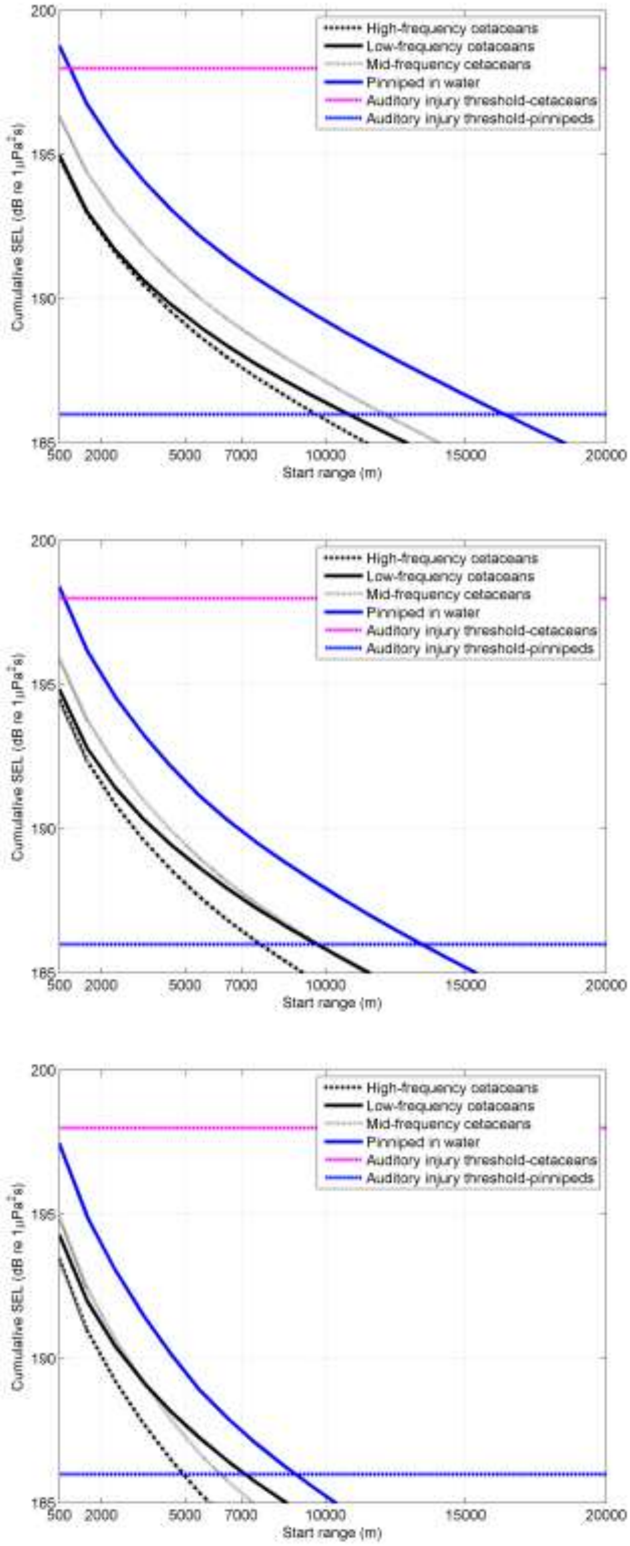


Figure 6.2 - Required start range for the marine mammal functional hearing groups (Southall *et al*. 2007) from the pile when piling starts, such that the animal is not over exposed and does not suffer auditory injury (PTS onset) for monopole parameters described in Table 4.4. The modelled results are for Dogger Bank Teesside B assuming 12,600 pile strikes (top), 5,000 pile strikes (middle), and 2,000 pile strikes (bottom) and animal swim speeds at 1.5m/s, but for the low frequency cetacean where a swim rate of 3.25m/s was used.

80. The modelling only considers the noise dose received from a single pile installation due to the lack of information on the amount of hearing recovery between piling events. The gap between pile installations is expected to allow almost complete recovery of any TTS and the gap between successive pile installations for a multi pile foundation would be sufficient for measurable hearing recovery to occur. Finneran *et al.* (2010), for example, predict better than a 50% (in dBs) recovery over just a 1 hour period for a bottlenose dolphin exposed to 3kHz sounds. For harbour porpoise, the range over which piling is expected to result in an avoidance response and the associated likely period of this avoidance (Brandt *et al.* 2011) should be sufficient to minimise the risk of auditory injury during longer installation operations.

6.1.1.3 Behaviour

81. The fleeing ranges for marine mammals, shown in **Tables 6.1** to **6.4** for Dogger Bank Teesside A and **Tables 6.5** to **6.8** for Dogger Bank Teesside B, are based on the acoustic levels which are deemed to cause the onset of TTS, reported by Lucke *et al.* (2009) for harbour porpoises and Southall *et al.* (2007) for low, mid and high-frequency cetaceans and pinnipeds. The marine mammal behavioural disturbance criteria adopted for this assessment are outlined in detail in Appendix B of this report. Assuming a hammer blow energy of 3,000kJ, the fleeing response range for Dogger Bank Teesside A is predicted to be less than 400m for low-frequency cetaceans, between about 4.0 and 5.5km for harbour porpoise and less than about 200m for mid-frequency cetaceans. For smaller hammer blow energies these ranges would be smaller. The same fleeing response ranges are predicted for Dogger Bank Teesside B for 3,000kJ hammer blow energy. Southall *et al.* (2007) criteria for mid-frequency cetaceans applied here (both, severity scaling and single pulse response) relate to larger species such as the beluga, killer and sperm whale and it was thought these may be less applicable to smaller mid-frequency cetaceans such as the dolphin species local to the North Sea. However, recent work by Finneran *et al.* (2012), exposing a bottlenose dolphin to a seismic airgun, indicates that this higher level threshold may not be unrealistic and small mid-frequency cetaceans may well be less sensitive to impulsive sounds than suggested by Tougaard *et al.* (2009), Lucke *et al.* (2009) and Brandt *et al.* (2011) for the harbour porpoise. For pinnipeds, several of the studies reviewed by Southall *et al.* (2007) indicate that fleeing and indeed avoidance only occur at noise levels which are considered sufficient to cause the TTS. Based on this information, the predicted fleeing response for a pinniped and the avoidance ranges during construction at Dogger Bank Teesside A and Dogger Bank Teesside B would be less than around 1.7km for any assumed hammer blow energy (see **Figure 6.3** for the maximum 3000kJ hammer blow energy). These ranges are summarised in **Tables 6.4** and **6.8** for Dogger Bank Teesside A and Dogger Bank Teesside B, respectively.

82. Avoidance information is not provided in the Marine Mammal Noise Exposure Criteria (Southall *et al.* 2007) for high-frequency cetaceans exposed to pulsed sounds except for the more severe fleeing response based on TTS. Recent work in Denmark (Tougaard *et al.* 2009 and Brandt *et al.* 2011) shows that behavioural disturbance/avoidance may occur over larger distances (around 20km for the specific setting) than that implied by the fleeing response. Work by Lucke *et al.* (2009) for exposure of a harbour porpoise to seismic airgun provides indicative noise levels at which avoidance may occur. For Dogger Bank Teesside A, this results in possible avoidance range of between about 22.0 and 33.0km and between about 22.0 and 33.5km for Dogger Bank Teesside B, both for a 3,000kJ hammer blow energy (these ranges are summarised in **Tables 6.1** and **6.5** for Dogger Bank Teesside A and Dogger Bank Teesside B, respectively, for hammer

energies of 300kJ, 1900kJ, 2300kJ and 3000kJ). The spread in the estimated avoidance ranges for each project is due to variations in bathymetry and therefore propagation efficiency. As could be seen in **Figures 4.2** and **4.3**, there is considerable variation in sound propagation across Dogger Bank Teesside A and Dogger Bank Teesside B that stems from the changes in bathymetry, with the largest propagation ranges generally occurring northwards, because of an increase in water depth in those directions. The effect of this on the behavioural disturbance ranges for harbour porpoise can be seen in **Figure 6.4** for the 3,000kJ hammer blow energy. **Figure 6.5** also shows the noise footprint which has been predicted for Dogger Bank Teesside A and Dogger Bank Teesside B for the harbour porpoise. This shows the possible spatial extent of the piling noise in terms of harbour porpoise behavioural disturbance, with no regard for specific temporal construction sequencing across the project (see Section 4.3 for more detail).

83. Applying the Marine Mammal Exposure Criteria for mid-frequency cetaceans it is predicted that an avoidance range up to about 2.5km is likely and that an avoidance range of between about 6.0 and 8.5km is possible for Dogger Bank Teesside A and Dogger Bank Teesside B. These behavioural disturbance ranges for mid-frequency cetaceans are illustrated in **Figure 6.6** for the 3,000kJ hammer blow energy and summarised in **Tables 6.2** and **6.6** for Dogger Bank Teesside A and Dogger Bank Teesside B, respectively, for hammer energies of 300kJ, 1900kJ, 2300kJ and 3000kJ. **Figure 6.7** also shows the noise footprint which has been predicted for Dogger Bank Teesside A and Dogger Bank Teesside B for the mid-frequency cetacean as described above.

84. Applying the Marine Mammal Exposure Criteria for low-frequency cetaceans it is predicted that an avoidance range of about13.5 to 18.0km is likely and that an avoidance range of between about 26.5 and 41km is possible for Dogger Bank Teesside A. Applying the same criteria to Dogger Bank Teesside B it is predicted that an avoidance range of about 13.0 to 19.0km is likely and an avoidance range of about 26.0 and 41km is possible for the low-frequency cetacean hearing group. These behavioural disturbance ranges for low-frequency cetaceans are illustrated in **Figure 6.8** for the 3,000kJ hammer blow energy and summarised in **Tables 6.3** and **6.7** for Dogger Bank Teesside A and Dogger Bank Teesside B, respectively, for different hammer energies of 300kJ, 1900kJ, 2300kJ and 3000kJ. **Figure 6.9** shows the noise footprint which has been predicted for Dogger Bank Teesside A and Dogger Bank Teesside B for the low-frequency cetacean as described above.

85. The noise levels present in the water will also depend on the depth of the receptor as described in Section 4.5 and marine mammals near the surface will be exposed to lower noise levels with correspondingly smaller impact ranges. For example, a pinniped with its ears just below the water line would be exposed to substantially reduced noise levels, and even at one metre below the surface of the water, would be exposed to lower levels than those predicted in the propagation modelling.

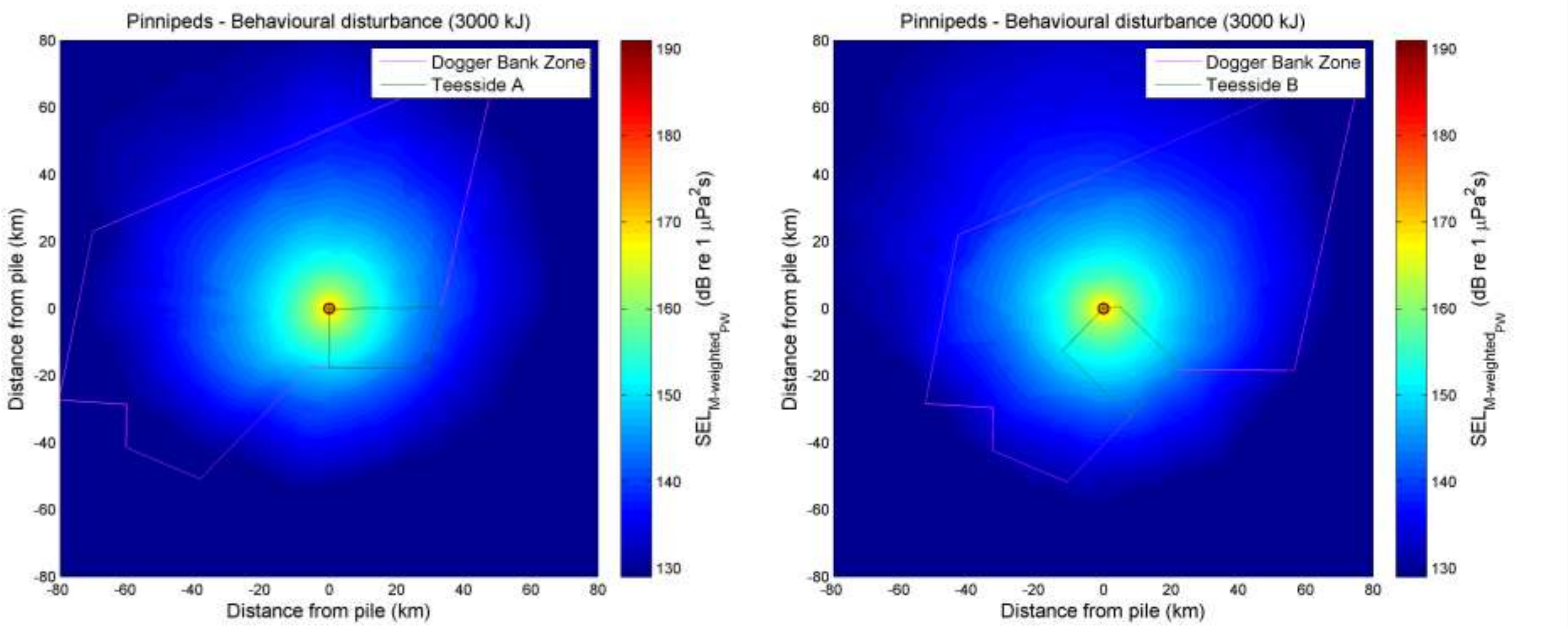


Figure 6.3 – Pinnipeds in water behavioural disturbance zones for Dogger Bank Teesside A (left) and Dogger Bank Teesside B (right) using 3,000kJ hammer blow energy. The behavioural disturbance threshold (171dB re 1 μPa^2·s, M_{pw} weighted) is indicated by a black contour line close to the pile location. Locations correspond to location ID 1 in Table 4.1 and location ID 4 in Table 4.2.

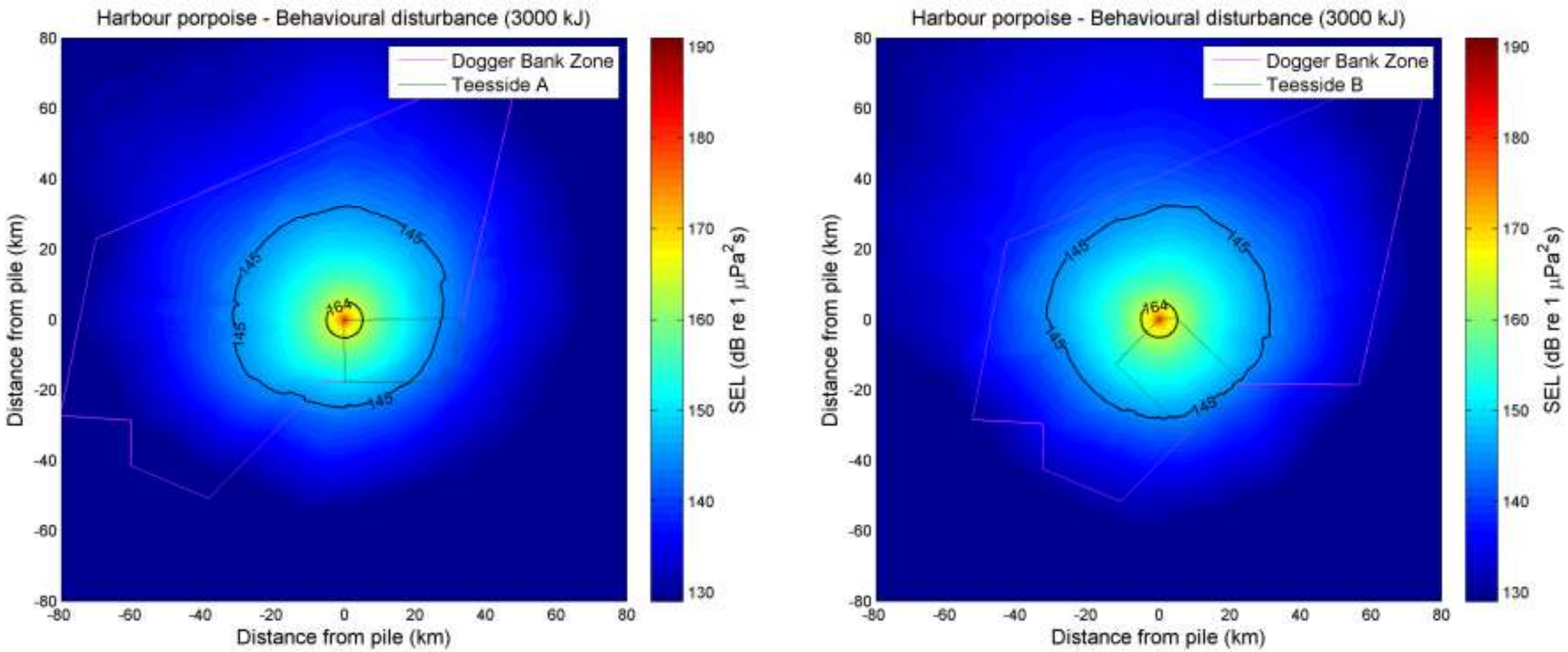


Figure 6.4 – Harbour porpoise behavioural disturbance zones for Dogger Bank Teesside A (left) and Dogger Bank Teesside B (right) using 3,000kJ hammer blow energy. Locations correspond to location ID 1 in Table 4.1 and location ID 4 in Table 4.

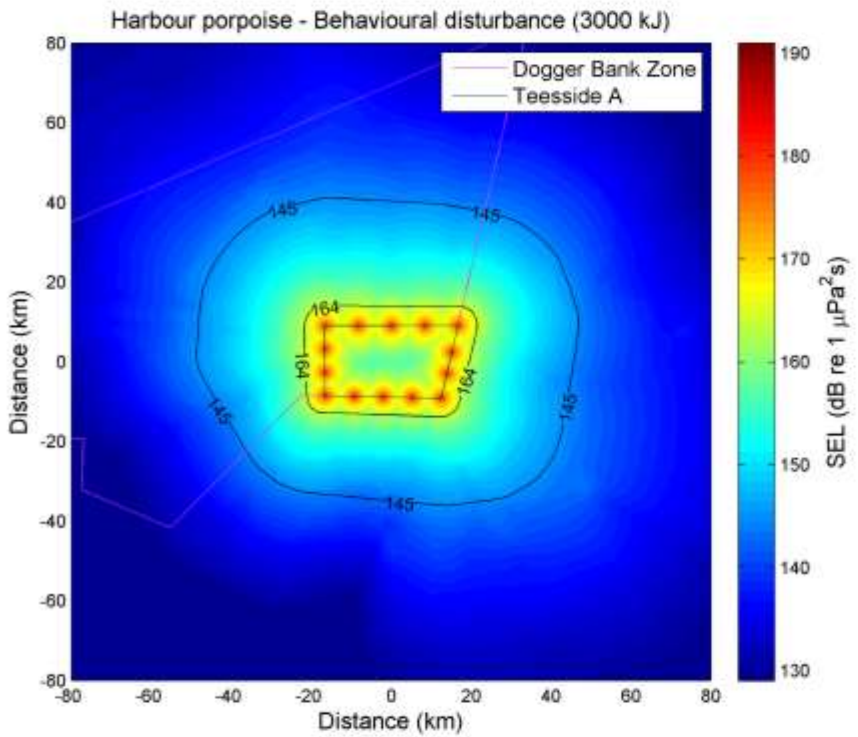


Figure 6.5 – Harbour porpoise behavioural disturbance footprint contours resulting from construction noise at Dogger Bank Teesside A (left) and Dogger Bank Teesside B (right) assuming 3,000kJ hammer blow energy. Underwater sound propagation was modelled for a number of locations along the project boundary to obtain an illustration of the possible spatial extent of the piling noise impact with no regard for temporal construction sequencing across the project (see Section 4.3 for more detail).

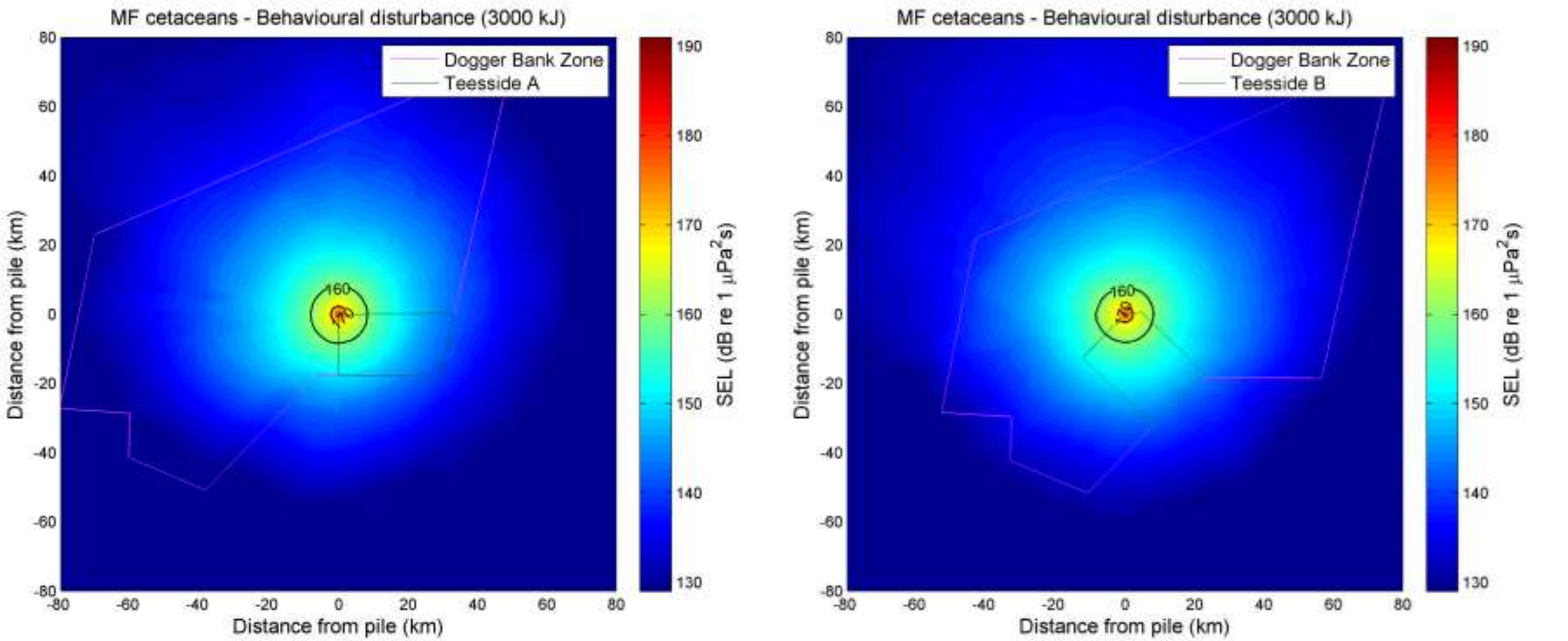


Figure 6.6 – Mid-frequency cetacean behavioural disturbance zones for Dogger Bank Teesside A (left) and Dogger Bank Teesside B (right) using 3,000kJ hammer blow energy. Locations correspond to location ID 1 in Table 4.1 and location ID 4 in Table 4.2.

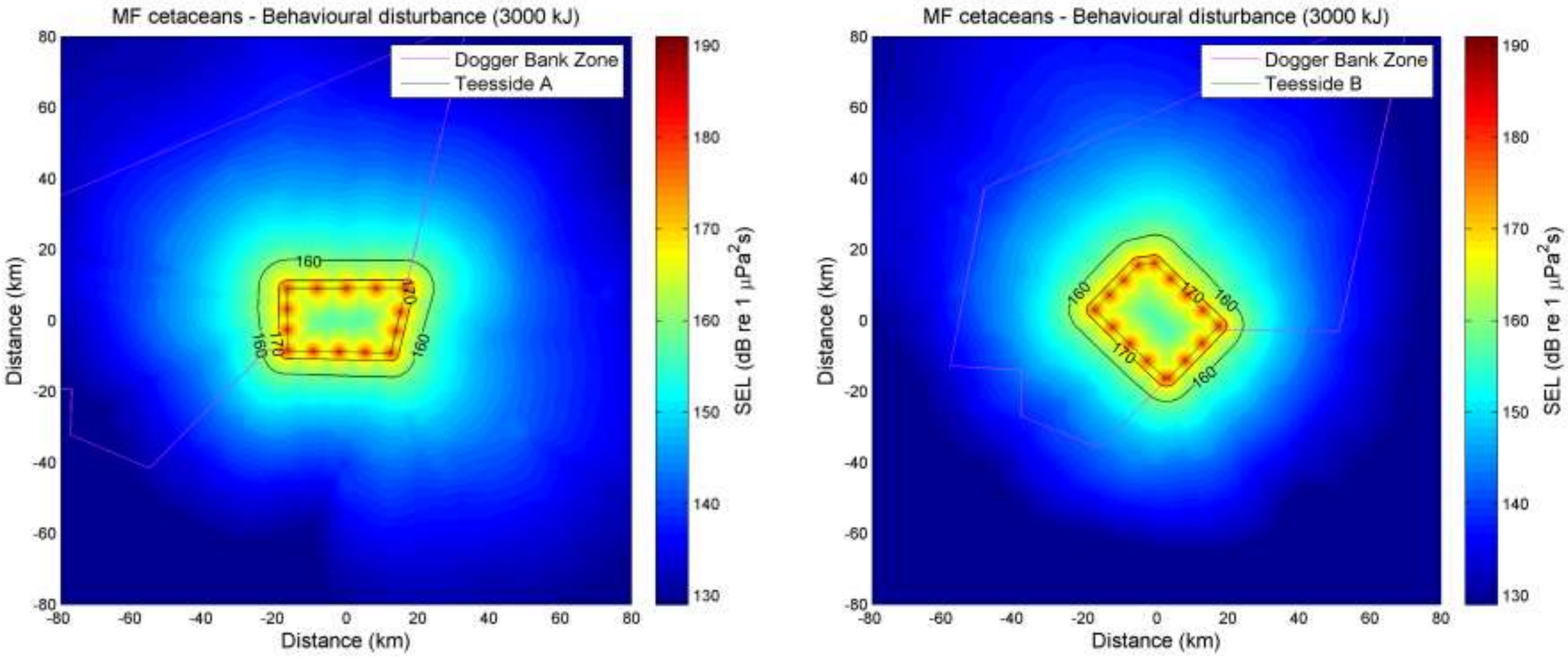
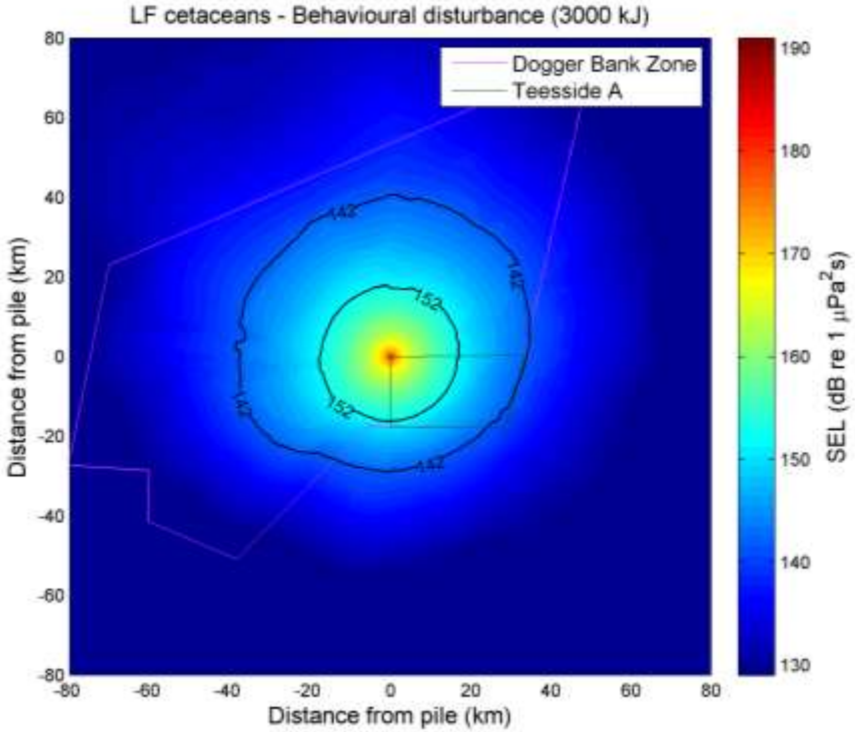


Figure 6.7 – Mid-frequency cetacean disturbance footprint contours resulting from construction noise at Dogger Bank Teesside A (left) and Dogger Bank Teesside B (right) assuming 3,000kJ hammer blow energy. Underwater sound propagation was modelled for a number of locations along the project boundary to obtain an illustration of the possible spatial extent of the piling noise impact with no regard for temporal construction sequencing across the project (see Section 4.3 for more detail).



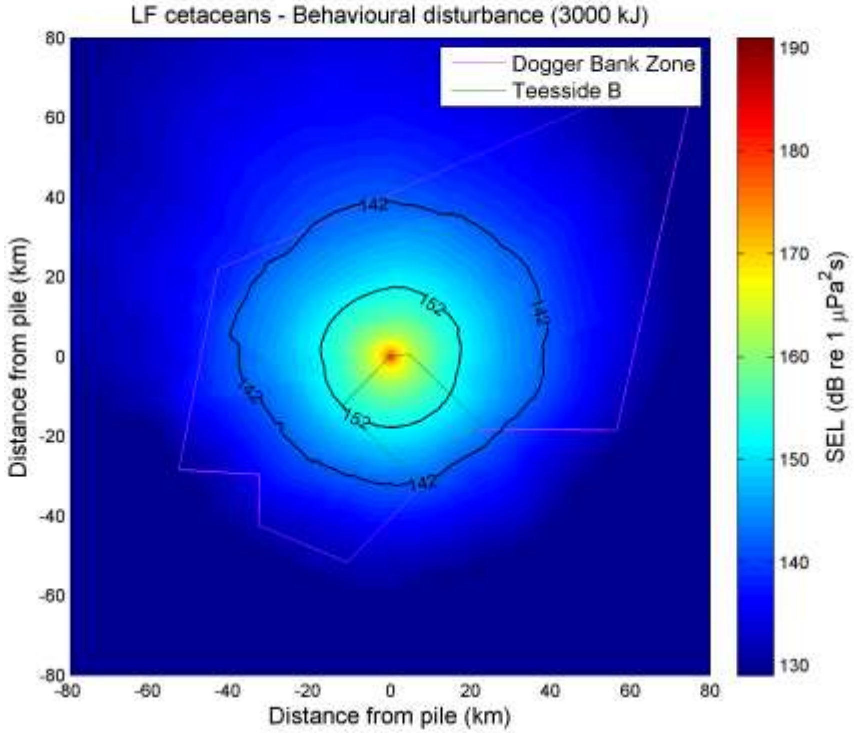


Figure 6.8 – Low-frequency cetacean behavioural disturbance zones for Dogger Bank Teesside A (left) and Dogger Bank Teesside B (right) using 3,000kJ hammer blow energy. Locations correspond to location ID 1 in Table 4.1 and location ID 4 in Table 4.2.

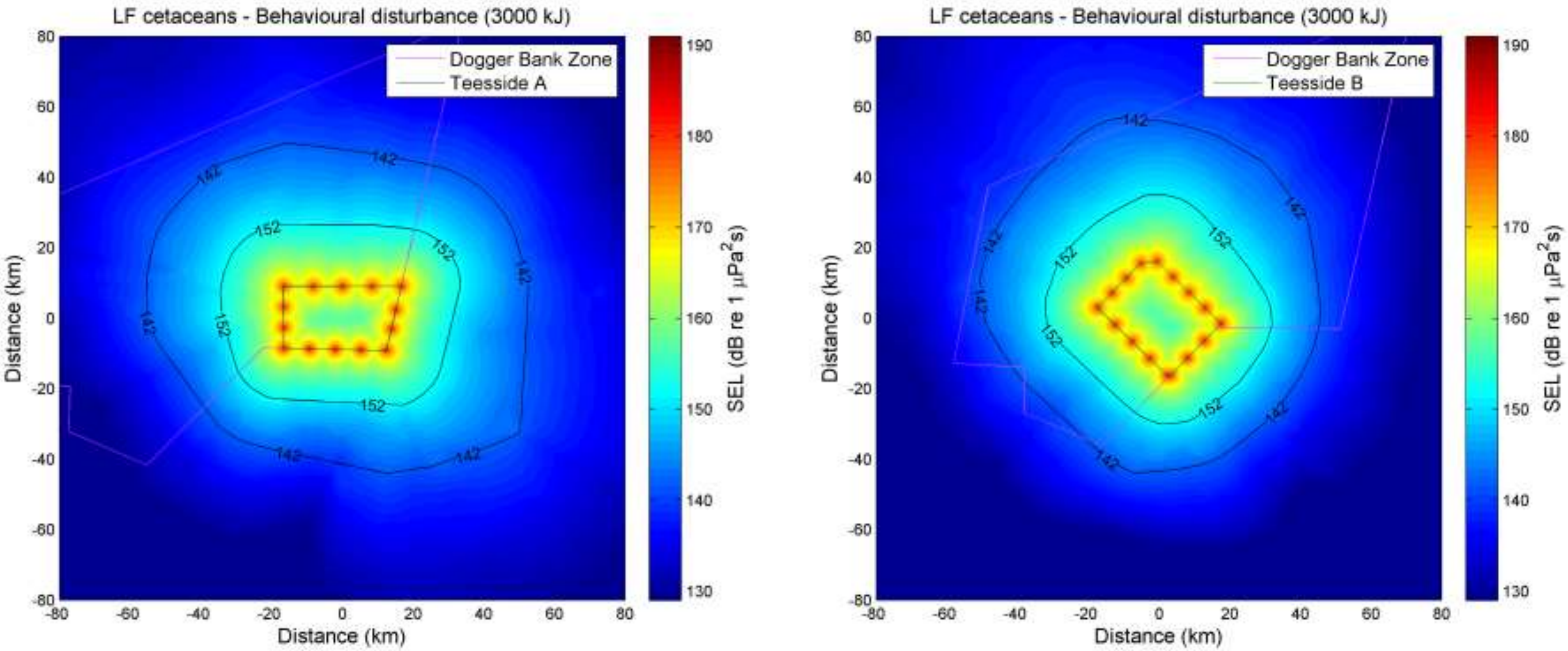


Figure 6.9 – Low-frequency cetacean disturbance footprint contours resulting from construction noise at Dogger Bank Teesside A (left) and Dogger Bank Teesside B (right) assuming 3,000kJ hammer blow energy. Underwater sound propagation was modelled for a number of locations along the project boundary to obtain an illustration of the possible spatial extent of the piling noise impact with no regard for temporal construction sequencing across the project (see Section 4.3 for more detail).

Table 6.1 – Summary of harbour porpoise impact ranges for construction at Dogger Bank Teesside A. The green cells indicate hammer blow energies where the potential for onset of auditory injury is mitigated by the use of a 500m mitigation zone, assuming the animal swims away from the source once piling commences.

Estimated Harbour Porpoise Impact Ranges – Dogger Bank Teesside A				
Impact Criterion	**Potential Range of Impact for Harbour Porpoise**			
	300kJ hammer energy	**1,900kJ hammer energy**	**2,300kJ hammer energy****	**3,000kJ hammer energy****
Instantaneous injury/PTS (pulse SEL 179dB re 1 $\mu Pa^2 \cdot s$)*	<100m	<500m	<600m	<700m
TTS/fleeing response (pulse SEL 164dB re 1 $\mu Pa^2 \cdot s$)*	<1.5km	~3.2 – 4.2km	~3.5 – 4.6km	~4.0 – 5.5km
Possible avoidance of area (pulse SEL 145dB re 1 $\mu Pa^2 \cdot s$)*	~10 – 13.5km	~20.0 – 28.0km	~21.0 – 30.0km	~22.0 – 33.0km

**Lucke et al. (2009)*
*** The potential for instantaneous onset of auditory injury (onset of PTS) at ranges exceeding 500m radius from the pile could potentially be mitigated by extending the mitigation zone to 700m from the pile or by ensuring the hammer energy does not exceed 1900kJ within the first seven minutes of piling. At a hammer blow energy of 1900kJ, the range for potential onset of auditory injury is less than 500m. Assuming that the animal swims away from the sound source at a relatively slow, cruising speed of 0.5m/s in a straight line, it would transit the distance between 500 and 700m in less than seven minutes from the first strike. In reality, an animal in close proximity to a high level sound source is likely to swim away faster (e.g. Brandt et al. 2013a; 2013b). Please note that, for precautionary reasons, the swim speed here is less than harbour porpoise fleeing speed adopted for calculation of the SEL dose response in Section4.6.*

Table 6.2 – Summary of mid-frequency cetacean functional hearing group impact ranges for construction at Dogger Bank Teesside A. The green cells indicate hammer blow energies where the potential for onset of auditory injury is mitigated by the use of a 500m mitigation zone, assuming the animal swims away from the source once piling commences.

Estimated mid-Frequency Cetacean Impact Ranges - Dogger Bank Teesside A				
Impact Criterion	**Potential Range of Impact for mid-Frequency Cetacean**			
	300kJ hammer energy	**1,900kJ hammer energy**	**2,300kJ hammer energy**	**3,000kJ hammer energy**
Instantaneous injury/PTS (M_{mf} weighted 198dB re 1 μPa^2·s)*	<100m	<100m	<100m	<100m
TTS/fleeing response (M_{mf} weighted 183dB re 1 μPa^2·s)*	<100m	<100m	<150m	<200m
Likely avoidance of area (pulse SEL 170dB re 1 μPa^2·s)***	<600m	<2.0km	<2.0km	<2.5km
Possible avoidance of area (pulse SEL 160dB re 1 μPa^2·s)***	<2.5km	~5.0 – 7.0km	~5.0 – 7.2km	~6.0 – 8.5km

Southall et al. (2007) Injury Criteria, **Southall et al. (2007) Single pulse behavioural disturbance.*Southall et al. (2007) Multiple pulses severity scoring behavioural disturbance (RMS SPL converted to pulse SEL by subtraction of 10dB).*

Table 6.3 – Summary of low-frequency cetacean functional hearing group impact ranges for construction at Dogger Bank Teesside A. The green cells indicate hammer blow energies where the potential for onset of auditory injury is mitigated by the use of a 500m mitigation zone, assuming the animal swims away from the source once piling commences.

Estimated Low-Frequency Cetacean Impact Ranges - Dogger Bank Teesside A				
Impact Criterion	**Potential Range of Impact for Low-Frequency Cetacean**			
	300kJ hammer energy	**1,900kJ hammer energy**	**2,300kJ hammer energy**	**3,000kJ hammer energy**
Instantaneous injury/PTS (M_{lf} weighted 198dB re 1 μPa^2·s)*	<100m	<100m	<100m	<100m
TTS/fleeing response (M_{lf} weighted 183dB re 1 μPa^2·s)*	<100m	<250m	<300m	<400m
Likely avoidance of area (pulse SEL 152dB re 1 μPa^2·s)***	~4.8 – 6.8km	~11.0 – 15.5km	~12.0 – 17.0km	~13.5 – 18.0km
Possible avoidance of area (pulse SEL 142dB re 1 μPa^2·s)***	~13.5 – 18km	~23.0 – 35.5km	~24.0 – 37.5km	~26.5 – 41.0km

Southall et al. (2007) Injury Criteria, **Southall et al. (2007) Single pulse behavioural disturbance.*Southall et al. (2007) Multiple pulses severity scoring behavioural disturbance (RMS SPL converted to pulse SEL by subtraction of 8dB).*

Table 6.4 – Summary of pinniped functional hearing group impact ranges for construction at Dogger Bank Teesside A. The green cells indicate hammer blow energies where the potential for onset of auditory injury is mitigated by the use of a 500m mitigation zone, assuming the animal swims away from the source once piling commences.

Estimated Pinniped Impact Ranges - Dogger Bank Teesside A				
Impact Criterion	**Potential Range of Impact for Pinnipeds**			
	300kJ hammer energy	**1,900kJ hammer energy**	**2,300kJ hammer energy**	**3,000kJ hammer energy**
Instantaneous injury/PTS * (M_{pw} weighted 186dB re 1 μPa^2·s)	<100m	<100m	<100m	<200m
TTS/Fleeing response/ Likely avoidance (M_{pw} weighted 171dB re 1 μPa^2·s) **	<400m	<1.5km	~1.5km or less	~1.7km or less

**Southall et al. (2007) Injury Criteria, **Southall et al. (2007) Single pulse behavioural disturbance.*

Table 6.5 – Summary of harbour porpoise impact ranges for construction at Dogger Bank Teesside B. The green cells indicate hammer blow energies where the potential for onset of auditory injury is mitigated by the use of a 500m mitigation zone, assuming the animal swims away from the source once piling commences.

Estimated Harbour Porpoise Impact Ranges – Dogger Bank Teesside B				
Impact Criterion	**Potential Range of Impact for Harbour Porpoise**			
	300kJ hammer energy	**1,900kJ hammer energy**	**2,300kJ hammer energy****	**3,000kJ hammer energy****
Instantaneous injury/PTS (pulse SEL 179dB re 1 $\mu Pa^2 \cdot s$)*	<200m	<500m	<550m	<700m
TTS/fleeing response (pulse SEL 164dB re 1 $\mu Pa^2 \cdot s$)*	<1.5km	~3.6 – 4.2km	~3.8 – 4.8km	~4.0 – 5.5km
Possible avoidance of area (pulse SEL 145dB re 1 $\mu Pa^2 \cdot s$)*	~10 to 14km	~19.5 –29.5km	~21.0 – 30.5km	~22.0 – 33.5km

**Lucke et al. (2009)*

*** The potential for instantaneous onset of auditory injury (onset of PTS) at ranges exceeding 500m radius from the pile could potentially be mitigated by extending the mitigation zone to 700m from the pile or by ensuring the hammer energy does not exceed 1900kJ within the first seven minutes of piling. At a hammer blow energy of 1900kJ, the range for potential onset of auditory injury is less than 500m. Assuming that the animal swims away from the sound source at a relatively slow, cruising speed of 0.5m/s in a straight line, it would transit the distance between 500 and 700m in less than seven minutes from the first strike. In reality, an animal in close proximity to a high level sound source is likely to swim away faster (e.g. Brandt et al. 2013a; 2013b). Please note that, for precautionary reasons, the swim speed here is less than harbour porpoise fleeing speed adopted for calculation of the SEL dose response in Section4.6.*

Table 6.6 – Summary of mid-frequency cetacean functional hearing group impact ranges for construction at Dogger Bank Teesside B. The green cells indicate hammer blow energies where the potential for onset of auditory injury is mitigated by the use of a 500m mitigation zone, assuming the animal swims away from the source once piling commences.

Estimated Mid-Frequency Cetacean Impact Ranges - Dogger Bank Teesside B				
Impact Criterion	**Potential Range of Impact for Mid-Frequency Cetacean**			
	300kJ hammer energy	**1,900kJ hammer energy**	**2,300kJ hammer energy**	**3,000kJ hammer energy**
Instantaneous injury/PTS (M_{mf} weighted 198dB re 1 $\mu Pa^2 \cdot s$)*	<100m	<100m	<100m	<100m
TTS/fleeing response (M_{mf} weighted 183dB re 1 $\mu Pa^2 \cdot s$)*	<100m	<150m	<200m	<200m
Likely avoidance of area (pulse SEL 170dB re 1 $\mu Pa^2 \cdot s$)***	<600m	<2.0km	<2.2km	<2.5km
Possible avoidance of area (pulse SEL 160dB re 1 $\mu Pa^2 \cdot s$)***	<2.5km	~3.6 – 4.2km	~6.0 – 7.5km	~6.0 – 8.5km

Southall et al. (2007) Injury Criteria, **Southall et al. (2007) Single pulse behavioural disturbance.*Southall et al. (2007) Multiple pulses severity scoring behavioural disturbance (RMS SPL converted to pulse SEL by subtraction of 10dB).*

Table 6.7 – Summary of low-frequency cetacean functional hearing group impact ranges for construction at Dogger Bank Teesside B. The green cells indicate hammer blow energies where the potential for onset of auditory injury is mitigated by the use of a 500m mitigation zone, assuming the animal swims away from the source once piling commences.

Estimated Low-Frequency Cetacean Impact Ranges - Dogger Bank Teesside B				
Impact Criterion	**Potential Range of Impact for Low-Frequency Cetacean**			
	300kJ hammer energy	**1,900kJ hammer energy**	**2,300kJ hammer energy**	**3,000kJ hammer energy**
Instantaneous injury/PTS (M_{lf} weighted 198dB re 1 μPa^2·s)*	<100m	<100m	<100m	<100m
TTS/fleeing response (M_{lf} weighted 183dB re 1 μPa^2·s)*	<100m	<250m	<300m	<400m
Likely avoidance of area (pulse SEL 152dB re 1 μPa^2·s)***	~5 – 7km	~11.0 – 15.5km	~12.0 – 17.0km	~13.0 – 19.0km
Possible avoidance of area (pulse SEL 142dB re 1 μPa^2·s)***	~13 – 19km	~23.0 – 36.0km	~24.5 – 38.0km	~26.0 – 41.0km

Southall et al. (2007) Injury Criteria, **Southall et al. (2007) Single pulse behavioural disturbance.*Southall et al. (2007) Multiple pulses severity scoring behavioural disturbance (RMS SPL converted to pulse SEL by subtraction of 8dB).*

Table 6.8 – Summary of pinniped functional hearing group impact ranges for construction at Dogger Bank Teesside B. The green cells indicate hammer blow energies where the potential for onset of auditory injury is mitigated by the use of a 500m mitigation zone, assuming the animal swims away from the source once piling commences.

Estimated Pinniped Impact Ranges - Dogger Bank Teesside B				
Impact Criterion	**Potential Range of Impact for Pinnipeds**			
	300kJ hammer energy	**1,900kJ hammer energy**	**2,300kJ hammer energy**	**3,000kJ hammer energy**
Instantaneous injury/PTS * (M_{pw} weighted 186dB re 1 μPa^2·s)	<100m	~100m or less	<200m	<200m
TTS/Fleeing response/ Likely avoidance (M_{pw} weighted 171dB re 1 μPa^2·s) **	<400m	<1.5km	~1.5km or less	~1.7km or less

**Southall et al. (2007) Injury Criteria, **Southall et al. (2007) Single pulse behavioural disturbance.*

6.1.1.4 Empirical evidence of the impact of underwater noise from marine piling on marine mammals

86. A number of recent studies on the behavioural response of marine mammals to impact piling activities have been carried out (e.g. Carstensen *et al.* 2006, Tougaard *et al.* 2009, Thompson *et al.* 2010, Brandt *et al.* 2011). These studies employed passive acoustic monitoring in the form of T-PODs (*Chelonia Ltd.)* to determine any change in vocalisation occurrence which was taken to be an indicator of reduced activity of cetaceans in the study area, including harbour porpoises and dolphins.

87. Carstensen *et al.* (2006) studied the echolocation activity of harbour porpoises around the Nysted Danish offshore wind farm in the Baltic Sea. The Nysted offshore wind farm is situated in relatively shallow water of around 6m to 9m depth. Although no noise levels due to the piling (impact and vibration) were recorded, T-PODs placed at a distance of around 15km from the foundation location indicated an observable reduction in vocalisation activity. This was interpreted as a reduction in harbour porpoise density in the area following the first piling activity, with a less severe reduction for further piling activity, perhaps indicating some level of habituation. It is also possible that the harbour porpoise density in the area remained constant, with a reduction in vocalisations. However, recent work by Brandt *et al*. (2013a; 2013b), exposing harbour porpoise to seal scarers, does indicate that harbour porpoise would be expected to avoid sounds of sufficiently high level. It should also be noted that for the study at the Nysted offshore wind farm, AMDs were used at the foundation location prior to piling activity. A more detailed study by Tougaard *et al.* (2005) for the Nysted wind farm reported partial recovery in harbour porpoise abundance, based on T-POD detections, two years into the operational cycle of the wind farm.

88. Tougaard *et al.* (2009) studied the echolocation of harbour porpoises, for the Danish Horns Rev offshore wind farm in the North Sea. Pile driving was used to install 4m diameter monopoles in water depths of around 6 to 12m using a 600kJ hammer, generating an estimated peak pressure level source level of 229dB re 1 μPa. T-PODs were deployed out to a distance of 21km from the foundation. The study also employed acoustic pinger deterrents prior to piling. All T-PODs recorded a noticeable change in vocalisation patterns during and after piling, but did not show any correlation with distance from the foundation as expected i.e. the observed effect was the same at 21km as it was at less than 4km. Also, there was no indication of habituation for the subsequent piling events. Thompson *et al.* (2010) used a combination of T-PODs and visual sightings to study the effects of impact piling of 1.8m diameter quad jacket foundations in more than 40m of water for the Beatrice Demonstrator project in the Moray Firth on harbour porpoise and dolphin populations. T-PODs were positioned both near the foundation site and 40km away at a control site. The findings of Thompson *et al.* (2010) suggest there was some short-term response to the installation activities within 1 to 2km around the foundation location, although Bailey *et al.* (2010) measured piling noise beyond 50km at levels which were deemed sufficient to influence behaviour in harbour porpoises and dolphins. Monitoring vocalisation activity at greater distances was not undertaken or reported.

89. Brandt *et al.* (2011) studied the response of harbour porpoise to the installation of the Danish Horns Rev II wind farm in the North Sea using a number of T-PODs out to a distance of 22km from the foundation. The 3.9m diameter monopole foundations were installed in water depths of around 4 to 14m using a 1200kJ hammer.

90. The work by Brandt *et al.* (2011) is perhaps the most informative, stating that harbour porpoise T-POD click detections reduced by 100% during the first hour after piling and stayed below normal levels for 24 to 72 hours at a distance of 2.6km from the foundation. The noise level at a similar range (2.3km) was measured to be 184dB re 1 μPa peak pressure level (164dB re 1 $\mu Pa^2 \cdot s$ SEL) for an 850kJ hammer blow energy, albeit in a different direction from the source. Significantly, the period following piling activity during which reduced harbour porpoise echolocation click activity was observed, diminished with distance away from the foundation, with reduced click activity observed out to 17.8km for 10 to 23 hours following the completion of pile driving. At the farthest T-POD position of 22km from the pile, no reduction in click activity (i.e. no change in T-POD detections) was observed, rather there was an increase in detections following the onset of piling. The recorded mean recovery periods (>17 hours) observed for ranges up to 4.7km were longer than the 16 hour period between foundation installations. The implication may be that the harbour porpoise population abundance within this range remained reduced over the entire construction period of the Horns Rev II wind farm (Brandt *et al.* 2011).

91. Assuming a homogenous propagation environment in all directions from the pile, the noise levels from impact piling at which reduced harbour porpoise acoustic click detections were observed by Brandt *et al.* (2011) indicate that the received level thresholds stated by the US Marine Mammal Criteria Group (Southall *et al.* 2007) for behavioural disturbance of high-frequency cetaceans, of 224dB re 1 μPa peak pressure level and 183dB re 1 $\mu Pa^2 \cdot s$ SEL, are not conservative enough. This is also supported by Lucke *et al.* (2009) who suggested that averse behavioural reactions are likely to occur at received levels of 168dB re 1 μPa peak pressure level and 145dB re 1 $\mu Pa^2 \cdot s$ SEL. In general, observational studies indicate that harbour porpoise will potentially avoid an area around marine impact piling which can extend out to ranges of several tens of kilometres (e.g. around 20km for the specific studies described above).

92. Although no studies of pinniped response to pile driving are available in the literature, a study in the Beaufort Sea (Blackwell *et al.* 2004) during pile driving activities showed no aversive response at any distance for resident ringed seals *P. hispida* in air or water. The noise levels generated in water, however, were lower than those generally associated with wind farm construction. Other pinniped studies in the Beaufort Sea (Harris *et al.* 2001) found seals to show only limited aversion response to a seismic survey which would likely generate noise levels similar to or in excess of those associated with wind farm construction. The seals only showed aversion of an area of around 250m around the source. The findings of Southall *et al.* (2007), on which the aversion ranges for this assessment are based, were that pinnipeds are only likely to show aversion for impulsive type sources when noise levels approach those associated with the onset of TTS. A study on the response of harbour *P. vitulina* and grey seals *Halichoerus grypus* to seismic survey showed a clear fleeing response to the high intensity impulsive sounds which appeared to be short lived with no apparent long-term effects (Thompson *et al.* 1998). There is also indicative evidence from *in situ* monitoring of seals during wind farm construction and operation from around Europe that indicate little or no apparent effect.

6.1.2 Fish

6.1.2.1 Injury

93. The fish injury criteria adopted for this assessment are outlined in detail in Appendix B. Potential instantaneous injury ranges for fish, shown in **Tables 6.9** to **6.12**, are relatively small and are based on the onset of auditory tissue damage. These ranges would only be of the order of tens to perhaps a few hundred metres and are predicted to be less than 200m for Dogger Bank Teesside A and less than 250m for Dogger Bank Teesside B, assuming a 3,000kJ hammer blow energy. At lower hammer blow energies the ranges are smaller and were estimated to be less than 200m for a 2,300kJ hammer and shorter than 100m at the onset of a soft-start at 300kJ. Mortality would only be likely to occur in extreme proximity to the pile. Prolonged exposure to repeated hammer strikes (SEL dose) may increase the distance over which there would be a risk of injury. If it is assumed that the fish move away from the pile during installation then the risk of injury due to prolonged exposure, and therefore the injury range, would be reduced. For fish larvae, the risk of mortality due to prolonged noise exposure would be significantly reduced by any drift of larvae away from the source, due to water currents and would substantially reduce the risk of mortality based on recent work by Bolle *et al.* (2011 and 2012). During periods of zero to very low tidal currents around Dogger Bank when fish larvae might be considered static, no risk of mortality would be expected beyond a few kilometres from the pile location. It is however, not possible to establish if mortality might occur or indeed at what range from the pile, as the study by Bolle *et al*. (2011 and 2012) was unable to induce a statistically significant change in survival rates of fish larvae following a prolonged exposure with a substantial cumulative SEL dose.

6.1.2.2 Behaviour

94. The behavioural influence of the piling noise has been classified into two distinct criteria; i) startle/C-turn reaction and very strong avoidance; and ii) general change in swimming and schooling behaviour with possible moderate to strong avoidance.

95. The underwater noise modelling indicates that the startle response or C-turn reaction, which indicates a very strong dislike to the sound, is unlikely to occur at ranges beyond 600m from the pile for 3,000kJ hammer blow energy (**Tables 6.9** to **6.12**). At the onset of a soft start this range would likely be less than 100m.

96. The impact ranges for disturbance or avoidance indicate that changes in swimming and schooling behaviour may occur. For 3,000kJ hammer blow energy, the ranges are predicted to be about 10.0 to 21.0km for Dogger Bank Teesside A and Dogger Bank Teesside B, for hearing sensitive fish swimming in or around the middle of the water column. For hearing sensitive species dwelling near or on the seabed, the ranges for disturbance or avoidance using 3,000kJ hammer blow energy are predicted to be about 7.5km to 17.0km for Dogger Bank Teesside A and about 8.5 to 17.5km for Dogger Bank Teesside B. At the onset of a soft-start these ranges are estimated to be about 3.8 to 8.5km for Dogger Bank Teesside A and about 3.2 and 7.0km for Dogger Bank Teesside B. Because this criterion is stated as a spread of noise levels (see Section 5 and Appendix B), the impact ranges estimated for changes in swimming and schooling behaviour with possible moderate to strong avoidance are also stated as an impact range spread (also see **Tables 6.9** to **6.12**). This spread indicates the uncertainty associated with this criterion due to the type of fish, its sex, age and condition, as well as other stressors to which the fish is or has been exposed. The response of the fish may also depend on the reasons and drivers for the fish being in the area. Fish may also exhibit

some reaction to the noise, whist not exhibiting an avoidance response, at greater ranges, although this is not likely to be a significant effect.

97. As can be seen in **Figures 6.10** and **6.11**, there is some variation in this avoidance range across the Dogger Bank Teesside projects A and B and also depending on the bearing from the source because of changes in bathymetry, in addition to differences between fish near the centre of the water column (see **Figure 6.10** for pelagic fish) and near the seabed (see **Figure 6.11** for demersal fish). Favourable sound propagation conditions generally to the north of Dogger Bank Teesside A and Dogger Bank Teesside B mean that the impact ranges are generally larger westwards. In general, the deeper water areas of the site also result in larger impact ranges for behavioural disturbance.

98. As with marine mammals the presented impact ranges encompass a range of hammer energies chosen to help estimate the maximum ranges where potential for impact exists and also help indicate potential for mitigation from soft-start. The range maxima stated in the text above generally correspond to hammer blow energy of 3,000kJ, thus impact ranges during construction at Dogger Bank Teesside A and Dogger Bank Teesside B will likely be smaller than the maximum possible impact ranges stated in the text, which may be present for short periods of the construction. The estimated impact ranges for each of the hammer energies are summarised in **Tables 6.9** to **6.12** and are illustrated in **Figure 6.12** which shows the noise footprint which has been predicted for Dogger Bank Teesside A and Dogger Bank Teesside B for pelagic fish. **Figure 6.13** shows the equivalent for demersal fish. These show the possible spatial extent of the piling noise, in terms of fish behavioural disturbance, with no regard for temporal construction sequencing across the project (see Section 4.3 for more detail).

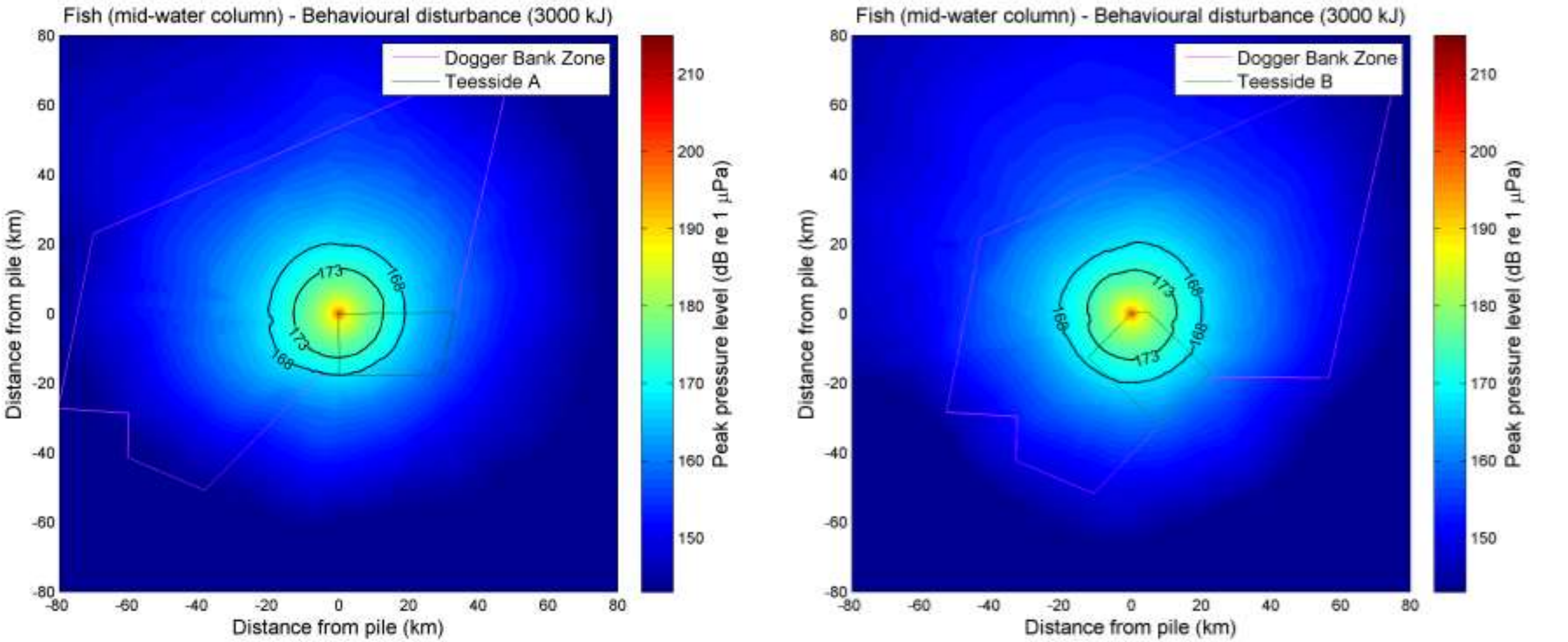


Figure 6.10 –Fish behavioural disturbance zones for pelagic fish (near mid-water column) at Dogger Bank Teesside A (left) and Dogger Bank Teesside B (right) assuming 3,000kJ hammer blow energy. Locations correspond to location ID 1 in Table 4.1 and location ID 4 in Table 4.2.

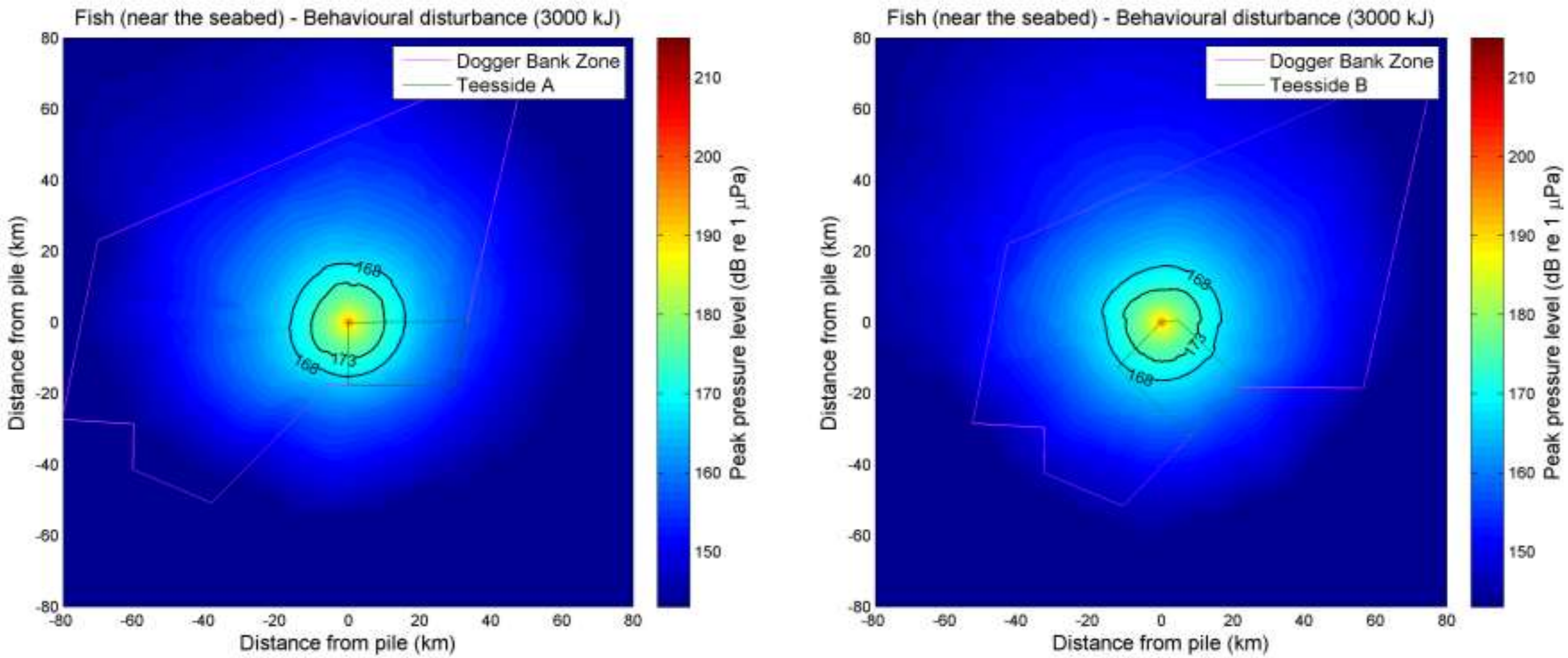


Figure 6.11 – Fish behavioural disturbance zones for demersal fish (near seabed) at Dogger Bank Teesside A (left) and Dogger Bank Teesside B (right) assuming 3,000kJ hammer blow energy and the animal positioned near the seabed. Locations correspond to location ID 1 in Table 4.1 and location ID 4 in Table 4.2.

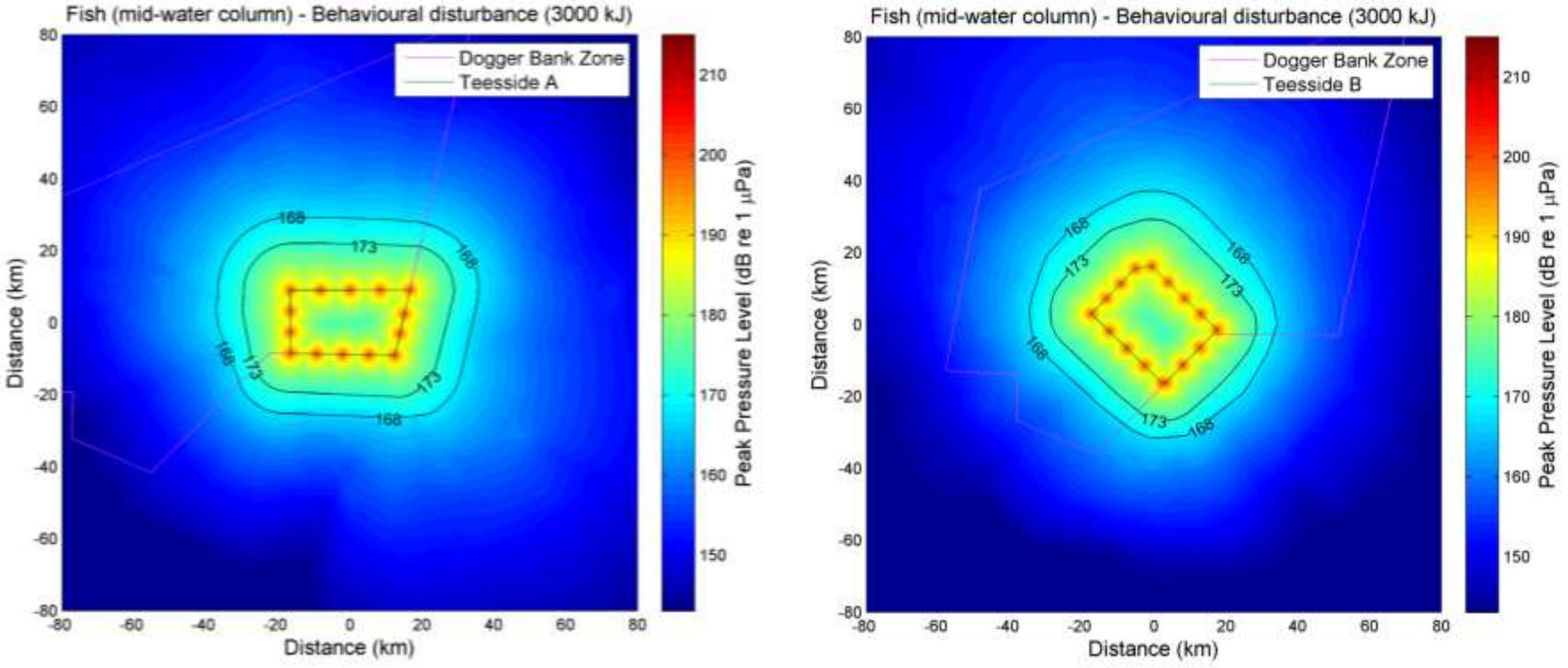


Figure 6.12 – Pelagic fish (near mid-water column) behavioural disturbance footprint contours resulting from construction noise at Dogger Bank Teesside A (left) and Dogger Bank Teesside B (right) assuming 3,000kJ hammer blow energy. Underwater sound propagation was modelled for a number of locations along the project boundary to obtain an illustration of the possible spatial extent of the piling noise impact with no regard for temporal construction sequencing across the project (see Section 4.3 for more detail).

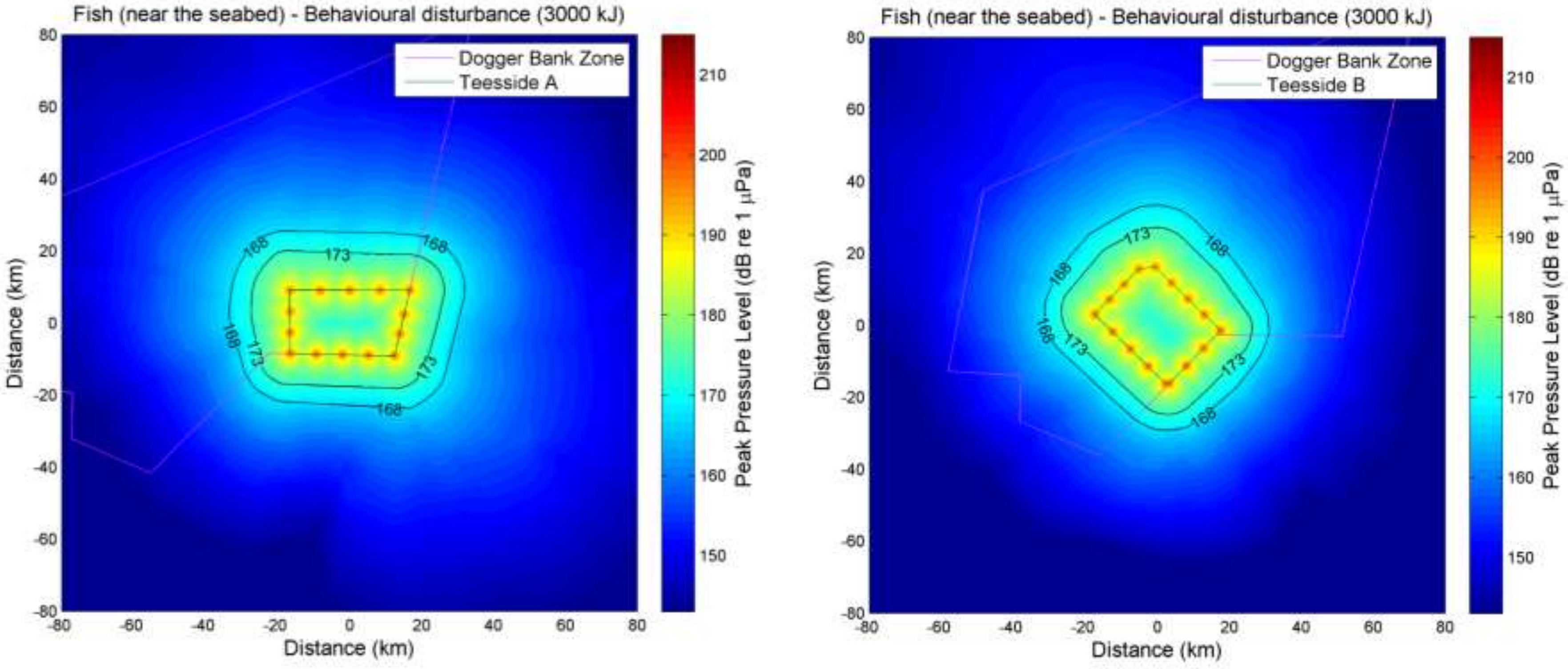


Figure 6.13 – Demersal fish (near seabed) behavioural disturbance footprint contours resulting from construction noise at Dogger Bank Teesside A (left) and Dogger Bank Teesside B (right) assuming 3,000kJ hammer blow energy. Underwater sound propagation was modelled for a number of locations along the project boundary to obtain an illustration of the possible spatial extent of the piling noise impact with no regard for temporal construction sequencing across the project (see Section 4.3 for more detail).

Table 6.9 - Summary of impact range for hearing sensitive pelagic fish for Dogger Bank Teesside A.

Estimated Impact Ranges For Pelagic Fish - Dogger Bank Teesside A				
Impact Criterion	**Potential Range of Impact for Fish in mid-Water**			
	300kJ hammer energy	**1,900kJ hammer energy**	**2,300kJ hammer energy**	**3,000kJ hammer energy**
Instantaneous injury/PTS (peak pressure level 206dB re 1 µPa)	<100m	<200m	<200m	<200m
Startle response (peak pressure level 200dB re 1 µPa)	<100m	<500m	<500m	<600m
Possible avoidance of area* (peak pressure level 168 - 173dB re 1 µPa)	~ 3.8 – 8.5km	~8.0 – 17.5km	~10.0 – 19.0km	~10.0 – 21.0km

** Some particularly insensitive species of fish might only exhibit avoidance behaviour at lesser ranges*

Table 6.10 - Summary of impact range for hearing sensitive fish near or on the seabed for Dogger Bank Teesside A.

Estimated Impact Ranges for Demersal Fish - Dogger Bank Teesside A				
Impact criterion	**Potential Range of Impact for Fish Near or on the Seabed**			
	300kJ hammer energy	**1,900kJ hammer energy**	**2,300kJ hammer energy**	**3,000kJ hammer energy**
Instantaneous injury/PTS (peak pressure level 206dB re 1 µPa)	<100m	<200m	<200m	<200m
Startle response (peak pressure level 200dB re 1 µPa)	<100m	<500m	<500m	<600m
Possible avoidance of area* (peak pressure level 168 - 173dB re 1 µPa)	~3 – 6.6km	~6.5 – 14.0km	7.0 – 15.5km	7.5 – 17.0km

** Some particularly insensitive species of fish might only exhibit avoidance behaviour at lesser ranges.*

Table 6.11 - Summary of impact range for hearing sensitive pelagic fish for Dogger Bank Teesside B.

Estimated Impact Ranges For Pelagic Fish - Dogger Bank Teesside B				
Impact Criterion	**Potential Range of Impact for Fish in Mid-Water**			
	300kJ hammer energy	**1,900kJ hammer energy**	**2,300kJ hammer energy**	**3,000kJ hammer energy**
Instantaneous injury/PTS (peak pressure level 206dB re 1 µPa)	<100m	<200m	<200m	<250m
Startle response (peak pressure level 200dB re 1 µPa)	<200m	~400m or less	<500m	<600m
Possible avoidance of area* (peak pressure level 168 - 173dB re 1 µPa)	~4 – 8.5km	~8.5 – 18.5km	~9.5 – 19.5km	~10.0 – 21.0km

** Some particularly insensitive species of fish might only exhibit avoidance behaviour at lesser ranges*

Table 6.12 - Summary of impact range for hearing sensitive fish near or on the seabed for Dogger Bank Teesside B.

Estimated Impact Ranges For Pelagic Fish - Dogger Bank Teesside B				
Impact Criterion	**Potential Range of Impact for Fishin Mid-Water**			
	300kJ hammer energy	**1,900kJ hammer energy**	**2,300kJ hammer energy**	**3,000kJ hammer energy**
Instantaneous injury/PTS (peak pressure level 206dB re 1 µPa)	<100m	<200m	<200m	<250m
Startle response (peak pressure level 200dB re 1 µPa)	<200m	<400m	<500m	<600m
Possible avoidance of area* (peak pressure level 168 - 173dB re 1 µPa)	~3.2 – 7km	11.0 – 26.5km	7.5 – 15.5km	8.0 – 17.5km

** Some particularly insensitive species of fish might only exhibit avoidance behaviour at lesser ranges.*

99. Despite the numerous wind farm installations currently underway or planned in European waters, very few studies have been undertaken on the behavioural reaction of any marine fauna to marine piling activities. This is particularly the case for fish species. Furthermore, the level and type of response will be dependent on the type of fish, its sex, age and condition and on the reasons and drivers for the fish being in the area (e.g. spawning, migrating). The type of fish and the reason for it being in the area are likely to influence where in the water column the fish is when exposed to the sound. As indicted in **Table 6.9** to **6.12**, this will influence the level of sound to which the fish will be exposed, both in terms of pressure and particle velocity. Fish which are present near the seabed beyond a few kilometres from the pile are likely to be exposed to lower

broadband sound levels and the potential impact ranges will therefore be less, as described in Section 4.5. Most fish will be able to perceive ambient noise and this will likely dictate the lower sound level which they can detect, except for species with particularly poor hearing sensitivity.

100. There have been a number of studies on individual species which do indicate some variation in the response to sound, characteristic of impact piling noise. Hassel *et al.* (2004) studied the effect of seismic sounds sources (representative of impact piling noise i.e. impulsive, high peak acoustic levels, and low frequency) for a prolonged duration on lesser sandeels *Ammodytes marinus* which showed no apparent change in their abundance and only moderate effect on their behaviour.

101. The study by Maes *et al.* (2004) showed that low frequency sound had a statistically significant effect on reducing sole, sprat *Sprattus sprattus* and herring *Clupea harengus* from entering a power plant cooling intake. This is indicative of an avoidance response to low frequency sound and sprat and herring may show avoidance within the ranges indicated in **Tables 6.9** to **6.12**. Shad *Alosa spp.* which are also considered hearing specialists should also be assumed to show similar sensitivity to sprat and herring. The same study found that the sound had a statistically insignificant effect at reducing European/common eel *Anguilla anguilla* and river lamprey *Lamptera fluviatilis* indicating that these species may show avoidance within the ranges indicated in **Tables 6.9** to **6.12**, and this may also be true for the sea lamprey *Petromyzon marinus*.

102. Nedwell *et al.* (2006) investigated the effect of underwater piling noise on salmonids which showed very little effect on brown trout *Salmo trutta*. Nedwell *et al.* (2006) considers the possible inadequacies of extending the observed effects in brown trout to salmon *S. salar* with significant disagreement between audiograms. As the absolute exposure levels to which they were exposed are unknown, a precautionary approach should consider that salmonids may show avoidance within the ranges indicated in **Tables 6.9** to **6.12**, with the likelihood of a lesser response than other more sensitive fish i.e. with possible avoidance towards the higher peak pressure level threshold of 173dB re 1 µPa.

103. It should be noted that no long-term observational studies have been reported in the literature to assess the response of fish populations to marine impact piling and so any fish behaviour impact criteria should strictly only be used for guidance.

6.1.3 The effect of using multiple piling vessels and the influence of vessel separation distance

104. The effect on the noise levels generated from the use of multiple piling vessels has been modelled using the methodology described in Section 4. As described in Section 4.4, the potential effect of vessel separation distance during concurrent piling operations has been illustrated for a set of six Dogger Bank projects, each with a maximum of two piling vessels *per* projects and a maximum of twelve piling vessels. To illustrate the influence of vessel separation distance, this has been modelled for piling vessels assumed 1,500m apart or piling vessels at different corners of the project boundaries.

105. **Figures 6.14** to **6.15** show the modelling results assuming a hammer blow energy of 3,000kJ *per* pile. Contour lines are shown to help illustrate how the use of multiple piling vessels may affect the potential impacted area. The contours correspond to fish behavioural disturbance derived from McCauley *et al.* (2000) and Pearson *et al.* (1992)

(see Section 5 and Appendix B) and harbour porpoise behavioural disturbance based on data from Lucke *et al.* (2009) (see Section 5 and Appendix B).

106. The plots show that the least surface area is impacted at any one time if the vessels are as close together as possible, thus forming one, slightly larger impact zone than a single vessel. When the vessels are far enough away that the impact zones do not overlap then the corresponding impacted area is at its maximum, subject to local propagation conditions. Although the use of multiple piling vessels may increase the impacted area at any given time, it also reduces the overall construction time without necessarily substantially increasing the total impacted area over the construction period of the wind farm. When considering the complete construction period of the wind farm, the reduction in construction time resulting from the use of multiple piling vessels may result in a reduced impact, particularly if the vessels are close together. This will depend on the impact type and the species being impacted.

107. However, the increased extent of the impacted area, particularly if the piling vessels are a substantial distance apart, may result in an increased short-term impact at the time of construction, which may have consequences in terms of receptor displacement. It may also result in an increase in the overall SEL dose.

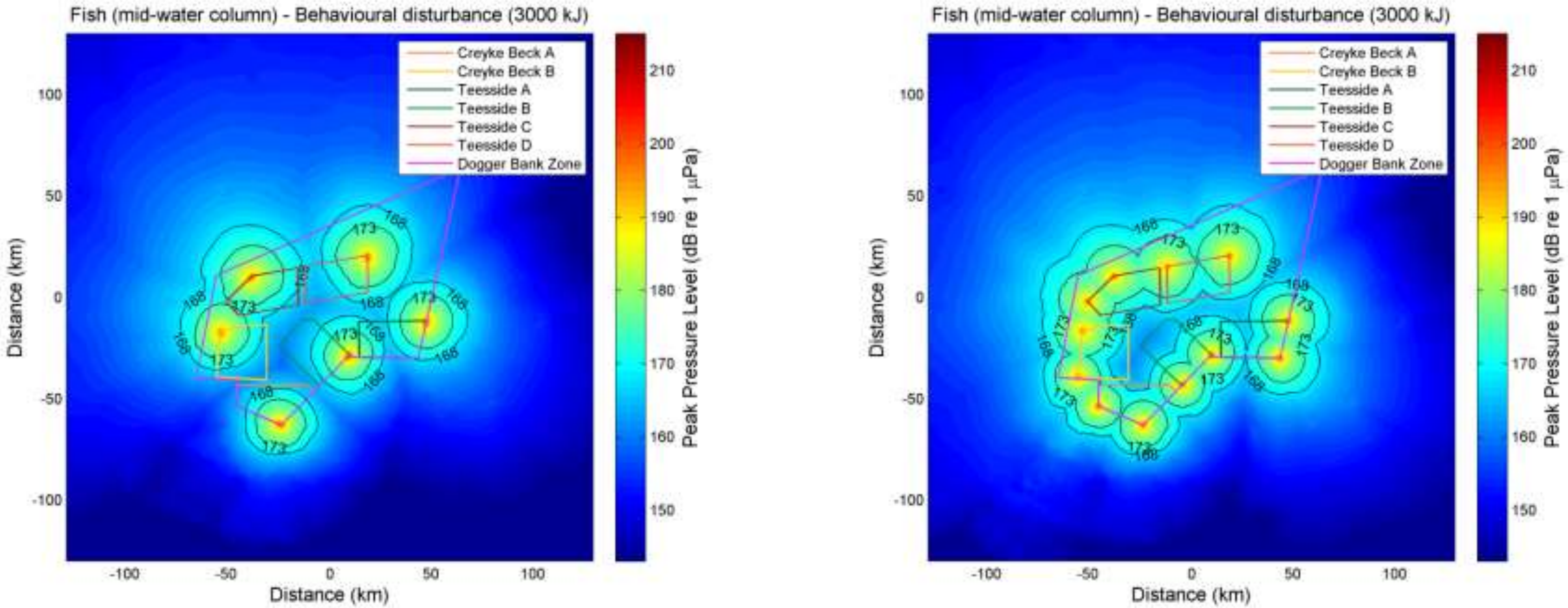


Figure 6.14 – Propagation modelling for twelve piling vessels each operating with a 3,000kJ hammer blow energy, and a maximum of two vessels *per* project for six Dogger Bank offshore wind farm projects. Piling vessels within the same project are approximately 1,500m apart (left) or spread out to approximate a larger area affected (right). Contour lines indicate behavioural disturbance criteria for pelagic fish (near mid-water column).

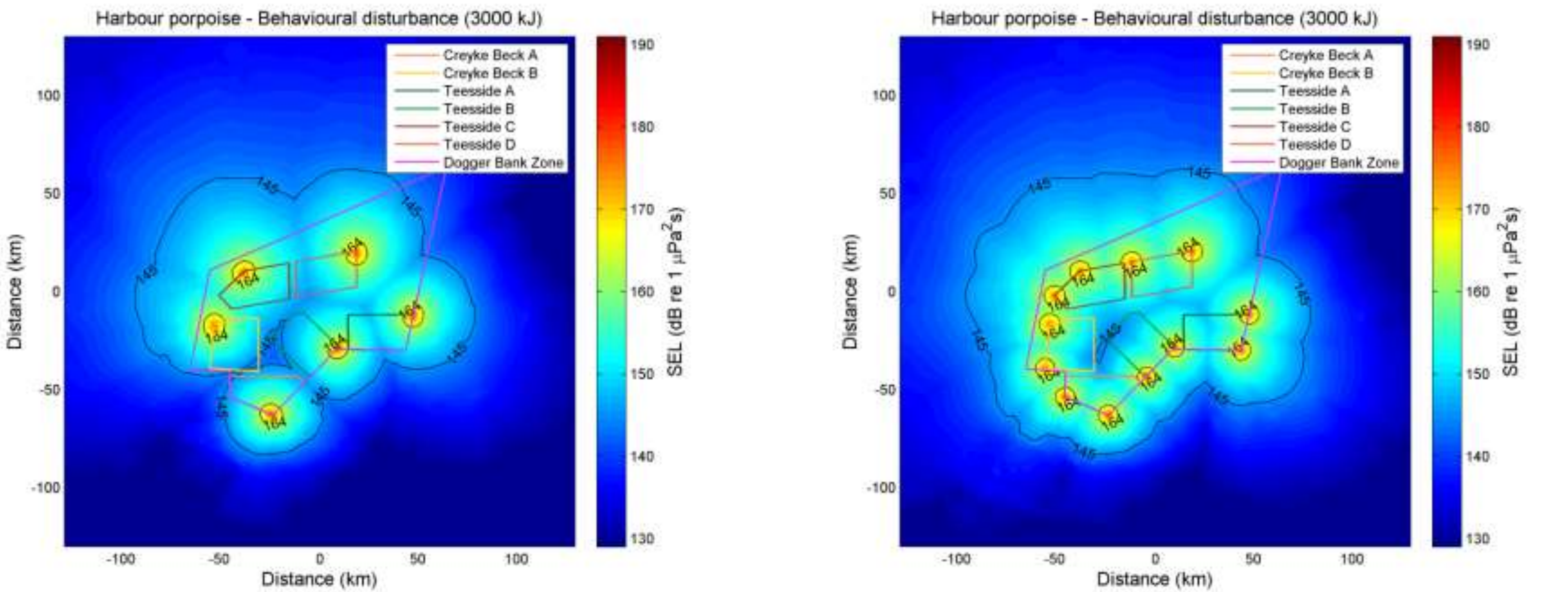


Figure 6.15 – Propagation modelling for twelve piling vessels each operating with a 3,000kJ hammer blow energy, and a maximum of two vessels *per* project for six Dogger Bank offshore wind farm projects. Piling vessels within the same project are approximately 1,500m apart (left) or spread out to approximate a larger area affected (right). Contour lines indicate behavioural disturbance criteria for harbour porpoise.

6.1.4 *Mitigation methods to reduce significance of environmental impact from construction phase on marine mammals*

108. A range of mitigation strategies have been reviewed in Appendix C and the measures which may be further considered, in-line with JNCC guidance (JNCC 2010a), are:

- use of techniques to reduce noise output when piling (soft-start for example);
- use of passive acoustic monitoring (PAM) of marine mammals to inform of any necessary delays to piling;
- use of mitigation zones using qualified marine mammal observers during piling activities; and
- use of acoustic mitigation devices (AMD), if appropriate.

109. The use of lower hammer blow energy during a soft-start procedure can reduce the risk of instantaneous injury (see Appendix C and **Tables 6.1** to **6.12**). A soft-start can be used to reduce the range over which instantaneous injury may occur. It may also deter animals in the vicinity of the pile to a safe distance before the full energy piling is reached reducing the potential for instantaneous injury to occur once maximum piling energy is achieved.

110. The estimated ranges for instantaneous onset of auditory injury for marine mammals (shown in **Tables 6.1** to **6.8**) indicate that harbour porpoise may be at risk of instantaneous injury beyond around 600m once the hammer energy reaches around 2,300kJ at Dogger Bank Teesside A and Dogger Bank Teesside B and up to a range of around 700m for the maximum hammer energy of 3,000kJ. Although this is larger than the minimum recommended 500m mitigation zone (JNCC 2010a), it is expected that the soft-start period would provide sufficient time for receptors to move to a distance where the risk of auditory injury during full piling is reduced. At a hammer blow energy of 1900kJ, the estimated range for the potential onset of auditory injury at Dogger Bank Teesside A and Dogger Bank Teesside B projects is less than 500m. Assuming the animal swims away from the sound source at a slow, cruising speed of 0.5m/s (Otani *et al.* 2000), it would transit the distance between 500m, the minimum recommended mitigation range, and 700m, the maximum impact range for potential PTS onset, in less than seven minutes from the first strike. Based on these assumptions, the potential for auditory injury (onset of PTS) could therefore be mitigated by; the implementation of a 500m radius mitigation zone, provided that the hammer blow energy does not exceed 1900kJ within the first seven minutes; or by extending the mitigation zone to 700m from the pile.

111. Mitigation zone can be achieved using active or passive techniques or a combination of the two. Passive methods generally involve the use of marine mammal observers and/or PAM whilst an active method could include the use of AMDs. A combination of the two may be the most effective strategy by actively seeking to repel animals to a safe distance and then monitoring to check that this has been successful. Further discussion of these mitigation approaches is given in Appendix C.

6.2 Operational phase

112. There are very few reported measurements of wind turbine noise and much of the data that is publicly available is summarised in Wahlberg and Westerberg (2005) and Madsen *et al.* (2006), with Tougaard *et al*. (2009) providing a more recent update.

113. Measurement data of operational turbine noise from UK and abroad show that underwater noise from an operational turbine is continuous in nature and has tonal characteristics that likely originate from the gearbox and the generator (Betke, 2004; Madsen *et al*., 2005; Nedwell *et al*., 2007; Edwards *et al*., 2007; Tougaard *et al*., 2009; Nedwell *et al*., 2011). These tonal components have been shown to vary from tens of hertz to about 200Hz and above, with variation due to the rotational speed of the turbine (Sigray *et al*., 2011).

114. The available measured data are generally for smaller capacity wind turbines ranging from about 0.2 to 3.6 MW (Betke, 2004; Wahlberg and Westerberg, 2005; Madsen et al., 2006; Tougaard et al., 2009; Nedwell *et al.*, 2011). At present, at least 20 UK offshore wind farm projects are reported operational (RenewableUK, 2013) employing turbines with a rated capacity of 2MW or above, however, at present none employ turbines rated higher than 3.6MW capacity. Previous measurements indicate that different sound spectral characteristics may be observed for different wind turbines and probably relate to wind speeds (rotational speeds) and mechanical properties of the turbine (e.g. Madsen *et al.,* 2006, Betke, 2004). The radiating sound is also likely to depend on foundation type and potentially on the seabed supporting the foundation. However, it is also worth noting that reported measurements at the Gunfleet Sands offshore wind farm (Nedwell *et al.*, 2011), which uses a 3.6MW turbine, showed operational noise data which had noise levels and characteristics comparable with previous measurements of 2MW or smaller turbines reported in Wahlberg and Westerberg (2005), Madsen *et al.* (2006) and Tougaard *et al.* (2009). The reported sound levels are not, however, always directly comparable due to the inherent variability in propagation conditions for the measured sound levels and also as a result of variable analysis, notably time averaging. The reported radiated noise levels are generally low and the spatial extent of the potential impact of the operational wind farm noise on marine receptors is widely estimated to be small. There is also no evidence to suggest that injury to marine mammals or fish may occur (Madsen *et al*., 2006, Tougaard *et al.*, 2009b, Wahlberg and Westerberg, 2005) and previously reported noise levels in proximity to the turbines are substantially lower than those expected to result in the onset of a permanent threshold shift in hearing response (PTS), or even a temporary threshold shift in hearing response (TTS), for marine mammals (Southall *et al*., 2007).

115. Besides the sound source characteristics, the potential for impact will also depend on the propagation environment, the receptor's hearing ability and the ambient noise levels. Marine animals may perceive the radiated tonal components, where they exist, above the ambient noise levels, and this may result in a behavioural response of the receptor or lead to a reduced detection of other sounds due to masking. Previous studies show that behavioural response is only likely to be expected at distances close to the wind turbine (a few metres for fish and harbour porpoise (Wahlberg and Westerberg 2005 and Tougaard and Henriksen 2009, respectively) and possibly up to a few hundred metres for seals (Tougaard and Henriksen 2009 and McConnell *et al.* 2012). Tougaard and Henriksen (2009) further show that even masking from operational noise is unlikely to impact harbour porpoise and seal acoustic communication due to the low frequencies and low levels produced.

116. Most *in situ* monitoring of harbour porpoise distribution in relation to operational wind farms also generally supports the notion that operational turbines may not have an apparent negative behavioural effect. A recent study by Scheidat *et al.* (2011) has reported an attraction of harbour porpoises to an operational Dutch wind farm site, where abundance was higher within the wind farm compared to a similar environment in near-by areas. This was assumed to be due to decreased fishing and vessel activity and increased food availability (Scheidat *et al.* 2011). The authors, however, caution against generic transfer of these results to other wind farms, as the response is likely a net result of various factors, which may differ between scenarios. A study at the Nysted offshore wind farm, an area where harbour porpoise numbers are considered relatively low (compared with Horns Reef for example), showed a slow partial recovery in harbour porpoise abundance over the nine year period that it has been operational, following an initial decline during construction (Tougaard *et al*., 2005; Teilmann and Carstensen, 2012). However, a study at the neighbouring Rødsands 2 offshore wind farm, showed no detectable difference in harbour porpoise numbers, either acoustically or visually, between one-year monitoring programmes during the pre-construction phase and again during the operational phase, and no detectable difference with neighbouring reference areas (Teilmann *et al*., 2012). It should be noted that the response of a receptor will depend on its physical state and its presence may depend on the drivers for it being in the area and may also result from a change in the environment or habitat.

117. Although the effect on fish response is more difficult to establish, given the lack of information available in the scientific literature, there is indicative evidence that fish would be unlikely to show significant avoidance to the noise levels radiating from the turbine. The International Council for the Exploration of the Sea (ICES) has formulated recommendations for maximum radiated underwater noise from research vessels which are approximately 30dB above the hearing threshold of Atlantic cod and herring (ICES:209, 1995). The implication of this is that the presence of continuous noise that is not significantly above the hearing threshold of fish is not thought to cause any significant movement of fish away from the source. In studies of very low frequency sound, Sand *et al.* (2001) indicate that consistent deterrence from the source is only likely to occur at particle accelerations equivalent to a free-field sound pressure level of 160dB re 1 µPa (RMS). This is higher than the noise levels reported in the open literature for operational wind farms measured at a number of ranges, all within a few hundred metres of the turbine (Nedwell *et al.* 2007a; Edwards *et al.* 2007; Betke *et al.* 2004, see also Wahlberg and Westerberg 2005 and Madsen *et al.* 2006). The particle acceleration resulting from an operational wind turbine has also been measured by Sigray *et al.* (2011), with the resultant levels being considered too low to be of concern in relation to behavioural reactions in fish. Furthermore, the particle acceleration levels measured at 10m from the turbine were comparable with hearing thresholds. Whilst limited, the available data provides an indicator that operational wind turbines are unlikely to result in disturbance of fish except within very close proximity of the turbine structure, as postulated by Wahlberg and Westerberg 2004.

118. Although the above mentioned previous studies indicate that there is unlikely to be any significant impact on marine mammals and fish, operational noise from the wind turbines would be present, when the wind farm is operating, for the operational life of the wind farm. Whilst the actual broadband radiated noise levels would possibly be relatively low, i.e. not significantly above the baseline ambient level and decaying to

ambient levels within a few hundred meters, depending on sea-state conditions and local shipping activity, the potential increase in ambient noise as a result of an operational wind farm, may influence the behavioural patterns of any species present which might be sensitive to increasing ambient noise levels.

119. Noise would also result from surface vessels servicing the wind farm. The noise levels reported by Malme *et al.* 1989 and Richardson *et al.* 1995 for large surface vessels indicate that physiological damage to marine fauna is unlikely, although the levels could be sufficient to cause local disturbance of sensitive marine fauna in the near vicinity of the vessel, depending on ambient noise levels. In general, wind farm service vessels will likely result in noise levels above ambient levels out to distances of several kilometres although distant shipping would perhaps be a more constant contributor to noise within Dogger Bank Teesside A and Dogger Bank Teesside B.

120. Considering the operational wind turbine noise of the wind farm and the associated service vessels, the broadband ambient noise levels within the site would likely be expected to be comparable to or lower than those present in the vicinity of the shipping lanes in the surrounding areas.

121. Although currently no information exists regarding the potential noise levels that could be expected from wind turbines larger than 3.6MW, previously reported data indicate that more efficient, modern wind turbines may not result in considerably higher noise levels, compared to older, smaller capacity turbines. However, as noted above, the potential for impact should also consider the propagation environment and the number of sources. To establish the level of noise resulting from the wind farm rather than an individual wind turbine, the radiated noise has been modelled using the methodology described in Section 5, combined with incoherent summation of the noise from each individual turbine, using indicative wind turbine operational noise measurement data summarised by Madsen *et al*. (2006) (based on measurements at Utgrunden offshore wind farm at a distance of 83m from a 1.5MW turbine with a monopole foundation operating during a wind speed of $13ms^{-1}$). The resulting, example, noise map for Dogger Bank Teesside A and Dogger Bank Teesside B projects combined (based on a limited number of turbines in each case), assuming a 750m wind turbine spacing, is shown in **Figure 6.16**.

122. The minimum wind turbine spacing of 750m was used as this was deemed to represent the worst case in terms of the highest noise levels within the wind farm (i.e. between turbines), due to the increased number of wind turbines, and the closer spacing, resulting in greater summation of the noise levels. Only a section of each project was modelled, each including 15 wind turbines, as this was deemed necessary to see the additive effects of having two neighbouring arrays of wind turbines. The dark blue background in **Figure 6.16** represents the lower levels of broadband ambient noise that might be expected, whilst the noise levels resulting from the wind turbines represent those measured in high wind conditions. In reality, these two conditions could not exist at the same time and so for the wind turbine noise shown in **Figure 6.16**, the ambient noise might be expected to be higher than illustrated.

123. The data used for the modelling shown in **Figure 6.16** is based on a 1.5MW turbine operating in a wind speed of 13m/s. The levels are broadly comparable with those measured at the Gunfleet Sands offshore wind farm, employing a 3.6MW turbine

(Nedwell *et al.* 2011). Thus, whilst the radiated sound characteristics may be expected to vary between turbine types, the overall broadband level may not necessarily be measurably higher for the larger turbine. Also, whilst increased wind speeds would be expected to result in increased acoustic output from the turbine, the corresponding increase in wind driven sea-state noise (i.e. ambient noise) might be expected to offset the distance at which the turbine noise can be detected above ambient noise.

124. The modelling indicates that the summation effect from having an array of wind turbines is relatively small due to the noise levels decaying rapidly from each wind turbine i.e. the broadband sound from one wind turbine may be below ambient noise levels before it reaches the adjacent wind turbine. Thus, larger separation distances would be expected to result in bigger gaps between turbines where general noise levels would be comparable to ambient noise, although individual tonal components may be detectable, depending on the background noise. Based on current knowledge, the effect of operational turbines is is not expected to result in noticeably increased broadband ambient levels beyond a few kilometres from the boundary of the individual wind farms, especially in the presence of near-by surface vessels which would be expected to mask the underwater sound radiated from the wind turbines.

125. The highest broadband noise levels will occur at ranges close to the sound source and may be expected to be about 130dB re 1 µPa (approximate RMS sound pressure level at receptor location) at around 50m distance from the pile. The distance between the Dogger Bank Teesside A & B projects is such that, the broadband noise level between the projects would be expected to be typical of the local ambient noise levels.

126. Given the low noise levels associated with wind turbine noise, any risk of significant behavioural disturbance for most marine mammals and fish would probably be limited to the area immediately surrounding the wind turbine, which represents a very small proportion of the area of Dogger Bank Teesside A and Dogger Bank Teesside B. It should be noted that a major natural contribution to the ambient noise would result from sea-state, which would be expected to increase as the turbine rotational speed increases with wind speed. Increased ambient noise may exceed the wind turbine noise, as has been observed by Tougaard *et al.* (2009) and result in no response to the wind turbine noise.

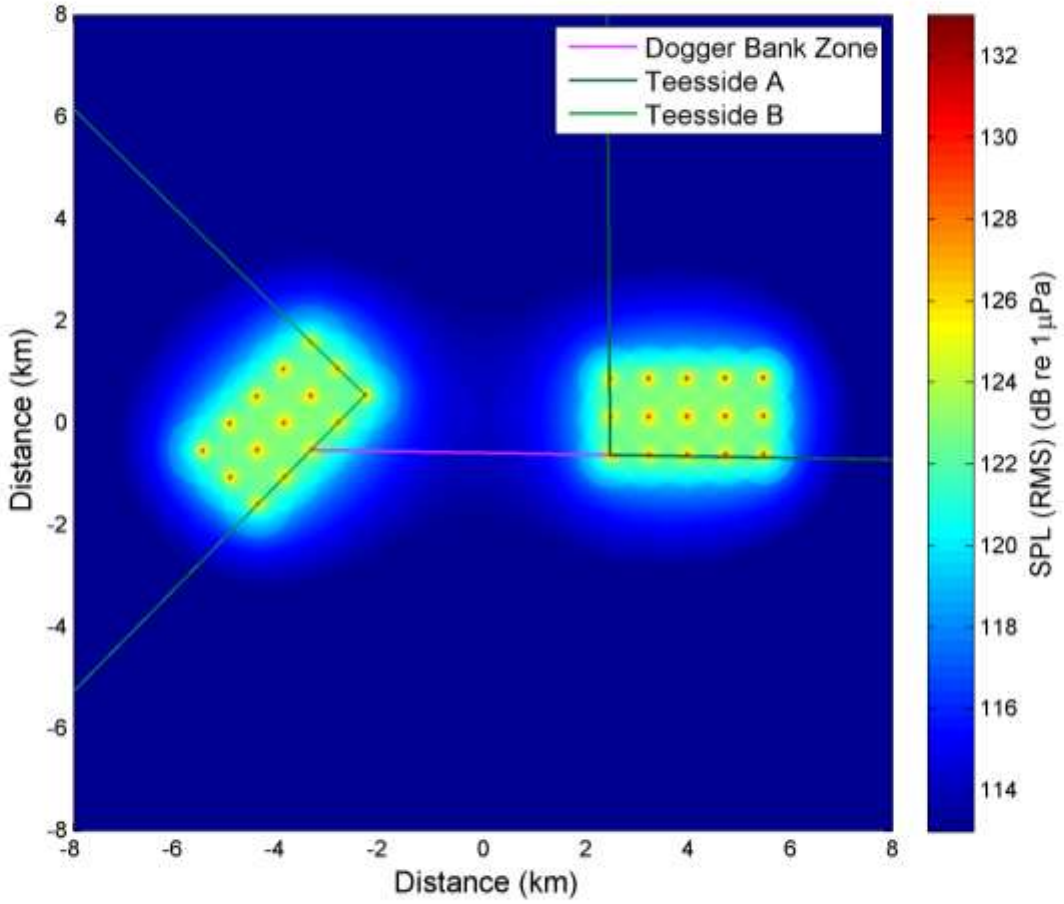


Figure 6.16 – Modelled noise map for a sample of operational turbines at Dogger Bank Teesside A and Dogger Bank Teesside B, assuming a 750m turbine spacing.

6.3 Decommissioning

127. Temporarily elevated underwater noise levels might be expected during the decommissioning phase due to increased vessel movements and removal of the wind turbine foundations. The resulting noise levels will depend on the method used for removal of the foundation. Noise resulting from abrasive cutting would not be expected to be significantly higher than general surface vessel noise. Studies of underwater construction noise, which could also be taken to be representative of decommissioning, report source levels which are similar to those reported for medium sized surface vessels and ferries (e.g. Malme *et al.* 1989; Richardson *et al.* 1995). The noise resulting from decommissioning is unlikely to result in any injury, avoidance or significant disturbance of local marine animals. Some temporary minor disturbance might be experienced in the immediate vicinity of the decommissioning activity, for example, from dynamically positioned (DP) vessels.

6.4 Potential for spatial overlap of underwater noise (potential for cumulative impact)

128. The greatest risk of impact resulting from underwater noise has been identified as being that produced by impact piling during the construction phase. Potential therefore exists for a cumulative effect on marine mammals and fish, as a result of underwater noise, from the construction phases of Dogger Bank Teesside A and Dogger Bank Teesside B

coinciding with other development projects. The most significant effect would likely result from the construction at Dogger Bank Teesside A and Dogger Bank Teesside B coinciding with construction noise from other near-by developments.

129. Many of the near-by planned or operational wind farm sites are along the east coast of the UK. Given the noise levels estimated in this assessment for construction at Dogger Bank Teesside A and Dogger Bank Teesside B and the propagation environment in the North Sea, it can be assumed that construction noise originating at ranges exceeding around 200km from the Dogger Bank Teesside A & B projects would likely be too far away for there to be spatial interaction of construction noise from each of the sites and the impact zones from the Dogger Bank Teesside A and Dogger Bank Teesside B would not overlap with those developments. The following UK wind farms were considered in the cumulative impact assessment, due to their proximity to the Dogger Bank Teesside A & B wind farms and also for their potential to temporally overlap with construction activities at Dogger Bank Teesside A & B (see **Figures 6.19, 6.20**):

- Dogger Bank Teesside C & D
- Dogger Bank Creyke Beck A & B
- Humber Gateway
- Dudgeon
- Westermost Rough
- Race Bank
- Hornsea Project One
- Hornsea Project Two; and
- Triton Knoll.

The East Anglia Projects One, Three and Four, Blyth Demonstration Site (Narec) and the Firth of Forth offshore wind farm, albeit further than 200km from Dogger Bank Teesside A & B, were additionally considered based on their construction time. It should also be noted that Humber Gateway may be fully commissioned before construction commences at Dogger Bank Teesside A & B, however, at the time of undertaking this assessment the specific construction end date could not be confirmed.

130. A number of neighbouring overseas wind farms also hold potential for spatial overlap in impact zone resulting from construction noise, including some of the closest German wind farms (e.g. *Nord-Ost Passat II,* H2-20, Euklas, Prowind and Diamant for example) and the Idunn offshore wind farm in Norway, for example, although there is limited data and potential for temporal overlap is uncertain.), The only Dutch offshore wind farm development considered to be close enough to Dogger Bank Teesside A & B to hold the potential for overlap of impact zones, the Oster Bank development, is currently dormant and the known Belgian and Danish offshore wind farm developments are expected to be too far away (over ~200km) for construction noise to overlap with impact zones at Dogger Bank Teesside A and Dogger Bank Teesside B.

131. Broadband noise levels associated with the operation of these wind farms are considered too low (see Section 6.3) to result in a potential spatial overlap with noise radiated during impact piling at Dogger Bank Teesside A & B.

132. Other main contributors to the anthropogenic noise in the North Sea include shipping (e.g. fishing, cargo carriers, cruise ships, ferries and aggregate extraction) and oil and gas related activities. As discussed in Section 3, shipping density local to Dogger Bank

Teesside A and Dogger Bank Teesside B is generally lower than closer in-shore or in some of the surrounding areas including areas to the south. There are no licenced dredging areas within or around the Dogger Bank Zone, although if the Aggregate Application Area 466/1, which is within the Dogger Bank Zone (western edge) becomes active, the noise may overlap with noise levels radiated during piling from within the Dogger Bank Teesside A and Dogger Bank Teesside B. There is also potential for spatial overlap of piling radiate noise from Dogger Bank Teesside A & B with Aggregate Application Areas 485/1 and 485/2 south of the Dogger Bank Zone. Other Aggregate Application Areas in the Humber Aggregate Region and Aggregate Regions further south (e.g. East Coast Region, Thames Region) can be considered too far away for noise to overlap with the predicted impact ranges at Dogger Bank Teesside A and Dogger Bank Teesside B. Impact zones predicted for Dogger Bank Teesside A and Dogger Bank Teesside B would not be expected to overlap with the near-by overseas dredging area at Cleaver Bank south of the Dogger Bank Zone (Dutch waters). Known Norwegian dredging areas appear to be located in the north of the country, potentially too far for dredging noise to overlap with construction at Dogger Bank Teesside A and Dogger Bank Teesside B.

133. Commercial shipping, fishing and dredging all radiate substantially lower noise levels compared to impact piling and are unlikely to increase the risk of physiological damage to marine fauna compared to the construction of Dogger Bank Teesside A and Dogger Bank Teesside B alone. There may be an increased risk of behavioural effects/disturbance to sensitive marine mammals and fish when piling and vessel activities overlap. However, in general cumulative effects of impact piling with other vessels (Malme *et al.* 1989; Richardson *et al.* 1995; Robinson *et al.* 2011) would not be expected to be increased compared to piling alone. In general, noise generated by transiting surface vessels will result in a very small contribution to the overall noise level resulting from impact pile driving activities. In summary, the cumulative impact is unlikely to result in physiological damage, although some local temporary disturbance of sensitive marine fauna in the immediate vicinity of the vessel may be observed.

134. Other offshore activities which may utilise impact piling during construction are oil and gas platforms. The sea surrounding Dogger Bank Teesside A and Dogger Bank Teesside B support a concentration of oil and gas fields, mainly to the north, south and south-east of the Dogger Bank Zone (DECC 2012a) which, if operational, may radiate low frequency machinery noise and general broadband noise into the water. Compared to underwater noise resulting from typical wind farm construction, the noise levels resulting from operational oil and gas platforms would be relatively low. Given the typical separation distances between oil and gas fields and Dogger Bank Teesside A and Dogger Bank Teesside B, operational platform noise would also generally not be expected to overlap with construction noise from Dogger Bank Teesside A and Dogger Bank Teesside B, or contribute to it noticeably. Many of the gas fields deemed to be close enough to Dogger Bank Teesside A and Dogger Bank Teesside B with the potential for construction noise to overlap (e.g. Forbes, Watt, Gordon, Flyndre and Cawdor[1]) appear to be currently inactive or producing (DECC 2013b), although some

1 Flyndre and Cowdor are expected to be operational by end 2014 (http://www.subseaiq.com/ data/ Project.aspx?project_id=1095) and Alma, Galia and Kew by end of 2013 (http://www.subseaiq.com/data/Project.aspx?project_id=1190&AspxAutoDetectCookieSupport=1),

sites are expected to undergo development (e.g. Alma, Galia, Dutch blocks (E block, A18-02, etc). In general, data outlining specific activities and planned times are limited. Given current knowledge, Cygnus may undergo platform construction during construction at Dogger Bank Teesside A and Dogger Bank Teesside B. Possible construction activity at Cygnus may result in noise levels that could potentially overlap with noise radiated during construction at Dogger Bank Teesside A and Dogger Bank Teesside B. Concurrent construction at the Cygnus oil and gas platform was considered in the cumulative impact assessment, although this overlap would only occur over short temporal scales due to the small number of piling events anticipated at Cygnus. Construction of oil and gas platforms also typically tends to entail use of smaller diameter piles and generally lower hammer blow energy than are currently being considered for offshore wind farm construction. For this assessment an 800kJ hammer blow energy was used based on the maximum anticipated hammer blow energy required for the platform construction. It is not certain if explosive decommissioning is planned in the neighbouring areas such that it would overlap with construction at Dogger Bank Teesside A and Dogger Bank Teesside B, but any overlap in radiated noise would only occur over short temporal scales.

135. Other identified offshore operations include archaeological exploration, and operation of other types of renewable technologies (e.g. wave and tidal). These will not include impact piling and will therefore not likely have an impact any greater than vessel traffic and dredging described above. Noise levels from the installation (Nedwell and Brooker 2008) and operation of a wave and tidal energy device have previously been reported in commercially sensitive reports to be of levels similar to vessel noise and are thus comparatively lower than the levels resulting from impact piling. There appear to be no wave or tidal devices indicated for areas which are close enough to Dogger Bank Teesside A or Dogger Bank Teesside B to result in any spatial overlap of impact zones.

136. **Figures 6.19 and 6.20** depicts propagation modelling for assumed concurrent piling at Dogger Bank Teesside A and Dogger Bank Teesside B and surrounding construction developments. Although the image shows elevated noise levels across a relatively large part of the central North Sea, it is likely that potential for overlap of the behavioural disturbance impact zones resulting from Dogger Bank Teesside A and Dogger Bank Teesside B only exists for the neighbouring Dogger Bank projects, Cygnus, Hornsea Project One and Two, H2-20 and Nord-Ost Passat. The potential extent of the behavioural impact zone will, of course, depend on the receptor in question. It should also be noted that the model assumed uniform seabed properties throughout the modelled area of the North Sea, which may not necessarily be representative of actual conditions for surrounding developments. In addition, a 3,000kJ hammer strike energy was assumed for all modelled wind farm developments and represents the current maximum rated hammer energy available (Menck, 2013). Existing knowledge indicates that such a hammer would not be utilised for all wind farm projects modelled.

137. Due to the low levels of noise resulting from wind farm operation and the limited potential for impact on marine mammals and fish, it is unlikely that there will be a cumulative effect resulting from the operation of Dogger Bank Teesside A and Dogger Bank Teesside B.

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http://articles.chicagotribune.com/2013-04-04/news/sns-rt-factboxn-sea-outputl5n0cq1at-20130404_1_boe-barrels-gas-energy).

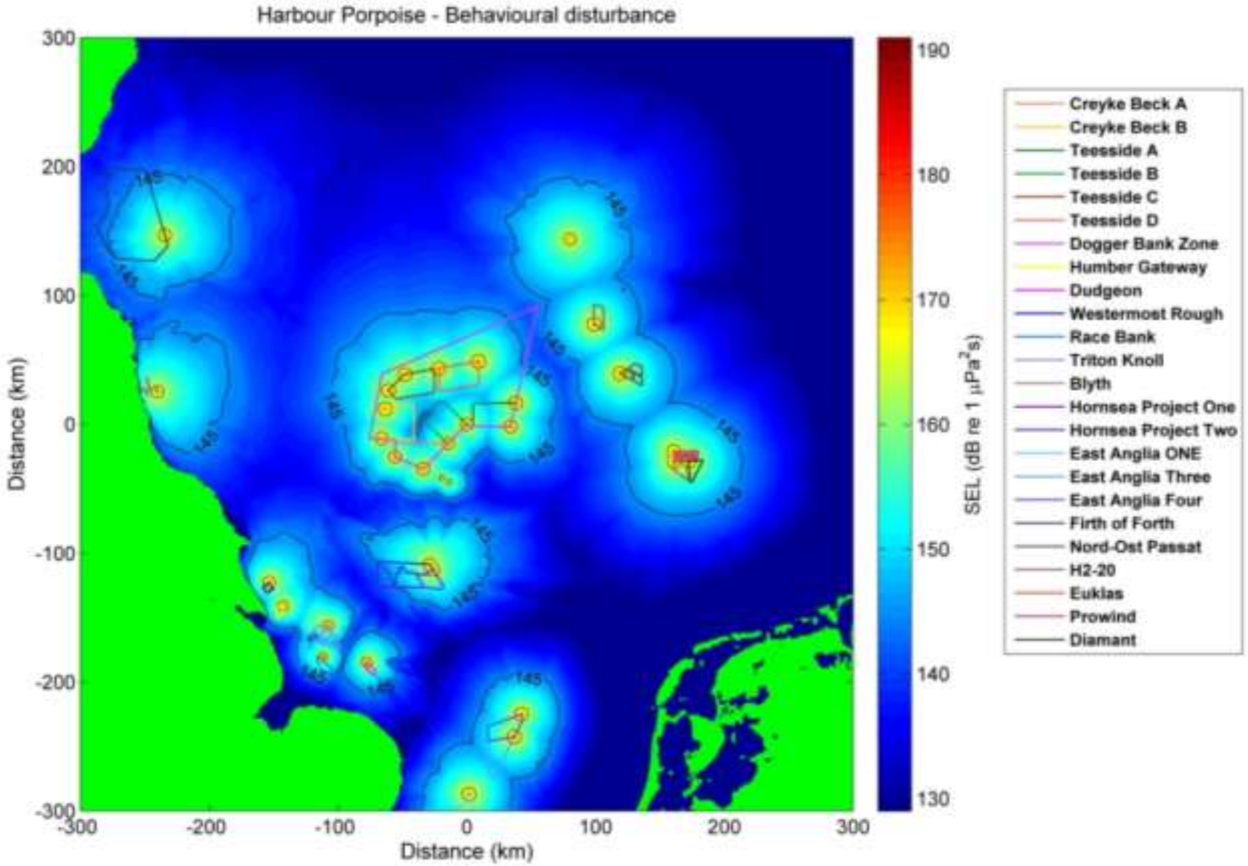

Figure 6.19– Map of the North Sea with an illustration of the noise generated from piling at various potentially concurrently occurring construction projects in relative proximity to Dogger Bank Teesside A and Dogger Bank Teesside B. The developments include other projects within the Dogger Bank Zone, other surrounding offshore wind farms where construction may overlap temporally and the Cygnus oil and gas platform construction south west of the Dogger Bank Zone. The image shows sound propagation assuming a 3,000kJ hammer blow energy applied to all modelled developments except Cygnus where a 800kJ hammer blow energy was used. It should be noted that a 3,000kJ hammer energy represents the current maximum rated hammer energy (Menck, 2013) and existing knowledge indicates that such a hammer would not be utilised at all wind farm projects modelled. Where available, project boundaries are shown. Contour lines indicate harbour porpoise behavioural response ranges. It should also be noted that the seabed properties and tidal data were based on data used for Dogger Bank Teesside A and Dogger Bank Teesside B modelling.

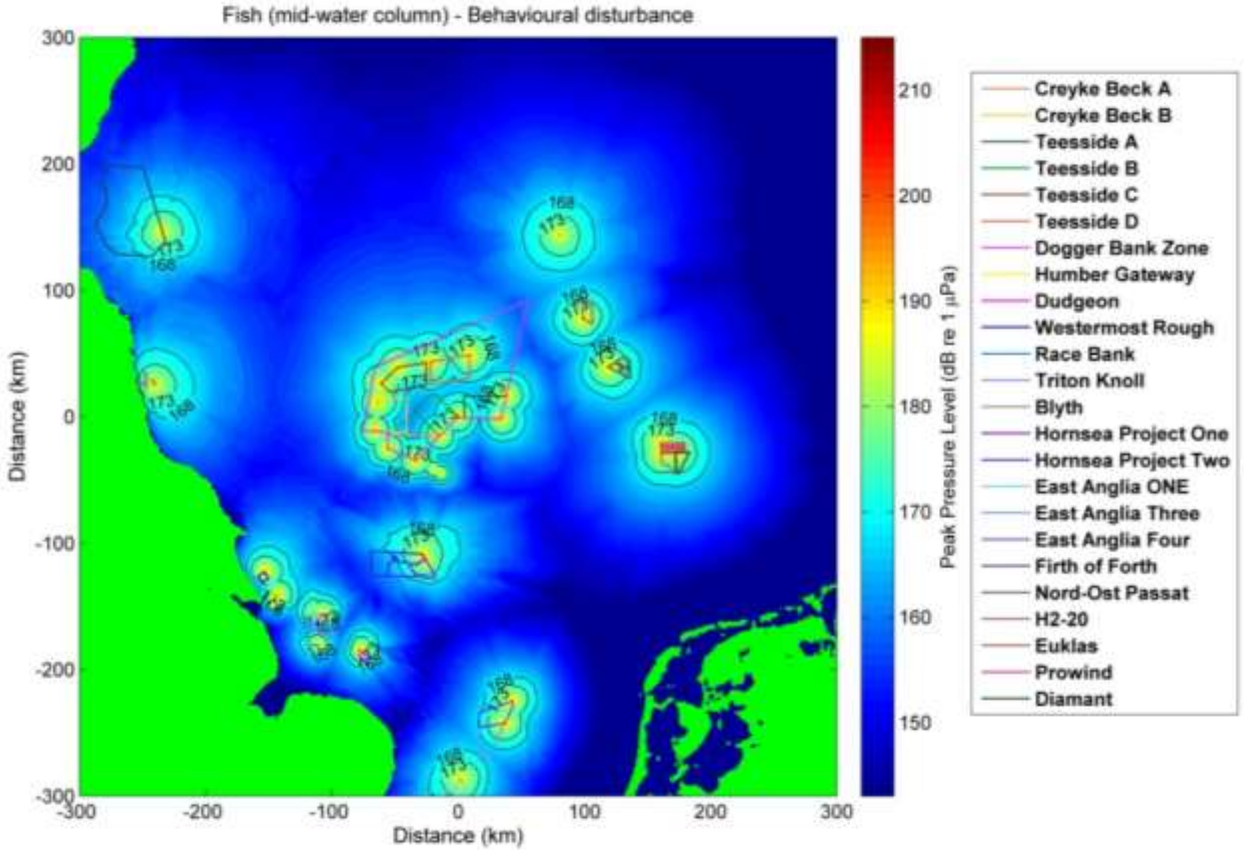

Figure 6.20– Map of the North Sea with an illustration of the noise generated from piling at various potentially concurrently occurring construction projects in relative proximity to Dogger Bank Teesside A and Dogger Bank Teesside B. The developments include other projects within the Dogger Bank Zone, other surrounding offshore wind farms where construction may overlap temporally and the Cygnus oil and gas platform construction south west of the Dogger Bank Zone. The image shows sound propagation assuming a 3,000kJ hammer blow energy applied to all modelled developments except Cygnus where a 800kJ hammer blow energy was used. It should be noted that a 3,000kJ hammer energy represents the current maximum rated hammer energy (Menck, 2013) and existing knowledge indicates that such a hammer would not be utilised at all wind farm projects modelled. Where available, project boundaries are shown. Contour lines indicate fish behavioural response ranges (near mid-water column). It should also be noted that the seabed properties and tidal data were based on data used for Dogger Bank Teesside A and Dogger Bank Teesside B modelling.

7. CONCLUSIONS

138. This report describes the underwater noise modelling undertaken to predict the likely underwater noise levels generated by the installation of wind turbine foundations at the Dogger Bank Teesside A and Dogger Bank Teesside B in support of the Environmental Impact Assessment. Marine impact piling is considered to be the most prevalent source of underwater noise during the development of a wind farm and has the potential for significant impact on marine fauna.

139. Multiple foundation locations were modelled, representing a range of water depths and bathymetry profiles across the sites. The modelled sources were based on the use of most likely hammer blow energies during construction at Dogger Bank Teesside A and Dogger Bank Teesside B, ranging from 230kJ to 3,000kJ. The propagation model used was based on an energy flux approach and provides SEL and peak pressure received level output as a function of range away from each modelled location whilst accounting for seabed properties and varying bathymetry. The modelling indicates that there is some variation in noise propagation across Dogger Bank Teesside A and Dogger Bank Teesside B and the surrounding areas due to variations in bathymetry.

140. The injury and behaviour criteria outlined in the report have been applied to the outputs of the underwater noise modelling to predict the potential impact ranges for Dogger Bank Teesside A and Dogger Bank Teesside B. From this it has been estimated that:

- Mortality of marine mammals or fish is unlikely to occur, except in very close proximity to the pile or in the case of prolonged noise exposure close to the pile. The latter case would likely be mitigated by the animal fleeing the noise at close range;
- Instantaneous injury (auditory) of marine mammals is unlikely to occur beyond about 100m from the pile for Dogger Bank Teesside A or Dogger Bank Teesside B, except for harbour porpoise, where instantaneous injury may occur within 700m of the pile; although the effect of SEL dose may increase the risk over larger ranges;
- Instantaneous injury (auditory and non-auditory) of fish is unlikely to occur beyond about 250m from the pile for Dogger Bank Teesside A or Dogger Bank Teesside B, although the effect of SEL dose may increase this range. However, fish in very close proximity to the pile would likely move away from the pile during installation thus decreasing their SEL dose;
- Pinnipeds may suffer TTS and exhibit a fleeing response to the noise at ranges up to about 1.7km for Dogger Bank Teesside A and Dogger Bank Teesside B;
- Low and mid-frequency cetaceans for Dogger Bank Teesside A and Dogger Bank Teesside B are unlikely to suffer TTS but may exhibit a fleeing response to the noise at ranges exceeding about 400m and 200m from the pile, respectively;
- Harbour porpoise may suffer TTS and exhibit a fleeing response to the noise at ranges of about 4.0km to 5.5km for Dogger Bank Teesside A and Dogger Bank Teesside B;
- Harbour porpoise may avoid a radius around the foundation of about 22.0km to 33.0km at Dogger Bank Teesside A and 22.0km to 33.5km for Dogger Bank Teesside B, depending on the location of the foundation within the site and the bearing away from the foundation, with the maximum avoidance range occurring

to the west of Dogger Bank Teesside A boundary and to the north and west of the Dogger Bank Teesside B boundary;
- Mid-frequency cetaceans for Dogger Bank Teesside A and Dogger Bank Teesside B are likely to avoid ranges less than about 2.5km from the foundation and may possibly avoid a greater radius of about 6.0km to 8.5km for Dogger Bank Teesside A and up to 8.5km for Dogger Bank Teesside B, depending on the location of the foundation and the bearing away from the foundation;
- Low-frequency cetaceans are likely to avoid a radius around the foundation of about 13.5km to 18.0km for Dogger Bank Teesside A and 13.0km and 19.0km for Dogger Bank Teesside B. Possible avoidance may be observed at a greater radius around the foundation, of about 26.5km to 41.0km for Dogger Bank Teesside A and 26.0km to 41km for Dogger Bank Teesside B, depending on the activity of the animal, the location of the foundation within the site and the bearing away from the foundation, with the maximum avoidance range occurring to the west of the Dogger Bank Teesside A boundary and to the north and west of the Dogger Bank Teesside B boundary; and
- Pelagic fish may avoid a radius around the foundation of about 10.0km to 21.0km for Dogger Bank Teesside A and Dogger Bank Teesside B. Seabed dwelling fish may avoid a smaller radius of about 7.5km to 17.0km and 8.0km to 17.5km for Dogger Bank Teesside A and Dogger Bank Teesside B, respectively. The extent of the range depends on the location of the foundation within the site, the surrounding bathymetry, the type of fish, its sex, age and condition, as well as other stressors to which the fish is or has been exposed. The response of the fish may also depend on the reasons and drivers for the fish being in the area (e.g. feeding and spawning).

141. The impact ranges stated above represent the highest anticipated hammer blow energy and characterise the largest expected impact ranges for Dogger Bank Teesside A and Dogger Bank Teesside B construction from a given foundation location. There is considerable variability in the extent of impact ranges across Dogger Bank Teesside A and Dogger Bank Teesside B due to variable bathymetry across the sites. Propagation at Dogger Bank Teesside A is generally similar across the site, with the greatest ranges observed for the sound propagating along the down sloping seabed a few tens of kilometres west of Dogger Bank Teesside A. In general, the noise propagated the greatest distances over the down-sloping bathymetry to the north and west of Dogger Bank Teesside B, whilst foundations installed in the south-eastern part of the Dogger Bank Teesside B project resulted in generally shorter propagation ranges and thus smaller impact ranges.

142. The effect of multiple piling vessels for concurrent pile driving has also been modelled. As the instantaneous sound pressure level is highly unlikely to add up in such a way as to increase the peak noise level, the size of the impacted area is dependent on the separation between the vessels.

143. Possible noise from the operation of the wind farm has also been modelled based on available measured data and shows that noise levels within the boundary of the wind farm are not likely to be significantly above ambient noise, although the operation of the turbines may increase the ambient noise slightly during periods of light winds, calm seas and low shipping traffic, assuming that the wind is sufficient to turn the turbines. There is not expected to be any significant behavioural disturbance associated with the

operation of the wind turbines although the potential increase in ambient noise within the boundaries of the site may influence behavioural patterns of species present which are sensitive to increasing levels of ambient noise.

144. When considering any potential cumulative effects of underwater noise with Dogger Bank Teesside A and Dogger Bank Teesside B from other offshore developments, the nearest sites with possible concurrent construction activities (piling) include Dogger Bank Teesside C & D, Creyke Beck A & B, Hornsea Project One and Two, H2-20, Nord-Ost Passat and the Cygnus oil and gas field. A temporal overlap of construction at these and other surrounding sites will result in elevated noise levels across a relatively large part of the central North Sea, and potential exists for overlap of behavioural disturbance from the neighbouring Dogger Bank projects, Cygnus, Hornsea Project One and Two, H2-20 and Nord-Ost Passat. There may also be some cumulative effects if the nearby dredging areas become active.

REFERENCES AND CITED LITERATURE

Acteon, 2013 [Online]. Available at: http://www.acteon.com/s2s-magazine/s2s-issue-7/offshore-experience-for-wind-power-244 [Accessed 21 January 2013].

Akamatsu, T., Teilmann, J., Miller, L.A., Tougaard, J., Dietz, R., Wand, D., Wand, K., Siebert, U. and Naito Y. (2007) Comparison of echolocation behaviour between coastal and riverine porpoises. Deep-sea Res. 54: 290-297.

Ainslie, M. A., de Jong, C. A. F., Dol., H. S., Blacquière, G. and Marasini, C. (2009) *Assessment of natural and anthropogenic sound sources and acoustic propagation in the North Sea*", TNO Report TNO-DV 2009 C084.

Ainslie, M. A., de Jong, C. A. F., Robinson, S. P. and Lepper, P. A. (2010) What is the Source Level of Pile Driving Noise in Water? *Proceedings of the 2ndInternational Conference on the Effect of Noise on Aquatic Life,* Cork, Ireland, August, 2010.

Ainslie, M. A. (2011) Standard for measuring and monitoring of underwater noise, Part 1: Physical quantities and their units. TNO Report, TNO-DV 2011 C235, September 2011.

Amorim, M. C. P. (2006) Diversity of sound production in fish. In Communication in Fishes. Vol. 1 (ed. F. Ladich, S. P. Collin, P. Moller and B. G. Kapoor), pp. 71-104. Enfield, NH: Science Publishers).

Andrew, R. K., Howe B. M. Mercer, J. A. (2011) Long-time trends in ship traffic noise for four sites off the North American West Coast. *J. Acoust. Soc. Am.* 129 (2), pp. 642-651.

Aubrey, F. T., Thomas, J. A. and Kastelein, R. A. (1988) Low-frequency underwater hearing sensitivity in belugas, *Delphinapterus leucas*. *J. Acoust. Soc. Am*. 8 (6), pp. 2273-2274.

Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G. and Thompson, P. M. (2010) Assessing underwater noise levels during pile-driving at an offshore wind farm and its potential effects on marine mammals, *Marine Pollution Bulletin*, 60, pp. 888-897.

Betke, K., Glahn, M. S-v. and Matuschek, R. (2004) Underwater noise emissions from offshore wind turbines. *Proceedings of CFA/DAGA '04*.

Betke, K. and Matuschek, T. (2010) *Messungen von Unterwasserschall beim Bau der Windenergieanlagen im Offshore-Testfeld "alpha ventus" - Abschlussbericht zum Monitoring nach StUK 3 in der Bauphase*. ITAP Report.

Blackwell, S. B., Lawson, J. W. and Williams, M. T. (2004) Tolerance by ringed seals (*Phoca hispida*) to impact pipe-driving and construction sounds at an oil production island. *J. Acoust. Soc. Am*., 115, pp. 2346-2356.

Blaxter, J. H. S., Gray, J. A. B. and Denton, E. J. (1981) Sound and startle responses in herring shoals. *J. Mar. Biol. Ass. UK*, 61, pp. 851-869.

Blix, A. S., and Folkow, L. ,(1995) Daily energy requirements in free living minke whales. *Acta Physiol. Scand.* 153, 61-66.

Brandt, M., Diederichs, A., Betke, K. and Nehls, G. (2011) Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. *Marine Ecology Progress Series*, 421, 205-215.

Brandt, M., Hoschle, C., Diedrichs, A., Betke, K., Matuschek, R., Witte, S. and Nehls G., 2013a, Far-reaching effects of a seal scarer on harbour porpoises, Phocoena phocoena. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 23, 222-232.

Brandt, M., Hoeschle C., Diedrichs, A., Betke, K., Matuschek, R. and Nehls G., 2013b, Seal scarers as a tool to deter harbour porpoises from offshore construction sites, *Ma. Ecol. Prog. Ser*., 475,291-302.

Bolle, L. J., de Jong, C. A. F., Bierman, S., de Hann, D., Huijer, T., Kaptein, D., Lohman, M., Tribuhl, S., van Beek, P., van Damme, C. J. G., van den Berg, F., van der Heul, J., van Keeken, O., Wessels, P. and Winter, E. (2011) Effect of piling noise on the survival of fish larvae (pilot study). IMARES Report number CO92/11.

Bolle, L. J., de Jong, C. A. F., Bierman, S., van Beek, P., van Keeken, O., Wessels, P., van Damme, C. J. G., Winter, E., de Hann, D. and Dekeling, R. P. A. (2012) Common Sole Larvae Survive High Levels of Pile-Driving Sound in Controlled Exposure Experiments. PLoS ONE, 7(3), pp.e33052 doi:10.1371/journal.pone.0033052.

Burns W. (1973) *Noise and Man*. Pub. John Murray, London, 2nd edition, 1973.

Carey, W. M. (2006) Sound sources and levels in the ocean. *IEEE Journal of Oceanic Engineering*, 31 (1), pp 61-74.

Carlson, T. Hastings, M. and Popper, A. N. (2007) Memorandum – *Update on Recommendations for Revised Interim Sound Exposure Criteria for Fish during Pile Driving Activities*, sent to California Dept. of Trans and Washington Dept. of Trans.

Carstensen, J., Henriksen, O. D. and Teilmann, J. (2006) Impact of offshore wind farm construction on harbour porpoises: acoustic monitoring of echo-location activity using porpoise detectors (T-PODs). *Marine Ecology Progress Series*, 321, pp. 295-307.

Chapman, C. J. (1973) Field studies of hearing in teleost fish. *Helgoländer wissenschaftliche Meeresuntersuchungen*, 24, pp. 371-390.

Chapman, C. J. and Hawkins, A. D. (1973) A Field Study of Hearing in the Cod, *Gadus morhua* L. *J. Comp. Physiol*., 85, pp. 147-166.

Chapman, C. J. and Sand, O. (1974) Field studies of hearing in two species of flatfish *Pleuronectes Platessa* (L.) and *Limanda limanda* (L.) (family Pleuronectidae). *Comp. Biochem. Physiol*., 47A, pp. 371-384.

Coates, R. (1988) An Empirical Formula for Computing the Beckmann-Spizzichino Surface Reflection Loss Coefficient. *IEEE Trans Ultrason Ferroelectr Freq Control*, 35(4), pp. 522-523.

Collins, M. D. (1993) A split-step Pade solution for parabolic equation method. *J. Acoust. Soc. Am*. 93, pp. 1736-1742.

Culik, B.M., Koschinski, S., Tregenza, N. and Ellis G.M. (2001) Reactions of harbour porpoise *Phocoena phocoena* and herring *Clupea harengus* to acoustic alarms, *Mar.Ecol,.Prog. Ser* 2011: 255-260.

de Jong, C. A. F. and Ainslie, M. A. (2008) Underwater radiated noise due to the piling for the Q7 offshore wind farm park, *J. Acoust. Soc. Am*., 123, pp. 2986. In: *Proceedings of the 9th European Conference on Underwater Acoustics (ECUA2008)*, ed. M. Zakaria, pub. Société Française d'Acoustique, July 2007.

DECC, 2009 [Online]. Available at: http://www.maritimedata.co.uk/default.aspx [Accessed 21 January 2013].

DECC, 2013a [Online] Available at:http://tools.decc.gov.uk/en/content/cms/tools/quad_maps/quad_maps.aspx [Accessed 18 February 2013].

DECC, 2013b, January [Online] Available at:https://www.og.decc.gov.uk/fields/fields_index.htm [Accessed 18 February 2013].

Edwards, B., Brooker, A., Workman, R., Parvin, S. J. and Nedwell, J. R. (2007) Subsea operational noise assessment at the Barrow Offshore Wind Farm site. Subacoustech Report No. 753R0109.

Elmer, K.-H. (2010) *Pile Driving Noise Using New Hydro Sound Dampers*. ECS 2010 Workshop: Pile driving in offshore wind farms Effects on harbour porpoises, mitigation measures and standards, March 2010, Stralsund. Available online: www.bsh.de/de/Das_BSH/Veranstaltungen/Cetacean_Society/Elmer.pdf

Elmer, K. -H., Gattermann, J., Kuhn, C., Bruns, B. and J. Stahlman (2012) *Mitigation of underwater piling noise using balloons and foam elements as hydro sound dampers*. Proceedings to the 11th European Conference on Underwater Acoustics, Edinburgh, July 2012

Engås, A., Lokkeborg, S., Ona, E., and Soldal, A. V. (1996) Effects of seismic shooting on local abundance and catch rates of cod (*Gadus Morhua*) and haddock (*Melanogrammus aeglefinus*). *Can. J. Fish. Aquat. Sci*., 53, pp. 2238–2249.

Enger, P. S. and Andersen, R. (1967) An electrophysiological field study of hearing in fish. *Comp. Biochem. Physiol.*, 22, pp. 517-524.

European Commission (2008) Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive), Off. J. European Union, L164, pp. 19 - 40.

Fay, R. R. and Popper, A. N. (2006) Working group on the effects of sound on fish and turtles: an update. *J. Acoust. Soc. Am*., 119, pp. 3284.

Ferla C. M., Porter M. B., Jensen F. B. (1996). C-SNAP: Coupled SACLANTCEN normal mode propagation loss model. SACLANTCEN Memorandum SM-274, Dec. 1993. SACLANT Undersea Research Centre, La Spezia.

FHWG (2008) Memorandum - *Agreement in Principle for Interim Criteria for Injury to Fish from Pile Driving Activities*, sent to NOAA, US Fish and Wildlife Service, Caltrans, California Dept. of Fish and Game, Oregon Dept of Trans. And Washington State Dept. of Trans.

Finneran, J. J., Schlundt, C. E., Carder, D. A., Clark, J. A., Young, J. A., Gaspin, J. B. and Ridgway, S.H. (2000) Auditory and behavioral responses of bottlenose dolphins (*Tursiops truncatus*) and white whales (*Delphinapterus leucas*) to impulsive sounds resembling distant signatures of underwater explosions. *J. Acoust. Soc. Am*., 108, pp. 417-431.

Finneran, J. J., Schlundt, C. E., Dear, R., Carder, D. A. and Ridgway, S. H. (2002a) Temporary shift in masked hearing thresholds in odontocetes after exposure to single underwater impulses from a seismic watergun. *J. Acoust. Soc. Am*., 111, pp. 2929 – 2940.

Finneran, J. J., Carder, D. A. and Ridgway, S. H. (2002b) Low-frequency acoustic pressure, velocity, and intensity thresholds in a bottlenose dolphin (*Tursiops truncatus*) and white whale (*Delphinapterus leucas*). *J. Acoust. Soc. Am*., 111, pp. 3256-3265.

Finneran, J. J., Carder, D. A. Schlundt, C. E. and Dear, R. L. (2010) Growth and recovery of temporary threshold shift at 3kHz in bottlenose dolphins: Experimental data and mathematical models. *J. Acoust. Soc. Am*., 127, pp. 447.

Finneran, J. J. and Schlundt, C. E. (2011) Subjective loudness level measurements and equal loudness contours in a bottlenose dolphin (*Tursiops truncatus*). *J. Acoust. Soc. Am*., 130(5), pp. 3124-3136.

Finneran, J., Schlundt, C., Branstetter, B., Trickey, J. and Jenkins, K. (2012) Auditory effects of seismic air guns impulses on bottlenose dolphins (*Tursiops truncatus*), Proceedings of the 11th European Conference on Underwater Acoustics, Edinburgh, United Kingdom, 2012.

Gordon, J., Thompson, D., Gillespie, D., Lonergan, M., Calderan, S., Jaffey, B. and Todd, V. (2007) *Assessment of the potential for acoustic deterrents to mitigate the impact on marine mammals of underwater noise arising from the construction of offshore wind farms*. COWRIE DETER-01-2006.

Grießmann, T. (2009) Forschungsplattform FINO 3 - Einsatz des großen Blasenschleiers. Presentation at the BSH Meeresumweltsymposiums 2009 - available online: http://www.bsh.de/de/Das_BSH/Veranstaltungen/MUS/2009/Dokumente/Griessman_P.pdf

Goh J. T. and Schmidt H. (1996). “A hybrid coupled wave-number integration approach to range-dependent seismo-acoustic modelling”, J. Acoust. Soc. Am., 100:1409-1420, 1995.

Halvorsen, M. B., Casper, B. M., Woodley, C. M., Carlson, T. J. and Popper, A. N. (2011) Predicting and mitigating hydroacoustic impacts on fish from pile installations. NCHRP Research Results Digest 363, Project 25-28, National Cooperative Highway Research Program, Transportation Research Board, National Academy of Sciences, Washington, D.C.

Halvorsen, M. B., Casper, B. M., Woodley, C. M., Carlson, T. J. and Popper, A. N. (2012) Threshold for Onset of Injury in Chinook Salmon from Exposure to Impulsive Pile Driving Sounds. PLoS ONE 7(6): e38967. doi:10.1371/journal.pone.0038967.

Hamilton, E. L. (1980) Geoacoustic modeling of the sea floor. J. Acoust. Soc. Am., vol. 68(5), pp. 1313-1340.

Harland, E. J., Jones, S. A. S. and Clarke, T. (2005) SEA 6 Technical report: Underwater ambient noise. Qinetiq Report QINETIQ/S&E/MAC/CR050574.

Harris, R. E., Miller, G. W. and Richardson, W. J. (2001) Seal responses to airgun sounds during summer seismic surveys in the Alaskan Beaufort Sea. *Marine Mammal Science*, 17, pp. 795-812.

Hassel, A., Knutsen, T., Dalen, J., Skaar, K., Løkkeborg, S., Misund, O. A., Øivind, Ø., Fonn, M. and Haugland, E. K. (2004) Influence of seismic shooting on the lesser sandeel (*Ammodytes marinus*), *ICES Journal of Marine Science*, 61, pp. 1165-1173.

Hastings, M. C. (2002) Clarification of the Meaning of Sound Pressure Levels and the Known Effects of Sound on Fish. White Paper. August 2002.

Hastings, M. C. and Popper, A. N. (2005) *Effect of Sound on Fish*. Report to California Department of Transportation, Contract No. 43A0139.

Hawkins, A. D. and Johnstone, A. D. F. (1978) The hearing of the Atlantic salmon, *Salmo salar*. *J. Fish. Biol*., 13, pp. 655-673.

Hawkins, A. (2006) Effects on fish of pile driving, wind turbines, and other sources. *J. Acoust. Soc. Am*., 119, pp. 3283.

Hawkins, A. (2009) The impact of pile driving upon fish. *Proc. Inst. Acoustics*, vol.31. pt.1, pp. 72-79.

Hazelwood, D. and Macey, P. (2012) Seabed vibration induced by impacts – theory and practice. Proceedings of the 11th European Conference on Underwater Acoustics, Edinburgh, United Kingdom, 2012.

Hoeschle, C., Brandt, M. J., Diedrichs, A., Betke, K and Nehls, G. (2011) Testing the effects of an acoustic harrasment device on behaviour of Harbour porpoises (*Phocoena phocoena*). *Proceedings of the 25th Conference of the European Cetacean Society*, Cadiz, Spain.

ICES:209 (1995) ICES Cooperative Research Report No. 209 '*Underwater Noise of Research Vessels*'

Jansen, H. W., de Jong, C. A. F. and B. C., Jung (2012) *Experimental assessment of the insertion loss of an underwater noise mitigation screen for marine pile driving*, Proceedings to the 11th European Conference on Underwater Acoustics, Edinburgh, July 2012

Jensen, F. B., Kuperman, W. A., Porter, M. B. and Schmidt, H. (2000) Computational Ocean *Acoustics*, AIP press Springer-Verlag, ISBN: 1-56396-209-8, p 36-37.

Joint Nature Conservation Committee (JNCC) (2010a) *Statutory nature conservation agency protocol for minimizing the risk of injury to marine mammals from piling noise*. JNCC, August 2010.

Joint Nature Conservation Committee (JNCC) (2010b) *JNCC guidelines for minimising the risk of injury to marine mammals from using explosives*. JNCC, August 2010.

Johnson, C. S. (1967) *Sound detection thresholds in marine mammals*. Tavolga W. N. (ed) Marine Bioacoustics II. Oxford: Pergamon, pp. 247-260.

Kastak, D. and Schusterman, R. J. (1998) Low–frequency amphibious hearing in pinnipeds: methods, measurements, noise and ecology. *J. Acoust. Soc. Am.*, 103, pp. 2216-2227.

Kastak, D. Southall, B. L., Schusterman, R. J. and Reichmuth, C. (2005) Underwater temporary threshold shift in pinnipeds: Effects of noise level and duration. *J. Acoust. Soc. Am.*, 118, pp. 3154-3163.

Kastelein, R. A., Bunskoek, P., Hagedoorn, M. and Au, W.W.L. (2002) Audiogram of a harbor porpoise (*Phocoena phocoena*) measured with narrow-band frequency modulated signals. *J. Acoust. Soc. Am*., 112, pp. 334-344.

Kastelein, R. A., Hagedoorn,m., Au, W. W. L. and de Haan, D. (2003) Audiogram of a striped dolphin (*Stenella coeruleoalba*). *J. Acoust. Soc. Am*., 113, pp. 1130-1136.

Kastelein, R, A., Robin Gransier, R., Hoek,l., Macleod, L., Terhune,J, M., (2011) *Auditory and behavioral responses of two harbor seals (Phoca vitulina) to playbacks of offshore pile driving sounds, phase 1: behavioural response in one seal, but no TTS. Available online (*http://www.we-at-sea.org/docs/ecologicalReports/underWater/noise/H%20seal%20TTS%20 *pile%20driving%20ms%20v14.pdf).*

Kastelein, R. A., Hoek, L., Jennings, N., de Jong, C. A. F., Terhune, J. M. & Dieleman, M. (2010) *Acoustic mitigation devices (AMDs) to deter marine mammals from pile driving areas at sea: Audibility & behavioural response of a harbour porpoise & harbour seals*. COWRIE Ref: SEAMAMD-09, Technical Report 31st July 2010.

Kaye, G. W. C. and Laby, T. H. (2004) *Tables of Physical and Chemical Constants*. (Available online at: http://www.kayelaby.npl.co.uk/).

Kinsler, L. E., Frey, A. R., Coppens, A. B and Sanders. J. V. (1982) *Fundamentals of Acoustics*, (3rd edition), Wiley.

Koschinski, S. and Lüdemann, K. (2011) Stand der entwicklung schallminimierender maßnahmen beim bau von offshore windenergieanlagen. Study commissioned by Bundesamt für Naturschutz (BfN), July 2011.

Lee, K., Hinojosa, K. T., Wochner, M. S., Argo IV, T. F., Wilson, P. S. and Mercier, R. S. (2011) Attenuation of low-frequency underwater sound using bubble resonance phenomena and acoustic impedance mismatching. *POMA* 11, pp. 005001.

Lepper, P. A., Pangerc, T. Robinson, S. P. and Theobald, P. D. (2011) Theoretical comparison of cumulative sound exposure estimates from jacket and tripod foundation construction. Proceedings 4th International Conference on Underwater Acoustic Measurement: Technologies and Results. Pp. 731-737.

Løkkeborg, S., Ona, E., Vold, A. and Salthaug, A. (2010) Effects of sounds from seismic air-guns on fish behaviour and catch rates. *Proceedings of the 2nd International Conference on the Effect of Noise on Aquatic Life*.

Lovell, J. M. (2003) *The hearing abilities of the bass, Dicentrarchus labrax*. Technical report commissioned by ARIA Marine Ltd. for the European Commission Fifth Framework Programme. Project Reference: Q5AW-CT-2001-01895.

Lucke, K., Lepper, P. A., Hoeve, B., Everaarts, E., van Elk, N. and Siebert, U. (2007) Perception of low-frequency acoustic signals by a harbour porpoise (Phocoena phocoena) in the presence of simulated offshore wind turbine noise. *Aquatic Mammals*, 33, pp. 55-67.

Lucke, K., Siebert, U., Lepper, P. A. and Blanchet, M. A. (2009) Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli, *J. Acoust. Soc. Am.*, 125 (6), pp. 4060-4070.

Lucke, K., Lepper, P. A, Blanchet, M. A and Siebert, U. (2011) The use of an air bubble curtain to reduce the received soundlevels for harbor porpoises (*Phocoena phocoena*). *J. Acoust. Soc. Am.*, 130 (5), pp 3406–3412.

Lurton, X. An introduction to underwater acoustics, Elsevier, 2003.

Madsen, P. T. (2005) Marine mammals and noise: problems with root mean square sound pressure for transients", *J. Acoust. Soc. Am.*, 117, pp. 3952-3956.

Madsen, P. T., Wahlberg, M., Tougaard, J, Lucke, K. and Tyack P. (2006) Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs. *Mar. Ecol. Prog. Ser*., 309, pp. 279 – 294.

Maes, J., Turnpenny, A. W. H., Lambert, D. R., Nedwell, J. R., Parmentiers, A. and Ollevier, F. (2004) Field evaluation of a sound system to reduce estuarine fish intake rates at a power plant cooling water inlet. *Journal of Fish Biology*, 64, pp. 938-945.

Malme, C. I., Miles, P. R., Miller, G. W., Richardson, W. J., Reseneau, D. G., Thomson, D. H., Greene, C. R. (1989) *Analysis and ranking of the acoustic disturbance potential of petroleum industry activities and other sources of noise in the environment of marine mammals in Alaska*, Malme, C. I, Miles, P. R., Miller, G. W., Richardson, W. J., Roseneau, D. G., Thomson, D. H. and Greene, C. R., BBN Report No. 6945 OCS Study MMS 89-0005. Reb. From BBN Labs Inc., Cambridge, MA, for U.S. Minerals Managements Service, Anchorage, AK. NTIS PB90-188673.

Matuschek, R. and Betke, K. (2009) Measurement of construction noise during pile driving of offshore research platforms and wind farms. *Proceedings of NAG/DAGA*, Rotterdam, 2009.

McCauley, R. D., Fewtrell, J., Duncan, A. J., Jenner, C., Jenner, M-N., Penrose, J. D., Prince, R. I. T., Adhitya, A., Murdoch, J. and McCabe, K. (2000) Marine seismic surveys – A study of environmental implications. *Appea Journal*, pp. 692-707.

McConnell, B., Lonergan, M., Dietz, R. 2012.'Interactions between seals and offshore wind farms.' The Crown Estate, 41 pages. ISBN: 978-1-906410-34-5.

McDonald, M. A., Hildebrand, J. A., Wiggins, S. M. And Ross, D. (2008) A 50 year comparison of ambient ocean noise near San Clement Island: A bathymetrically complex coastal region off Southern California. *J. Acoust. Soc. Am.*, 124, 1985-1992.

Medwin, H. and Beaky, M. M. (1989) Bubble sources of the Knudsen sea noise spectra. *J. Acoust. Soc. Am.*, 86, pp. 1124-1130.

Medwin, H. and Daniel, A. C. (1990) Acoustical measurements of bubble production by spilling breakers. *J. Acoust. Soc. Am.*, 88, pp. 408-412.

Menck, 2013 [Online] Available at: http://www.menck.com/uploads/media/ MHU_Brochure_English.pdf [Accessed 30 July 2013].

Møhl, B. (1968) Auditory sensitivity of the common seal in air and water. *J. Aud. Res.*, 8, pp. 27-37.

Mueller-Blenkle, C., McGregor, P. K., Gill, A.B., Anderson, M. H., M*etc*alfe, J., Bendall, V., Sigray, P., Wood, D. T. & Thomsen, F. (2010) *Effects of Pile-driving Noise on the Behaviour of Marine Fish*. COWRIE Ref: Fish 06-08, Technical Report 31st March 2010.

National Policy Statement (NPS) EN-1 (2011) Overarching National Policy Statement for Energy (EN-1), DECC, July 2011.

National Policy Statement (NPS) EN-3 (2011) National Policy Statement for Renewable Energy Infrastructure (EN-3), DECC, July 2011.

Nedwell, J. R, Turnpenny, A. W. H. and Edwards, B. (2002) Piling on the River Arun; implications for salmon migration. *Proceedings of the American Fisheries Society 132nd Annual Meeting*, USA.

Nedwell, J. and Howell, D. (2004) *A review of offshore wind farm related underwater noise sources*, SubAcoustech Report No. 544 R 0308 submitted to COWRIE Oct. 2004.

Nedwell, J. R., Edwards, B.,Turnpenny, A. W. H., Gordon, J. (2004) *Fish and Marine Mammal Audiograms: A summary of available information*, SubAcoustech Report No. 534 R 0214.

Nedwell, J. R., Turnpenny, A. W. H., Lovell, J. M. and Edwards, B. (2006) An investigation into the effects of underwater piling noise on salmonids. *J. Acoust. Soc. Am.*, 120, pp. 2550-2554.

Nedwell, J. R., Parvin, S. J., Edwards, B., Workman, R., Brooker, A. G. and Kynoch, J. E. (2007a) *Measurement and Interpretation of Underwater Noise During Construction and Operation of Wind farms in UK waters*, Subacoustech Report No. 544R0738 to COWRIE Ltd. ISBN: 978-0-9554279-5-4.

Nedwell J. R., Turnpenny A. W. H., Lovell J., Parvin S. J., Workman R., Spinks J. A. L. and Howell D. (2007b) *A validation of the dBht as a measure of the behavioural and auditory effects of underwater noise*, Subacoustech Report No. 534R1231, October 2006.

Nedwell, J. R. and Brooker, A. G. (2008) *Measurement and assessment of background underwater noise and its comparison with noise from pin pile drilling operations during* *installation of the SeaGen tidal turbine device, Strangford lough*. Subacoustech Report No. 724R0120 to COWRIE Ltd. ISBN: 978-0-9557501-9-9.

Nedwell, J. R., Brooker, A. G., Cummins, D, and Barham, R. (2009) *Thanet Offshore Wind Farm Measurement and assessment of underwater noise during impact piling operations to install monopile foundations*, Royal Haskoning, Final report 9T6750, September 2009.

Nedwell, J. R., Brooker, A. G., Cummins, D, and Barham, R. (2010) *Thanet Offshore Wind Farm Measurement and assessment of underwater noise during impact piling operations to install monopile foundations*, Royal Haskoning, Final report Version 2 9T6750, July 2010.

Nedwell, J. R., Brooker, A. G., Edwards, B. and Bird, H. (2011) *Subsea operational noise assessment of the Gunfleet Sands offshore wind farm*, Subacoustech Report No. E267R0103, June 2011.

Nehls, G., Betke, K., Eckelmann, S. and Ros, M. (2007) *Assessment and costs of potential engineering solutions for the mitigation of the impacts of underwater noise arising from the construction of offshore wind farms*, COWRIE ENG-01-2006.

Oestman, R., Buehler, D., Reyff, J. A., Rodkin, R. (2009) *Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish*. Prepared for California Department of Transportation. www.dot.ca.gov/hq/env/bio/fisheries_bioacoustics.htm

Otani, S., Naito, Y., Kato, A. and Kawamura, A. (2000) Diving behaviour and swimming speed for free-ranging harbour porpoise, *Phocean phocena*. *Marine Mammal Science*, l6(4), pp. 811-814.

Parvin, S. J., Nedwell, J. R., Workman, R. (2006) Underwater noise impact modelling in support of the London Array, Greater Gabbard and Thanet offshore wind farm developments, *Subacoustech Report No. 710R0516.*

Pearson, W. H., Skalski, J. R. and Malme, C. I. (1992) Effects of sounds from a geophysical survey device on behaviour of captive rockfish (*Sebastes spp.*). *Can. J. Fish. Aquat. Sci*., 49, pp. 1343-1355.

Popper A., Carlson T. J., Hawkins, A. D., Southall B. D. & Gentry R. L., (2006) Interim Criteria for injury of Fish Exposed to a pile Driving Operation: A white Paper, available from http://www.wsdot.wa.gov/NR/rdonlyres/84A6313A-9297-42C9-BFA6-750A691E1DB3/0/BA_PileDrivingInterimCriteria.pdf, 2005.

Popper, A. N. and Hastings, M. C. (2009). The effects of anthropogenic sources of sound on fishes. *Journal of Fish Biology*, 75, pp. 455-489.

Porter M. B. (1991) “The KRAKEN normal mode program,” SACLANTCEN Memorandum SM-245 (1991).

Reeves, R. R., Hofman, R. J., Silber, G. K. and Wilkinson, D. (1996) Acoustic Deterrence of Harmful Marine Mammal-Fishery Interactions. Acoustic deterrence of harmful marine mammal-fishery interactions: proceedings of a workshop held in Seattle, Washington, 20-22 March 1995. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-OPR-10, 68 p.

Reid, J. B., Evans, P. G. H. and Northridge, S.P. (2003) Atlas of Cetacean distribution in north-west European waters. JNCC, Peterborough.

Reinhall P. G. and P. H. Dahl (2012) Attenuation of noise from pile driving in water using an acoustic shield, *Proceedings to the 11th European Conference on Underwater Acoustics, Edinburgh, July 2012*

RenewableUK, 2013, June [Online] Available at:http://www.renewableuk.com/en/renewable-energy/ wind-energy/uk-wind-energy-database/index.cfm [Accessed 14June 2013].

Reyff (2007) *Compendium of pile driving sound data*. Report prepared by Illinworth & Rodkin Inc. for The California Department of Transportation.

Richardson, W. J., Greene, C. R. J., Malme, C. I. and Thomson D. D. (1995) *Marine mammals and noise*. San Diego: Academic Press, 1994.

Ridgway, S. H. and Joyce, P. L. (1975) Studies on seal brain by radiotelemetry. *Rapp. P.-v. Reun. Cons. Int. Explor. Mer*, 169, pp. 81-91.

Robinson, S. P., Lepper, P. A., Ablitt, J. (2007) The measurement of the underwater radiated noise from marine piling including characterisation of a “soft start” period, IEEE Oceans – Europe 2007. IEEE cat. 07EX1527C, ISBN: 1-4244-0635-8, 061215-074, Aberdeen, June 2007.

Robinson, S. P., Hayman, G. Lepper, P. A., Cucknell, A. C., Horswill, C., Duthie, N. (2009a) *Greater Gabbard offshore wind farm - Underwater noise monitoring during marine piling*. Gardline Environmental Report 7963 (Draft V.2) to Fluor Ltd July 2009.

Robinson, S. P., Lepper, P. A., Ablitt, J., Hayman, G., Beamiss, G. A., Theobald, P. D. and Dible, S. (2009b) A methodology for the measurement of radiated noise from marine piling, *Proceedings of the 3rd International Conference & Exhibition on "Underwater Acoustic Measurements: Technologies & Results"*, Napflion, Greece, June 2009.

Robinson, S. P., Theobald, P. D., Hayman, G., Wang, L-S., Lepper, P. A., Humphrey, V. and Mumford, S. (2011a) *Measurement of noise arising from marine aggregate dredging operations*, MALSF (MEPF Ref no. 09/P108).

Robinson, S. P., Theobald, P. D. and Lepper, P. A. (2011b) *The noise radiate by marine piling for the construction of offshore wind farms. Proceedings of the 4th International Conference & Exhibition on "Underwater Acoustic Measurements: Technologies & Results"*, Kos, Greece, 2011.

Sand, O., Enger P. S., Karlsen H. E., Knudesen, F. R. (2001) Detection of infrasound in fish and behavioural responses to intense infrasound in juvenile salmonids and European silver eels: a mini review, *Am. Fish Soc. Symp*. 26, pp. 183 - 193.

Scheidat, M., Tougaard, J., Brasseur, S., Patel, T., Teilmann J. and Reijnders P. (2011) Harbour porpoises (*Phocoena phocoena*) and wind farms: a case study in the Dutch North Sea. *Environmental Research Letters*, 6, pp. 1 -10.

Shapiro, A. D., Tougaard, J., Jørgensen, P. B., Kyhn, L. A., Balle, J. D., Bernardez, C., Fjälling, A., Karlsen, J. and Wahlberg, M. (2009) Transmission loss patterns from acoustic harassment and deterrent devices do not always follow geometrical spreading predictions. *Marine Mammal Science*, 25(1), pp. 53-66.

Sigray, P. and Andersson, M. H. (2011) Particle motion measured at an operational wind turbine in relation to hearing sensitivity in fish. *J. Acoust. Soc. Am*., 130, pp. 200-206.

Skalski, J. R., Pearson, W. H. and Malme, C. (1992) Effects of sounds from a geophysical survey device on catch-per-unit-effort in a hook-and-line fishery for rockfish (*Sebastes spp.*). *Can. J. Fish. Aquat. Sci*., 49, pp. 1357-1364.

Slotte, A., Hansen, K., Dalen, J., Ona, E. (2004) Acoustic mapping of pelagic fish distribution and abundance in relation to a seismic shooting area off the Norwegian west coast. *Fish Res.*, 67, pp. 143-150.

Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene Jr., C. R., Kastak, David, Ketten, D. R., Miller, J. H., Nachtigall, P. E., Richardson, W. J., Thomas, J. A., and Tyack, P. L. (2007) Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations, *Aquatic Mammals*, 33 (4), pp. 411-509.

Spence J. and H. Dreyer (2012) The Design, Predictive Performance Modeling and Field Testing of Underwater Sound Attenuation Systems – A Review of Two Case Studies, Proceedings to the 11th European Conference on Underwater Acoustics, Edinburgh, July 2012

Stewart, S. S. (2009) Diving Behaviour. *In* Encyclopedia of marine mammals. W. F. Perrin, B. Wursig and J. G. M. Thewissen (Editors). San Diego, USA, Academic Press, pp. 333 – 339.

Szymanski, M. D., Bain, D. E., Kiehl, K., Pennington, S., Wong, S. and Henry, K. R. (1999) Killer whale (*Orcinus orca*) hearing: Auditory brainstem response and behavioural audiograms. *J. Acoust. Soc. Am.*, 106, pp. 1134-1141.

Teilmann J. and Carstensen J. (2012) Negative long term effects on harbour porpoises froma large scale offshore wind farm in the Baltic – evidence of slow recovery

Teilmann, J., Tougaard, J. and Carstensen, J. (2012) *Effects on harbour porpoises from Rødsand 2 Offshore Wind Farm*, Aarhus University, DCE – Danish Centre for Environment and Energy, 66 pp. Scientific Report from DCE – Danish Centre for Environment and Energy No. 42 http://www.dmu.dk/Pub/SR42.pdf

Terhune, J. M. and Ronald, K. (1975) Underwater hearing sensitivity of two ringed seals (*Pusa hispida*). *Can. J. Zool*., 53, pp. 227-231.

The Crown Estate, 2013, January [Online]. Available at: http://www.thecrownestate.co.uk/ marine/aggregates/ our-portfolio/ [Accessed 21 January 2013].

Theobald, P. D., Lepper, P. A., Robinson, S. P., and Hazelwood, R. A. (2009) Cumulative noise exposure assessment for marine using Sound Exposure Level as a metric. *Proceedings of the 3rd International Conference & Exhibition on "Underwater Acoustic Measurements: Technologies & Results"*, Napflion, Greece, June 2009, ISBN; 978-960-98883-4-9.

Theobald, P. D., Robinson, S. P., Lepper, P. A., Pangerc, T., Lloyd, N. (2010) *Underwater noise monitoring during marine piling*. Gardline Environmental Report 8503 to Fluor Ltd September 2010. Gardline Environmental Report 8503 to Fluor Ltd September 2010.

Thiele, R. (2002). Propagation loss values for the North Sea. Handout Fachgesprach: Offshore-Windmills-sound emissions and marine mammals. FTZ-Busum, 14.01.2002.

Thompson, D., Sjoberg, M., Bryant, M. E., Lovell, P. and Bjorge, A. (1998). *Behavioral and physiological responses of harbour (Phoca vitulina) and grey (Halichoerus grypus) seals to seismic surveys*. Report to European Commission of BROMMAD

Thompson, P. M., Lusseau, D., Barton, T., Simmons, D., Rusin, J. and Bailey, H. (2010) Assessing the responses of coastal cetaceans to the construction of offshore wind turbines. *Mar. Pollut. Bull.*, 60, pp. 1200-1207.

Thomsen, F., Lüdemann, K., Kafemann, R. and Piper, W. (2006) *Effects of offshore wind farm noise on marine mammals and fish, biola*, Hamburg, Germany on behalf of COWRIE Ltd.

Thorpe, W. H. (1967) Analytic description of the low frequency attenuation coefficient. *J. Acoust. Soc. Am.*, 42, pp. 270-270.

Tougaard, J., Carstensen, J., Teilmann, J. and Bech N., I. (2005) *Effects of the Nysted Offshore Wind Farm on Harbour Porpoise. Annual status report for the T-POD monitoring program.*

Tougaard, J., Carstensen, J. and Teilmann, J. (2009) Underwater noise form three types of offshore wind turbines: Estimation of impact zones for harbor porpoises and harbor seals. *J. Acoust. Soc. Am*., 125, pp. 3766-3773.

Tougaard, J. and Henriksen, O. D. (2009) Pile driving zone of responsiveness extends beyond 20km for harbour porpoises (*Phocoena phocoena* (L.)) (L). *J. Acoust. Soc. Am*., 126, pp. 11-14.

Tougaard, J., Kyhn, L. A., Amundin, M., Wennerberg, D. and Bordin, C. (2011) Harbour porpoises are deterred by simulated pile driving noise. *Proceedings of the 25th Conference of the European Cetacean Society*, Cadiz, Spain.

Urick, R. J. (1983) *Principles of Underwater Sound*, Peninsula Publishing, New York.

Van der Graaf A. J., Ainslie M., A., André M., Brensing K., Dalen J., Dekeling R.,P.,A, Robinson S., Tasker M., L., Thomsen F., Werner S. (2012).European Marine Strategy Framework Directive -Good Environmental Status (MSFD GES): Report of the Technical Subgroup on Underwater noise and other forms of energy.

Verfuß T., January 2012 [Online] *Noise Mitigation Measures & Low-noise Foundation Concepts – State of the Art*, Projektträger Jülich Available at:http://www.bfn.de/fileadmin/ MDB/documents/themen/erneuerbareenergien/Tgng_offshore2012/6_1_verfuss.pdf [Accessed 20 February 2013].

Wahlberg, M. and Westerberg, H. (2005) Hearing in fish and their reactions to sounds from offshore wind farms. *Mar.Ecol. Prog. Ser.*, 288, pp. 295 - 309

Webb, J. F., Popper, A. N., and Fay, R. R. (eds) (2008) *Fish Bioacoustics*. New York. Springer.

Wenz, G. M. (1962) Acoustic ambient noise in the ocean: spectra and sources. *J. Acoust. Soc. Am.*, 34, pp. 1936-1954.

Weston, D. (1976) Propagation in water with uniform sound velocity but variable-depth lossy bottom. *Journal of Sound and Vibration*, 47, pp. 473-483.

Wind Power, 2013, Offshore piling noise reduction research launched [Online]. Available at: http://www.windpowermonthly.com /news/rss/1114496/Offshore-piling-noise-reduction-research-launched [Accessed 21 January 2013].

Wood, M. A. and Humphrey, V. F. (2012), Dependence of radiated piling noise on the hammer cushion properties. Proceedings to the 11th European Conference on Underwater Acoustics, Edinburgh, July 2012

WSDOT (2011) Biological Assessment Preparation for Transportation Projects - Advanced Training Manual - Version 02-2011 http://www.wsdot.wa.gov/Environment/Biology/BA /BAguidance.htm

Wursig, B., Greene, C. R. J. and Jefferson, T. A. (2000) Development of an air bubble curtain to reduce underwater noise of percussive piling. *Marine Environmental Research* 49(1), pp. 79-93.

Yelverton, J. T., Richmond, D. R., Fletcher, E. R. and Jones, R. K. (1973) *Safe distances from underwater explosions for mammals and birds*. DNA 3114T, Lovelace Foundation for Medical Education and Research, Final Technical Report, July 1973.

Yelverton, J. T., Richmond, D. R., Hicks, W., Saunders, K. and Fl*etc*her, E. R. (1975) *The relationship between fish size and their response to underwater blast*. DNA 3677T, Lovelace Foundation for Medical Education and Research, Final Technical Report, June 1974.

Yelverton, J. T., Richmond, D. R., Jones, R. K. and Fl*etc*her, E. R. (1976). *A review of the treatment of underwater blast injuries*. A553430, Lovelace Foundation for Medical Education and Research, Final Technical Report.

APPENDIX A – BASICS OF UNDERWATER ACOUSTICS

145. This appendix introduces some basic underwater acoustic concepts for considerations when assessing and interpreting the potential for impact on marine life arising from wind farm related underwater noise.

Metrics and units

146. Two primary acoustic amplitude parameters have been widely used in the UK relating to marine piling. These are peak-to-peak pressure (Nedwell *et al.* 2006; Nedwell *et al.* 2007a), and Sound Exposure Level (SEL) (Southall *et al.* 2007). In addition, for some exposure criteria, the zero-to-peak pressure level has been used (Southall *et al*. 2007).

147. The peak pressure refers to the pressure amplitude of the pulse where, often described as the peak positive pressure. Peak-to-peak pressure is also used which is the difference between the peak positive pressure and the peak negative pressure of the pulse. It is common to state these levels in decibels (dB) as a zero-to-peak pressure level (PPL) for peak pressure referenced to a zero-to-peak pressure of 1 μPa. The Sound Exposure Level is a measure of the pulse energy content and is calculated from the integral of the squared sound pressure over the duration of the pulse (Madsen 2005; Ainslie 2011). It is also used to express the overall exposure (hereafter SEL dose), which in this case is done by summation of sound exposure levels of the entire piling event. The SEL can also be expressed in dB notation referenced to 1 $\mu Pa^2 \cdot s$.

148. It should be noted that the metric used for continuous type sounds is different to those used for impulsive sounds like piling. For continuous noise such as vessel noise or operational turbine noise, the Sound Pressure Level (SPL) metric would normally be used which by convention describes the root mean square (RMS) level over a one second interval referenced to an RMS pressure of 1 μPa.

i) Zero-to-peak pressure level (PPL)

149. For a specific pulse or waveform, the peak pressure level, *PPL*, is defined as the zero-to-peak pressure of the pulse and can be expressed as the zero-to-peak pressure level (or peak pressure level, PPL) in units of dB re 1 μPa:

$$PPL = 20 \log \left[\frac{P_{zero-to-peak}}{P_0} \right]$$

where P_0 is the zero-to-peak reference pressure of 1 μPa.

ii) Peak-to-peak acoustic pressure

150. For a specific pulse or waveform, the peak-to-peak pressure, P_{pk-pk}, is calculated from the difference between the peak positive or maximum pressure p_{max} and the peak negative or minimum pressure p_{min}:

$$P_{pk-pk} = p_{\max} - p_{\min}$$

151. Since the peak negative pressure has a negative value, the peak-to-peak pressure is equivalent to the sum of the magnitudes of the peak positive and peak negative

pressures. The value is usually expressed as the peak-to-peak pressure level in dB re 1 μPa. This level is calculated from:

$$PL_{pk-pk} \quad = \quad 20 \log \left[\frac{P_{pk-pk}}{P_{0\,pk-pk}} \right]$$

where P_0 is the peak-to-peak reference pressure of 1 μPa.

152. The use of peak-to-peak pressure has previously been adopted for UK marine piling measurements, especially for measurements reported on early wind farm projects. However, it should be noted that this metric has not been widely adopted outside of the UK or by the recently drafted EC Marine Strategy Framework Directive (MSFD), Descriptor 11 for underwater noise (MSFD, 2008). The MSFD has adopted the peak sound pressure level (in addition to the sound exposure level) defined as the zero-to-peak amplitude of the pulse (PPL). For consistency with the MSFD, all levels referenced from previous studies are either stated in their original form of peak, or converted where necessary from peak-to-peak to peak values by halving the value (subtracting 6dB), thereby assuming a symmetrical pulse shape.

153. For this assessment, the approach of Southall *et al.* (2007) has been adopted such that the SPL term is always qualified to indicate the type of metric intended: for example, peak SPL, RMS SPL, *etc*. It should be noted that the peak SPL used by Southall *et al.* 2007 is equivalent to the zero-to-peak pressure level or PPL used here.

iii) Sound Pressure Level (RMS SPL)

154. The more common convention in underwater acoustics for expressing Sound Pressure Level (SPL) is for it to be expressed as a root mean square (RMS) value. The RMS value is a time-averaged pressure value, which allows the SPL to be related to the time-averaged acoustic power (the original use of the decibel notation is for expressing power ratios) (Carey 2006). This causes little problem for sinusoidal waveforms where there is a fixed relationship between the peak value of a sine wave and the RMS value. However, for pulse waveforms, there is no general relationship between the peak of the pulse and the RMS value (the RMS value for a pulse depends on the pulse length, which depends on the pulse shape, the decay time, *etc*.) (Madsen 2005; Ainslie 2011). This can cause confusion and make comparisons between pulse type sounds and continuous type sounds meaningless even though they appear to be described using the same units.

155. For this assessment, the root mean square of the sound pressure is used when considering continuous type noise sources such as turbine operational noise and can be expressed in units of dB re 1 μPa and is calculated from:

$$RMS\ \ SPL \quad = \quad 20 \log \left[\frac{P_{RMS}}{P_0} \right]$$

where P_0 is the RMS reference pressure of 1 μPa.

iv) Sound Exposure Level

156. For piling pulse, SEL is related to the sound energy in the pulse and is calculated by integrating the square of the pressure waveform over the duration of the pulse. The duration of the pulse is defined as the region of the waveform containing the central 90% of the energy of the pulse. The calculation is given by:

$$E_{90} = \int_{t_5}^{t_{95}} p^2(t)\,dt$$

157. The value is then expressed in dB re 1 μPa²·s and is calculated from:

$$SEL = 10\log\left[\frac{E_{90}}{E_0}\right]$$

where E_0 is the reference value of 1 $\mu Pa^2 \cdot s$.

158. Note that for a plane-wave in a free-field environment (an unbounded medium), the pulse pressure squared integral in $\mu Pa^2 \cdot s$ can be converted to units of energy flux density in J/m^2 (joules per square metre) by dividing the cumulative squared acoustic pressure by the specific acoustic impedance, *Z*, of the medium, the specific acoustic impedance being the product of medium density and sound speed in the medium (ρc). When expressed in decibel notation, this means that 0dB re 1 J/m^2 is equivalent to 182dB re 1 $\mu Pa^2 \cdot s$ in water. Note also that the definition above uses the central 90% of the energy in the pulse, i.e. the pulse duration is defined as the time occupied by the central portion of the pulse, where 90% of the pulse energy resides. This is because it can be difficult to determine the exact start of the pulse when the waveform contains noise. For the 100% value of SEL, it would be necessary to add 0.45dB to the 90% value.

159. The SEL for each impulsive noise event can also be aggregated by summation to calculate the total SEL (or SEL dose) for the entire piling sequence (Southall *et al.* 2007; Theobald *et al.* 2009). The concept of SEL dose is entirely analogous to the use in air acoustics to quantify the total noise dose for a subject receiver. The pulse duration is defined as the time occupied by the central portion of the pulse, where 90% of the pulse energy resides.

160. The calculation of the pulse duration and SEL are described graphically in **Figure A.1**. **Figure A.1-A** shows a typical pulse waveform, and **Figure A.1-B** shows a plot of the normalised energy in the pulse waveform against time. Indicated on the plot are the 5% and 95% energy levels and the t_5 and t_{95} times that define the pulse duration.

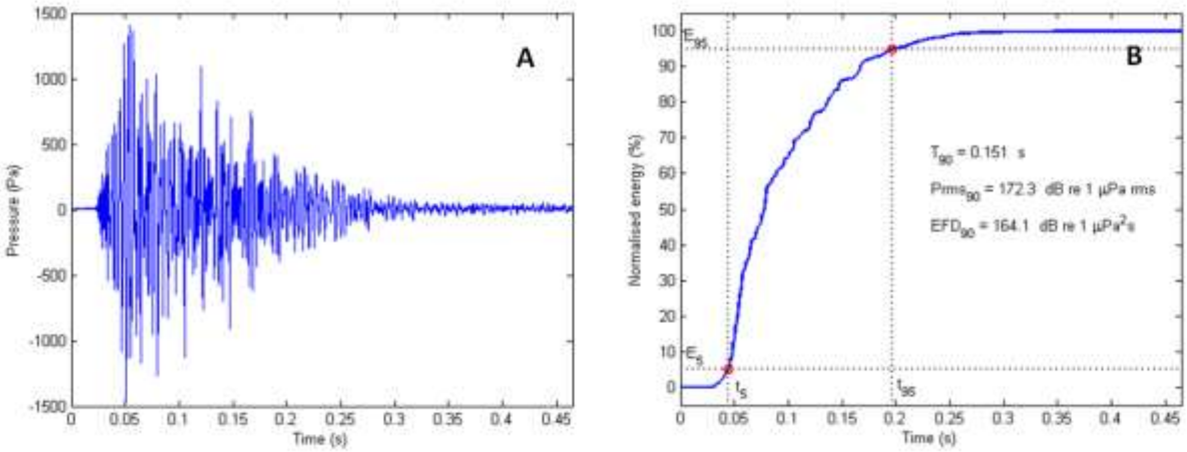

Figure A.1 – A: Example of pulse time waveform for analysis, and B: Calculation of SEL over pulse duration.

v) Source level

161. A metric used frequently in underwater acoustics to describe the source output amplitude is that of Source Level (SL), a term not commonly seen in air acoustics where the acoustic power is more commonly used. This term originates from sonar engineering, and as with acoustic power, the Source Level may be considered as a characteristic of the source itself. The decibel units for this quantity may be written as dB re 1 μPa·m, however the unit is much more commonly seen expressed as dB re 1 μPa at 1m in spite of these units, It should be noted that Source Level is an idealised acoustic far-field parameter and is not necessarily equal to the acoustic pressure or received level measured at a distance of 1 metre from the source. Instead, it may be considered as the sound pressure level that would exist at a nominal range of 1m from the acoustic centre of an equivalent simple monopole source, which radiates the same acoustic power into the medium as the source in question (Ainslie 2011). However, for real sources which are acoustically large (such as occurs for marine piling), the value of the Source Level will not be equivalent to the sound pressure level at the reference range of 1m.

162. In practice, for real sources, the Source Level is calculated by measuring the received level at a distance from source which is in the acoustic far-field and propagating the acoustic pressure back to the reference distance of 1m from the acoustic centre of the source using an appropriate propagation model. This distance required to be in the far-field is related to both the dimensions of the source and the wavelength of the sound. Indeed, for large distributed sources, this reference distance of 1m may be in the acoustic near-field (or sometimes even inside the source). In the near-field region, the sound field amplitude fluctuates due to interference between the waves that radiate from different parts of the source.

163. It should also be noted that propagation of sound in the ocean rarely corresponds to simple spreading laws. This is especially true in shallow water typical of offshore wind farms. In general, source level (SL) may be given by:

$$SL \quad = \quad RL + PL \; ,$$

where RL is the received level in the acoustic far-field and PL is the propagation loss (dependent on frequency, seabed, bathymetry, *etc*).

164. Estimation of Source Level from sound pressure measurements in shallow reverberant channels is not straightforward since an estimate must be made of the true propagation loss (sometimes termed transmission loss) (Urick 1983), which is complicated by the interactions of sound with the seafloor and sea surface. An important fact to note is that the source levels for marine piling reported in previous wind farm studies, which are summarised in this report, have almost exclusively been obtained by extrapolation back to the source using simple spreading formulae. This means that these reported values are not true Source Levels and are generally not consistent with the accepted definition of source level by Urick (1983) and others (Ainslie 2011). This means that comparisons may not be possible with other sources measured in deep water. However, since it is not possible to convert the all the previously reported data to the desired format, this format has been maintained for Section 3 where a review of existing data is provided. To distinguish between formats, data derived from simple spreading formulae are referred to as "Effective" Source Level. Note that for the acoustic modelling undertaken for this report, data were converted to true monopole Source Level for use with the acoustic energy flux model adopted (Section 4).

165. Source level might be expressed in a number of ways, for example in terms of sound pressure level (in units of dB re 1 μPa·m), or in terms of energy or sound exposure level (units: dB re 1 $\mu Pa^2 \cdot s \cdot m^2$).

vi) Propagation/Transmission loss

166. Propagation Loss (PL) or Transmission Loss (TL) is the term used to describe the reduction of the sound level as a function of distance from an acoustics source. The mechanisms by which the sound intensity reduces are primarily geometrical spreading, sound absorption in the water and losses into the seabed or other boundaries. In shallow water, particularly with varying bathymetry, this can be quite complicated due to multiple interactions with the surface and seabed. In shallow water, the depth can also restrict the propagation of lower frequency.

167. It is normal for propagation/transmission loss to be stated as a positive number in dB representing the loss for the total range between the reference distance (1m for Source Level) and the receiver location. The quantity is a function of frequency, and depends on seabed type, bathymetry, surface roughness, sound speed profile *etc*.

vii) Received level

168. The received level (RL) is the acoustic pressure measured by a hydrophone at some distance away from a sound source. It is also considered to be the sound pressure which arrives at any acoustic receptor which is exposed to a sound.

169. The received level might be expressed in a number of ways, for example as a sound pressure level (dB re 1 μPa) or a sound exposure level (dB re 1 $\mu Pa^2 \cdot s$).

170. When predicting received levels from estimated source levels for zones of impact, the received level is simply determined by subtracting the transmission loss in dB from the source level in dB, RL = SL – TL, where the TL is estimated using a transmission loss model (see below). When the source level is estimated from measured received levels then the source level is simply found by addition of received level and transmission loss, SL = RL + TL. To calculate TL accurately requires an accurate model for the propagation of the sound and its interaction with the seabed and sea surface.

Sometimes, the TL is empirically estimated from the measured received level data as a function of range. Ideally the TL should still be estimated by fitting an appropriate transmission loss model capable of accurately modelling propagation for a complex environment.

Sound propagation modelling

viii) Environmental dependence

171. Perhaps even more so than for airborne sound, noise levels in the ocean produced by human activities are determined not only by the acoustic power output of the source, but equally importantly by the local sound transmission conditions (Urick 1983). A moderate level source transmitting over an efficient propagation path may produce the same received sound pressure level as a higher level source transmitting through a lossy propagation path. In deep water, variations in water properties strongly affect the sound propagation. In shallow water, effects due to the surface and bottom become more influential. Variations in bathymetry (depth) can have a significant effect on the transmission of the sound, and for piling noise significant proportions of the sound may be transmitted through the seabed itself.

172. The sound speed profile may be divided into several layers. Just below the surface is what is sometimes called the surface layer where the speed is susceptible to daily changes due to heating, cooling and wind action. This is followed by a seasonal thermocline, a region characterised by a negative sound speed gradient due to the decrease in temperature with depth. Below the main thermocline and extending into the deep ocean is the deep isothermal layer, which is nearly constant in temperature at about 4 ºC. In this layer, the sound speed increases with depth due to the increasing hydrostatic pressure. Between the thermocline and the isothermal layer is a sound speed minimum, toward which sound tends to be bent by the action of refraction. Some of the sound from a source placed in this channel can be trapped within the channel and travel great distances without appreciable losses due to surface or bottom reflections. Whilst spreading losses will still occur, they are reduced from spherical spreading and in certain cases may approximate to cylindrical spreading. The variation with salinity is less of an influence in deep water, but can have a strong influence where water layers of different salinity are mixing, for example at the estuaries of fresh-water rivers.

173. In shallow water around the UK coast, the sound speed is less likely to vary strongly with depth due to the shallow conditions, and the often rapid tidal flow which leads to a mixed isothermal water column.

174. The sound speed is such an important oceanographic parameter that it is routinely measured as a function of depth. This may be done using an instrument such as a velocimeter, which measures the time for a high frequency pulse to travel over a known path. Alternatively, a measurement is made of the conductivity (to derive salinity), temperature and depth using a CTD meter with the sound speed calculated from empirically-derived relationships.

ix) Shallow water specific environmental dependence

175. One effect not always appreciated is that shallow water channels do not allow the propagation of low frequency signals due to the wave-guide effect of the channel (Urick 1983; Jensen *et al.* 2000). This effect means that there will be a lower cut-off

frequency, below which sound waves will not propagate (instead the sound generated propagates into the sea-bed).

176. For an idealised water channel consisting of a rigid bottom and a pressure-release surface, the cut-off corresponds to a quarter-wave resonance. However, for a realistic seabed, a slightly more complicated formula depending on the ratio of sound speed in the bottom to that in the water can be used (Urick 1983). The result of plotting this formula is shown in **Figure A.2**. The effect of the loss of sound from the water column due to shallow water is sometimes referred to as 'mode-stripping'.

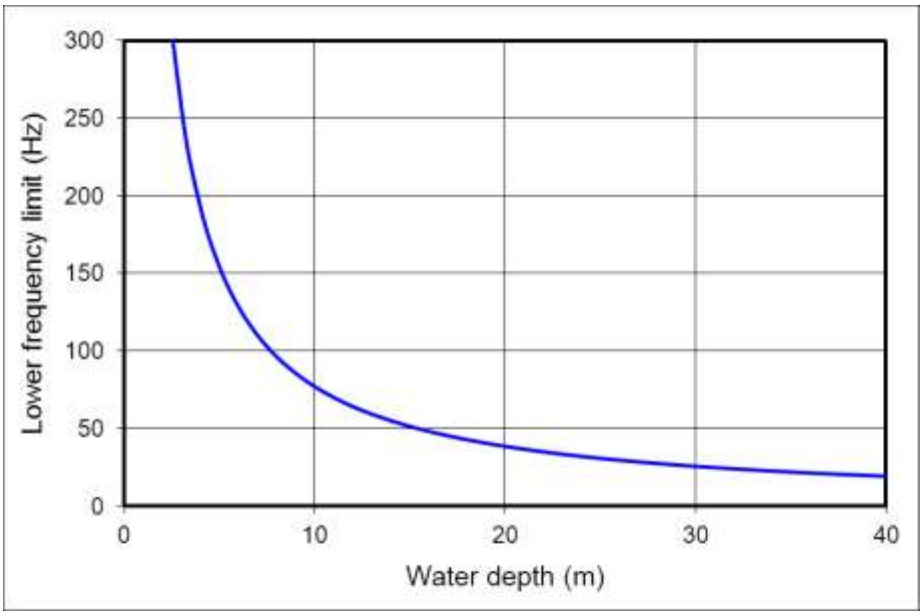

Figure A.1 – B: The lower cut-off frequency as a function of depth for a shallow water channel with a seabed sound speed of 1702m/s (sand) and water sound speed of 1490m/s.

177. It can be seen from **Figure A.1** that for an approximate water depth of 20 m, representative of water depths in and around the Dogger Bank Teesside A and Dogger Bank Teesside B project, frequencies below around 40Hz would not be expected to propagate through the water. For piling, most of the energy in the resulting sound pulse falls between frequencies of around 100Hz and 400Hz.

x) Types of propagation model

178. The wave equation describing the propagation of an acoustic field is often difficult to solve in real-world situations. A good model describing the propagation of sound in the ocean should take into account:
   (i) The interaction with the sea-surface;
   (ii) The interaction with (and transmission through) the sea-bed;
   (iii) The refraction of the sound due to the sound speed gradient;
   (iv) Absorption of the sound by the sea-water and the sea-bed;
   (v) The geometrical spreading of the sound away from the source; and
   (vi) Relative source and receiver depth.

179. One common approach is to use a method of normal modes, often applied in cases where the sound speed is stratified (changes vertically with depth but not horizontally with range). The normal mode method is useful to calculate the field in shallow water where the water column acts as a waveguide for a limited number of propagating

modes. The theory can be expanded to account for different types of sea-bed (assuming the properties are known), and variations in sound speed gradients. The problem of solving the wave equation for range dependent conditions such as sloping or irregular bottoms and range-varying sound speed profiles has been overcome by an approximation called the parabolic equation. Here, small incremental changes in range and depth are used to accommodate changes in propagation parameters without the occurrence of large errors. However, in deep water with large numbers of modes propagating, the method is computationally demanding (Lurton 2003; Richardson *et al.* 1995). The Parabolic Equation method provides a frequency domain solution for transmission loss and can provide distance and depth dependent transmission loss predictions. An alternative approach which can prove useful for broadband impulsive sounds is to use a time-domain approach such as a finite-difference method. This method has been used extensively in the geophysical surveying industry.

180. In water deep enough for propagation of ten or more modes, ray theory may be used. This requires that the sound speed changes slowly, with little change over a distance of one acoustic wavelength, making it best suited to the higher frequencies (and thus smaller wavelengths). The sound field is calculated by tracing ray paths, starting from the source, at uniformly spaced angular intervals. For each increment in range, the ray direction is determined from the ray equations and the local gradient of sound speed versus depth. This method is useful in deep water, where a small number of rays transmit most of the acoustic energy from source to receiver, where there is a direct path from source to receiver, and where only a limited number of surface and bottom reflections contribute. For shallow water, the large number of reflected paths makes the method somewhat impractical (Lurton 2003; Richardson *et al.* 1995).

181. In simple cases, acceptable accuracy may be obtained by use of relatively simple geometrical spreading models. Commonly used models include spherical spreading (in decibel notation, this corresponds to a reduction in received level with range, r, of "20.log(r)"), or cylindrical spreading, (corresponding to a reduction in received level with range of "10.log(r)"). In practice, the spreading may lie somewhere between these two geometries and be described by "N.log(r)" where N typically has a value between 10 and 20. Such simple models do not include the effect of absorption in the medium. This may be included in a simplified manner by introducing a term which describes the reduction due to absorption with range (leading to a term of the type "$\alpha.r$" where α is the absorption in dB per meter). A composite model of this kind would then be used to calculate the received level (RL) from the source level (SL) by: $RL = SL - N.\log(r) - \alpha.r$ (Nedwell *et al.* 2007a). This type of model can also be adapted to include frequency dependent attenuation (Thiele 2002; Thomsen *et al.* 2006).

xi) Comparisons of models

182. Simple "lumped parameter" spreading models which incorporate simplified absorption, and conform to the general type "$RL = SL - N.\log(r) - \alpha.r$", have been used in previous UK studies which attempt to estimate the likely noise levels generated by wind farm construction (Nedwell *et al.* 2007a). These models have the advantage that they do not require a large amount of input data (only values of N and α), are simple to compute for measured values of received level versus range, and may be set up to replicate the apparent transmission loss of the sound measured during piling operations at other wind farm sites. However, the limitations of these models should be considered carefully. Such a model does not account for transmission loss effects due to changes in bathymetry, and so cannot (for example) predict the extra reductions in level caused by

sand banks and shallow coastal areas (for example due to the effect of mode stripping). In addition, such models do not include reverberation or consider the sound transmitted through the sediment, except in a highly simplistic way (e.g. by use of a composite value of α). Such a model is also frequency independent if it is applied to a time-domain parameter such as peak-to-peak sound pressure. This means it will depend only on range from the source. In practice, the transmission of sound in shallow water will show a strong dependence on frequency due to the modal nature of the propagation and the frequency-dependent absorption in the water and in the sediment. These phenomena will cause the time waveform to distort during propagation away from the source, typically causing a dilation of the acoustic pulse (an increase in pulse duration) and a reduction in high frequency content.

183. For the very shallow water environments, the normal mode and Parabolic Equation approach outlined above has the potential to provide good accuracy. This method can be made to incorporate the effects of variable bathymetry, sound speed profiles and frequency dependent absorption. However, such models do require a large amount of input data to describe the bathymetry, sound speed profiles, and sediment properties in the local area. Such information may not always be available, and any model is only as accurate as its input data. In addition, to describe the propagation of short broadband pulses, typically this type of model would be run at a number of discrete frequencies in order to predict the transmission loss at all the frequencies present in the pulse, and this requires greater computational power (and time).

184. It should also be noted that the accuracy of any model depends on accurate representation of the source. The source in the case of marine piling is very complex, with noise being radiated from the surface of the pile itself, and with noise also being launched directly into the sea-bed by the impact of the pile through the sediment. Currently, a perfect model does not exist for such a complex distributed source, and representations of the source in terms of simplified idealised sources such as point sources and line sources will inevitably limit the accuracy of predictions. This is particularly true for the acoustic field close to the pile (in the near-field), and possibly for greater ranges where sound propagating through the sea-bed re-enters the water column.

xii) Choice of model

185. A propagation model must be adopted in order to make any attempt to estimate the acoustic field at ranges other than those where measurements have been made. For example, to estimate the acoustic field within a few hundred metres of the source from measurements made at greater ranges. Similarly, if the source is to be described in terms of simplified concepts such as source level (useful, for example, if there is a desire to make comparisons with other sources), a propagation loss model is needed in order to estimate the transmission loss required to derive the source level. For the work described here, the model adopted is the Energy flux model described by Weston (Weston, 1976). This propagates the sound energy in the water column, and takes full account of geometric spreading, interaction with boundaries, modal propagation in shallow-water, frequency-dependent absorption in the water and seabed, and scattering from the sea-surface (caused by wave agitation). The implementation of this model has been benchmarked by NPL against several other standard models such as methods based on normal modes such as Kraken (Porter 1991) and CSNAP (Ferla *et al.* 1996), as well as the RAM parabolic equation solution (Collins, 1993), and the OASES wave-number integration code (Goh and Schmidt 1996). The Weston model decomposes the

acoustic field into third octave band levels and propagates each frequency band independently, recombining the frequency bands at a new range to calculate the broadband levels.

APPENDIX B - EFFECTS OF SOUND ON MARINE FAUNA

Potential effects of sound on marine fauna

186. Underwater sound can potentially have a negative impact on marine mammals and fish ranging from changing their acoustic habitat to scaring them away and even causing physical injury. In general, biological damage as a result of sound is either related to a large pressure change (barotrauma) or to the total quantity of sound energy received by a receptor. Barotrauma injury can result from exposure to a high intensity sound even if the sound is of short duration, such as an explosion. However, when considering injury due to the energy of an exposure, the time of the exposure becomes important. For example, a continuous source operating at a given sound pressure level has a higher energy and is therefore more damaging (Southall *et al.* 2007) than an intermittent source reaching the same sound pressure level. The harmful effects of high-level underwater sound can be summarised as lethal, physical injury and hearing impairment. Other ways in which sound or noise can be detrimental to the marine mammals and fish is by causing behavioural disturbance and auditory masking.

i) Lethality

187. Very close to the source, the high peak pressure sound levels have the potential to cause death, or severe injury leading to death, of marine mammals and fish. Some of these effects may be considered to be barometric pressure effects due to the shock experienced by the animal, rather than acoustic effects *per se*. There has been considerable research into the levels of incident peak pressure and impulse (integral of the peak pressure over time) that cause lethal injury in species of fish and in human divers. The work of Yelverton *et al.* (1973; 1975 and 1976) on fish, highlighted that for a given pressure wave, the severity of the injury and likelihood of a lethal effect is related to the duration of the pressure wave- i.e. a pulse of the same peak pressure but with a longer duration would be more likely to cause injury. In the Yelverton model, smaller fish are generally more vulnerable than larger ones. Richardson *et al.* (1995) converted Yelverton's expressions for fish mortality into those representative of larger marine mammals.

ii) Injury and hearing impairment

188. High exposure levels from underwater sound sources can also cause hearing impairment. This can take the form of a temporary loss in hearing sensitivity, known as a Temporary Threshold Shift (TTS), or a permanent loss of hearing sensitivity known as a Permanent Threshold Shift (PTS). For transient and continuous sounds the potential for injury is not just related to the level of the underwater sound and the hearing bandwidth of the animal, but is also influenced by the duration of exposure. For example, for two separate piling events where the total energy expended inserting the pile is the same, but one with a lower blow energy but a higher number of strikes and one with a higher blow energy and fewer hammer strikes, the overall noise dose of the animal would be expected to be the same, assuming that the animal does not move and that the sound energy in each sound pulse is linearly proportional to the hammer energy. However, if the animal were to flee the sound at its onset, then the lower blow energy example would be expected to result in a lower overall exposure to the sound and thus reduce the likelihood of TTS or PTS.

iii) Behavioural

189. At levels where the underwater sound wave may not directly injure animals or cause hearing impairment, the underwater sound may have the potential to cause behavioural

disturbance. Studies of the behavioural response of marine species to sound describe a variety of different behavioural reactions, and a general consensus for criteria has been slow to emerge. However, there is general agreement that the hearing sensitivity of the animal should be taken into account with a frequency weighting applied to the received levels. This approach has been recommended by a Marine Mammal Noise Criteria Group, set up to review the subject in the USA (Southall *et al.* 2007). Some COWRIE funded work in the UK suggested the use of a similar approach using frequency weighting (Nedwell *et al.* 2007b). Frequency weighting provides a sound level referenced to an animal's hearing ability either for individual species or classes of species, and therefore a measure of the potential of the sound to cause an effect. The measure that is obtained represents the perceived level of the sound for that animal. This is an important consideration because even apparently loud underwater sound may have no effect on an animal if it is at frequencies outside the animal's hearing range.

190. Further work funded by COWRIE in the UK has considered the use of piling playback sounds to caged fish which has provided an indicator of levels which might provoke a behavioural response for both cod *Gadus morhua* and sole *Solea solea* species (Mueller-Blenke *et al.* 2010).

iv) Auditory Masking

191. Auditory masking occurs when an unwanted sound or noise may partially or entirely reduce the audibility of a signal which occurs in the same critical hearing band, even if the signal level is above the absolute hearing threshold. Auditory masking can reduce the ability of an animal to communicate or detect predators. For sonar equipped animals, masking can also reduce their ability to hunt and navigate. However, the short pulse length and relatively low repetition rate of hammer strikes used for marine piling reduce the likelihood of this sound masking out the short, higher frequency vocalisations of marine mammals. Even at larger distances where the pulse length might be lengthened due to reverberation, the high frequency noise levels should be sufficiently reduced. It should also be noted that the predominant acoustic energy generated during marine impact piling is well below the frequencies used for communication and echolocation in odontocetes and so there is no cross-over at levels which might cause significant masking in the critical hearing bands (Thomsen *et al.* 2006). This may not be true for fish which are most sensitive at lower frequencies or for pinnipeds that can vocalise at frequencies which overlap with marine impact piling (Thomsen *et al.* 2006). The operational noise from a wind turbine or wind farm will generate continuous type noise signal but these are generally considered to be too low in level and restricted to a small area such that impact if any will be small and restricted. For harbour porpoise specifically they are believed to be too low in level and frequency to cause masking problems (Tougaard and Henriksen 2009).

v) Audibility

192. The audible distance or the physical range over which marine species can hear the construction activity will extend to the distance that the sound either falls below the ambient perceived sea noise level or the auditory threshold of the animal. Whether the sound is audible to an animal is not usually a consideration used for impact assessment, since impact is usually judged in terms of physical or behavioural effects triggered at levels that exceed mere audibility thresholds, which may already be within the ambient noise level. There may be no consequence, negative or otherwise, of the animal hearing the sound.

Audiograms

193. For an estimate to be made of whether an animal will be affected by an underwater sound, the hearing sensitivity of the animal must be considered. If the sound is composed of frequencies which do not lie within the reception bandwidth of the animal, the impact is likely to be negligible. For example, a sound at an ultrasonic frequency of 50kHz will not be heard by a human observer (Kinsler *et al.* 1982).

194. It is therefore advantageous to apply weighting to the received sound pressure level according to the sensitivity of the exposed animal. This is most commonly done by making use of audiometric data for the animal of interest. For example, a frequency weighting which incorporates the relative frequency response of the human ear is commonly used to assess the effect of noise on humans. The most widely used metric in this case is the dB A-weighting which incorporates the frequency weighting and was originally based on the 40-phon Fl*etc*her-Munson human hearing curves (Burns, 1973). The A-weighting curve was most recently updated in 2003 and is the subject of an international standard (ISO 226:2003). It should be noted that in obtaining internationally agreed equal loudness curves which have resulted in the standardisation of the A-weighting curve, there have been several studies which in some cases vary to a large degree.

Audiogram techniques

195. Audiograms are a representation of the hearing sensitivity of a subject as a function of frequency. These are presented as the sound pressure levels required for the subject to just perceive the sound (hearing thresholds) or more commonly to perceive the sound with a certain loudness (e.g. for a loudness of 40 phon).

196. To determine an audiogram for an animal requires a technique which does not rely on direct cognitive compliance. The animal cannot be asked whether the sound is perceptible. Two principal techniques have been commonly used. The first often relies on behavioural response and requires the animal to be trained to perform a task in response to an aural stimulus. This can only be used for animals that can be trained. The second method involves measurement of the evoked auditory potential which is the electrical impulse in the auditory nerves that results from the sound being heard by the animal. In this approach, electrodes are attached to the animal to measure the electrical response to the sound directly.

Audiogram data

197. The audiogram data considered here has been chosen to match the data used in previous studies to estimate the impact of wind farm construction noise on marine life. Specifically, the data cited in the study by Parvin *et al.* (2006) have been used. A number of other audiometric studies have been undertaken, for example those by Finneran *et al.* (2000; 2002a and 2002b) which have not been used here although Finneran’s work has been used extensively in the marine mammal criteria discussed further in this appendix. Audiometric data is very limited and where no audiometric data exists for a species, another species is often taken as a surrogate. For example, data does not exist for sole and so another flatfish, dab *Limanda limanda* is often used instead. Similarly, though striped dolphin *Stenella coeruleoalba* is not prevalent in the area, good audiometric data is available and it may be considered (at least provisionally) as representative of other odontocetes for which no audiometric data currently exists. However, it should be noted that different species can exhibit significantly different hearing sensitivity, so this is a crude (though necessary) approximation.

198. **Figure B.1** shows audiograms for selected species of cetaceans, **Figure B.2** shows the audiograms for some example species of pinniped and **Figure B.3** shows the audiograms for a selection of fish species.

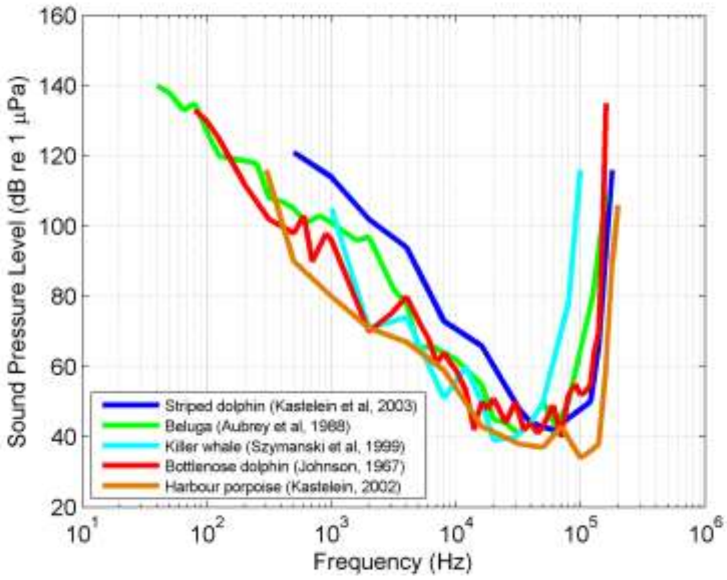

Figure B.1 – A: Hearing threshold data for a range of cetaceans.

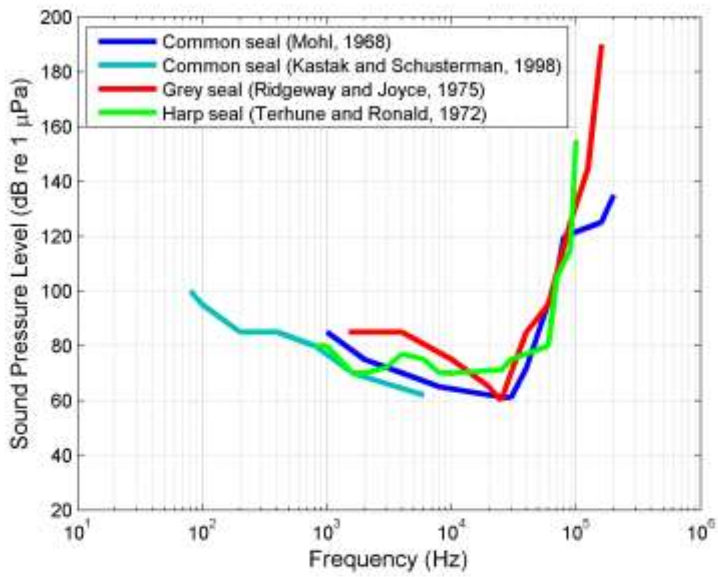

Figure B.2 – B: Hearing threshold data of a range of pinniped species.

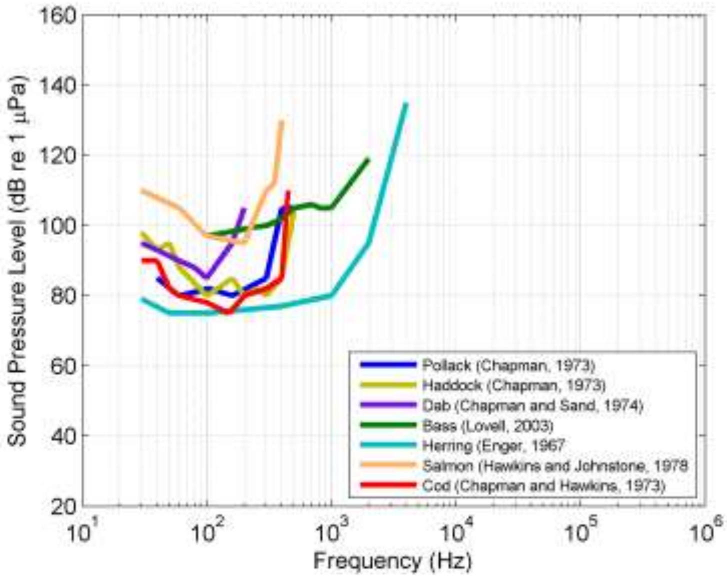

Figure B.3 – C: Hearing threshold data for a range of fish species.

199. These audiograms show the hearing response trends for some example species. Whilst these are useful, there is very limited data of its type, with audiograms for a given species often based on a measurement of an individual animal. As with human subjects, the absolute hearing sensitivity can change substantially from subject to subject and will likely depend on age and previous exposure etc. This can result in very different audiograms for individuals of the same species. Also, given the difficulties associated with performing either a behavioural response or an evoked auditory response audiogram measurement, there is also some uncertainty associated with the actual hearing response measurement on a given individual. Care should also be taken when using audiograms for response weighting, as the audiogram might only be representative of the hearing response of the animal to the sound level used to establish the audiogram. In humans the hearing response is considered to be a function of the sound level to which the auditory system is exposed. For example, for a human exposed to a loud sound, the dB C-weighted (dB(C)) level should be applied, not the more familiar A-weighted dB(A) scale (Burns 1973). The C-weighted response is considered to be the hearing frequency response of a typical human for a high intensity sound and so is used in place of the A-weighting for loud sounds, and has a much flatter response at lower frequencies. The dB(B) scale falls roughly between the two and applies to sounds with a moderate level.

200. The variability of hearing response with loudness may have implications for marine mammals. The audiograms generally used for marine mammals and fish are generally obtained for tonal sounds (single frequency sounds) to establish the threshold of hearing of the animal i.e. very quiet sounds. It is expected that the hearing response of a marine mammal would vary with loudness in the same way that it does for humans. This has in fact been shown for a bottlenose dolphin by Finneran and Schlundt (2011) where equal loudness curves were obtained in the same manner that they have been for humans in establishing the dB(A) and dB(C) weighting curves.

Review of criteria used for underwater noise impact on marine fauna

vi) Criteria for marine mammals

201. The US Marine Mammal Criteria Group of the NMFS (National Marine Fisheries Service part of NOAA) have proposed the 'M-weighting' model (Southall *et al.* 2007), as part of the Marine Mammal Noise Exposure Criteria. They classify marine mammals into one of five bands: three for cetaceans: low, mid and high-frequency and two for pinnipeds: water and air (See **Table B.1**). Harbour porpoise was considered as the only high frequency cetacean expected in the Dogger Bank area, as other species do not occupy UK waters, or are generally rare and found in deeper water (e.g. *Kogia*) (Reid *et al.* 2003). The M-weighting is applied in much the same way as the 'A-weighting' is applied in airborne acoustics when considering the perceived response of a human receptor. The marine mammal noise exposure criteria were developed through consensus of an expert committee and peer-reviewed. They are perhaps the most developed and recognised exposure criteria for marine mammals, compiling the findings of much of the published literature, including key work on the effects of noise on marine mammals by Finneran *et al.* (2000, 2002a and 2002b) and Lucke *et al.* (2007). In the development of the criteria, the published audiograms shown in **Figure B.1** and **B.2** were considered. The criteria are rapidly finding acceptance internationally and are now being recommended in the UK for use in environmental impact assessments.

202. In the case of the SEL, a series of filters have been developed analogous to human hearing response weightings (M-weighting is actually more analogous to the human C-weighting for high-amplitude sounds). In this method the signal is first weighted (filtered) relative to hearing abilities of species under test and the SEL or accumulated SEL is then calculated (Theobald *et al.* 2009). This has the advantage that, for signals containing multiple frequency components, energy contributions from frequency components outside the hearing band of the species will be reduced or removed from the overall exposure estimate. Again, this is analogous to human hearing accumulated exposure measurements. It should be noted that, in this treatment by Southall *et al.* (2007), the injury criteria consider both SEL and Sound Pressure Level (SPL), where the SPL is considered for a peak level and is not subjected to a weighted response.

203. A series of frequency weighting functions have been developed based on current knowledge and interpolation of appropriate marine mammal hearing data and grouped into functional marine mammal hearing groups (see **Table B.1**).

Table B.1 - Functional marine mammal hearing groups taken from Southall et al. (2007).

Function hearing group/Frequency-weighting network	Estimated auditory bandwidth	Genera represented
Low-frequency cetaceans – M_{lf}	7Hz to 22kHz	*Balaena, Caperea, Eschrichtius, Megaptera, Balaenoptera* (13 species/subspecies)
Mid-frequency cetaceans – M_{mf}	150Hz to 160kHz	*Steno, Sousa, Sotalia, Tursiops, Stenella, Delphinus, Lagenodelphis, Lagenorhynchus, Lissodelphis, Grampus, Peponocephala, Feresa, Pseudorca, Orcinus, Globicephala, Orcaella, Physeter, Delphinapterus, Monodon, Ziphius, Berardius, Tasmacetus, Hyperoodon, Mesoplodon* (57 species/subspecies)

Function hearing group/Frequency-weighting network	Estimated auditory bandwidth	Genera represented
High-frequency cetaceans – M_{hf}	200Hz to 180kHz	*Phocoena, Neophocaena, Phocoenoides, Platanista, Inia, Kogia, Lipotes, Pontoporia, Cephalorhynchus* (20 species/subspecies)
Pinnipeds in water – M_{pw}	75Hz to 75kHz	*Arcocephalus, Callorhinus, Zalophus, Eumetopias, Neophoca, Phocartos, Otaria, Erignathus, Phoca, Pusa, Halichoerus, Histriophoca, Pagophilus, Cystophora, Monachus, Mirounga, Leptonychotes, Ommatophoca, Lobodon, Hydruga, and Odobenus* (41 species/subspecies)
Pinnipeds in air – M_{pa}	75Hz to 30kHz	Same species as pinnipeds in water (above)

204. It is acknowledged by Southall *et al.* (2007) that these filters are much 'flatter' than audiograms and are probably quite precautionary even considering the expected flattening of equal-loudness contours for high-amplitude sounds. It is also true that they are precautionary in that regions of best hearing sensitivity for most species are likely considerably narrower that the M-weighting functions. These 'M-weighting' filters are plotted for each functional hearing group (as outlined in **Table B.1**) in **Figure B.4**.

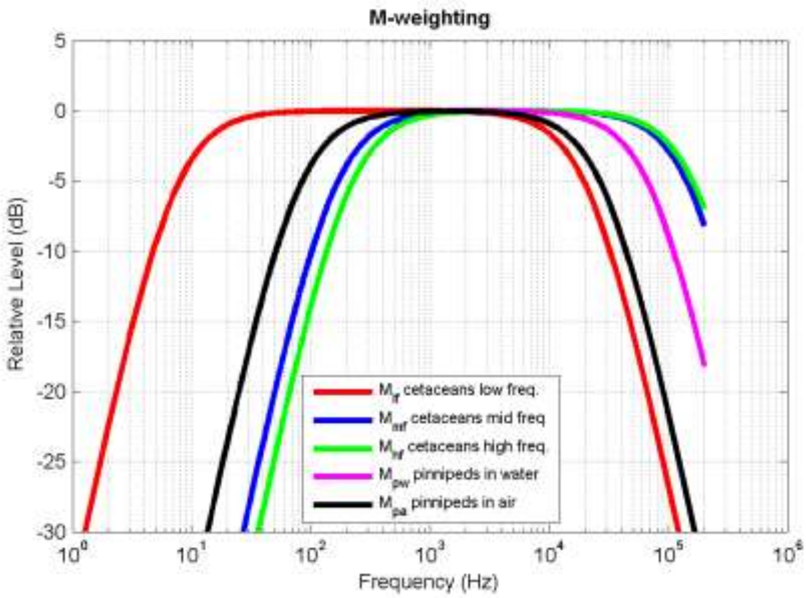

Figure B.4 – D: The M-weighting filters taken from Southall *et al.* (2007).

Injury criteria for marine mammals

205. The criteria for injury outlined by Southall *et al.* (2007) consider PTS-onset to constitute injury, as sound induced PTS represents irreversible damage to the cochlear hair cells, as opposed to TTS, which represents merely fatigue. As PTS has not been measured in marine mammals, the injury criteria are estimated from TTS-onset measurements and knowledge of the rate of TTS growth with increasing exposure levels above the level eliciting TTS-onset. It is assumed that a sound exposure capable of inducing 40dB of TTS will cause PTS-onset, based on available data from terrestrial mammals. The Marine Mammal Noise Exposure Criteria considers three sound types which cover the range of sound sources to which a marine mammal might be exposed. These are defined as: i) single pulses; ii) multiple pulses; and iii) nonpulses. Marine

piling strikes (i.e. not a single pile strike) are defined by Southall *et al.* (2007) as multiple pulses. The relevant injury criteria for multiple pulses as stated by Southall *et al.* (2007) are given below:

206. Injury criteria for low, mid and high-frequency cetaceans:

- *Sound Pressure Level injury criteria:* ***230dB re 1 µPa*** *(peak) (flat, un-weighted)*
- *Sound Exposure Level injury criteria:* ***198dB re 1 µPa²·s*** *(M-weighted)*

207. Injury criteria for pinnipeds in water:

- *Sound Pressure Level injury criteria:* ***218dB re 1 µPa*** *(peak) (flat, un-weighted)*
- *Sound Exposure Level injury criteria:* ***186dB re 1 µPa²·s*** *(M-weighted)*

208. These limits are applicable for either single or multiple exposures within a 24 hour period. These criteria for injury are based on the US Marine Mammal Criteria Group method, where the SPL limit is based on an addition of 6dB to the peak pressure known or assumed to elicit TTS-onset. The SEL limit is based on an addition of 15dB to the SEL known or assumed to elicit TTS-onset for any marine mammal exposed to single or multiple pulses.

209. More recent work by Lucke *et al.* (2009) suggested more precautionary injury criteria might be required specifically for harbour porpoise than that suggested by Southall *et al.* (2007) for a high-frequency cetacean. Lucke *et al.* (2009) measured TTS induced by a seismic airgun pulse with a peak pressure level of 194dB re 1 µPa (stated as $200\text{dB}_{\text{pk-pk}}$ in Lucke *et al.* (2009)) and an SEL of 164dB re 1 $\mu\text{Pa}^2\cdot\text{s}$. The approach adopted by Southall *et al.* (2007) of assuming PTS-onset (the basis for the injury criteria) results at an SPL 6dB above the level eliciting TTS-onset could also be adopted for harbour porpoises providing a **peak pressure level injury criteria threshold of 200dB re 1 µPa**. The same approach can be applied to SEL, where Southall *et al.* (2007) suggest an SEL 15dB above the level eliciting TTS-onset which provides an **SEL injury criteria threshold of 179dB re 1 $\mu\text{Pa}^2\cdot\text{s}$**.

Behavioural criteria for marine mammals

210. The behavioural response of marine mammals is perhaps somewhat easier to study than the relative health of their auditory system and several studies have been undertaken. There are, however, several species of interest and numerous potential sound sources and in addition to this, quantifying the mammal's behavioural response is not easy. The US Marine Mammal Criteria Group recognises this and so in addition to compiling a database of relevant studies, they have created a severity scaling system which ranks the behavioural response from a zero for 'no response' to a 9 for 'outright panic, flight, stampede, attack of conspecifics or stranding events' (Southall *et al.* 2007). A behavioural response with a severity scale of 5/6 is considered to represent a disturbance, with animals showing noticeable changes in swimming pattern to minor avoidance reactions.

Multiple pulses (general piling activity)

211. Based on the limited behavioural observations collated as part of the US NMFS criteria (Southall *et al.* 2007), the following statements can be made which are appropriate for multiple pulses:

212. i) Pinnipeds in water

Based on limited data for ringed seals, received levels of 190dB re 1 μPa (RMS over pulse duration) are likely to elicit responses with a possible severity scaling of 5.

213. ii) Low-frequency cetaceans

For low-frequency cetaceans not engaged in migration, the on-set of significant disturbance (severity scaling of 6 and above) is likely to occur over a range of received levels from 150 to 160dB re 1 μPa (RMS over pulse duration). Significant disturbance could occur at lower levels depending on the activity of the animal. It should be noted here that these are based on seismic airguns, which can generate very low frequencies when compared to piling, which might be significant for low-frequency cetaceans. They were also performed in deeper water than that in which piling it typically performed, allowing the lower frequencies to propagate.

214. iii) Mid-frequency cetaceans

Very little information exists for mid-frequency cetaceans exposure to multiple pulse source types. There is some indication that a received level of 170 – 180dB re 1 μPa (RMS over pulse duration) would elicit a response of 6 on the severity scale (Southall *et al.* 2007). A recent study by Finneran *et al.* (2012), exposing a bottlenose dolphin *Tursiops truncatus* to a seismic airgun, indicates that this higher level threshold may not be unrealistic and small mid-frequency cetaceans may well be less sensitive to impulsive sounds than harbour porpoise.

215. iv) High-frequency cetaceans

No data is reported in Southall *et al.* (2007) for high-frequency cetaceans (this category includes the harbour porpoise).

216. It should be noted that the RMS over the pulse duration results in dB values that would likely be higher than the equivalent SEL dB value for a piling pulse. Robinson *et al.* (2007) measured the difference to be around 11dB at a distance of 2km from the pile. However, this is only illustrative, as the difference would be expected to change with distance as the sound pulse dilates (McCauley *et al.* 2000). The above criteria are also predominantly based on seismic air guns and so the pulse lengths would be expected to be different to those associated with impact piling, although there would be cross-over in the frequency bandwidth of the sources. It would be precautionary to assume that the RMS (over the duration of the pulse) received levels stated above would be around 10dB lower when stated as pulse SEL received levels at closer ranges, and around 8dB lower at greater ranges (tens of km). In this assessment a 10dB difference was adopted at ranges of possible mid-frequency cetacean behavioural avoidance, while an 8dB difference was assumed for ranges corresponding to the larger impact ranges for the low-frequency cetacean.

Single pulse (single piling pulse)

217. A simpler approach to behaviour criteria can be considered by assuming a single pulse type source (i.e. assuming a response to a single hammer strike). The response of an

animal to a single pulse is important in terms of identifying the range at which instantaneous PTS and TTS might occur, so that appropriate mitigation methods can be applied. For the single pulse case, Southall *et al.* (2007) suggest the following behavioural criteria, based on TTS-onset levels:

218. Behavioural criteria for low, mid and high-frequency cetaceans:

- *Sound Pressure Level behavioural criteria:* ***224dB re 1 µPa*** *(peak) (flat)*
- *Sound Exposure Level behavioural criteria:* ***183dB re 1 µPa²·s*** *(M-weighted)*

219. Behavioural criteria for pinnipeds in water:

- *Sound Pressure Level behavioural criteria:* ***212dB re 1 µPa*** *(peak) (flat)*
- *Sound Exposure Level behavioural criteria:* ***171dB re 1 µPa²·s*** *(M-weighted)*

220. While single pulse criteria based on the TTS onset can help identify the fleeing response levels and ranges at which instantaneous TTS might occur, using these criteria does not account for the potential disturbance associated with the duration of the noise producing activity, which is incorporated in the severity scaling score for multiple pulses. Thus both should be considered, although it should be noted that Southall *et al.* (2007) do not propose the use of the single pulse criteria for sources categorised as multiple pulses, such as impact piling. Whilst Southall et al. (2007) do not suggest that the onset of TTS should be used as a measure of impact, the outlined criteria for behavioural disturbance resulting from a single pulse is based on the onset of TTS threshold.

221. Recent work by Lucke *et al.* (2009) suggested that more precautionary behavioural criteria might be required, specifically for harbour porpoise, than that suggested by Southall *et al.* (2007) for high-frequency cetaceans. This work by Lucke *et al.* (2009) resulted in an observation of TTS-onset at a received level 194dB re 1 µPa peak pressure level and 164dB re 1 $\mu Pa^2 \cdot s$ SEL from a seismic airgun pulse. Southall *et al.* (2007) assume TTS-onset to be the basis for the behaviour criteria. However, Lucke *et al.* (2009) show that this is potentially not the case for harbour porpoise with **aversive behavioural reactions being demonstrated at received levels of 168dB re 1 µPa peak pressure level** (reported at $174dB_{pk-pk}$ re 1 µPa) **or 145dB re 1 $\mu Pa^2 \cdot s$ SEL**. These findings are also supported by observational studies in Denmark that observed a reduction in harbour porpoise vocalisations out to ranges of around 20km during impact pile driving of monopole foundations for a Danish wind farm (Tougaard *et al.* 2009; Brandt *et al.* 2011).

Marine mammal behavioural criteria applied for this assessment

222. This assessment summarises behavioural impacts in light of relevant and published data which are considered to be the most applicable at the present time. The injury criteria described by Southall *et al.* (2007) were applied to pinnipeds and mid and low-frequency cetaceans. Experimental results by Lucke *et al.* (2009) were modified following the methodology proposed by Southall *et al.* (2007) to derive instantaneous injury criteria for the harbour porpoise. In terms of behavioural criteria, two general approaches are considered, both of which are described by Southall *et al.* (2007) and outlined above. These are the **single pulse behavioural disturbance** criteria and **behavioural response severity scaling for multiple pulses**.

223. The Single pulse criterion is based on the TTS onset and is referred to here as TTS/fleeing behaviour as it has previously been associated with fleeing response in belugas. The single pulse behavioural criterion was applied as, stated by Southall *et al.* (2007), to pinnipeds, low and mid-frequency cetaceans, while recent findings by Lucke *et al.* (2009) were used to estimate the harbour porpoise fleeing behaviour based on the onset of TTS following the criteria guidance proposed by Southall *et al.* (2007). When considering possible avoidance of the area due to the piling sequence, the multiple pulses severity scaling score 5/6 was adopted from Southall *et al.* (2007) which relates to possible avoidance, and is amongst the most moderate averse response listed by the authors. It is generally referred to in this assessment as *(possible) avoidance behaviour*, and it essentially suggests there may be some avoidance response with possible inter-individual variation. It should be stressed that there are no multiple pulse behavioural response criteria given in Southall *et al.* (2007) for high-frequency cetaceans, while single pulse behavioural criteria are stated but are based on work with belugas, which form the basis of the behavioural response criteria for all cetaceans exposed to a single pulse. Whilst it is accepted that the findings of Lucke *et al.* (2009) are not a complete representation of the harbour porpoise response to noise, these are the only available data that concern harbour porpoise behavioural response to pulsed sounds and likely provide a better representation than previous criteria extrapolated from other cetacean functional hearing groups as defined by Southall *et al.* (2007). The study by Lucke *et al.* (2009) exposed a single captive harbour porpoise to a single seismic air gun source and observed its response whist obtaining direct measures of the sound at the receptor location, making it the only data of its type available in the peer-reviewed literature. In addition to the work by Lucke *et al.* (2009), this assessment also considers other recent studies of harbour porpoise behaviour by Tougaard *et al.* (2009) and Brandt *et al.* (2011).

vii) Criteria for fish

224. The hearing capabilities of fish species are often characterised as either a hearing specialist or generalist. The term hearing specialist generally refers to fish species that have a structure linking the swim bladder and ears, whereas hearing generalist would not normally be considered to have this connection (Webb *et al.* 2008). Hearing generalists generally hear over relatively narrow frequency ranges from 50Hz or below to 1,000Hz or 1,500Hz with a hearing sensitivity which is often not very good, although there is considerable variation between species. Fish species categorised as hearing specialists usually have improved sensitivity over the same range and sensitivity to sound at higher frequencies extending above 3,000Hz. For marine piling, where most of the acoustic energy is radiated between around 100Hz to 400Hz, the high frequency capability of specialist species is of minor importance. Given that many fish species have their highest sensitivity to sound in or around this 100 to 400Hz frequency range (see **Figure B.3**) they will perceive piling noise at relatively large distances (Thomsen *et al.* 2006). It should also be noted that many fish which might be affected by marine piling will have a hearing threshold which is either close to or below the level of ambient noise in the area. This means that they perceive the ambient noise and that their ability to hear a sound is limited not by their threshold of hearing but by the level of the ambient noise.

225. One specific aspect of the sensitivity of fish species to sound is their sensitivity to acoustic particle velocity as opposed to sound pressure. This has been noted by a number of researchers (Hawkins 2006; Nedwell *et al.* 2007b; Popper and Hastings

2009; Sigray and Andersson 2011) and is acute at low frequencies where this particular sensitivity of their otoliths enables fish to discriminate sounds from different directions. The lateral line can also result in sensitivity to the particle velocity generated for certain sound field conditions where sound pressure is not predominant. The potential for marine piling to generate just the type of sound fields that may contain substantial acoustic particle velocity components has been noted in the literature (Hawkins 2009). Sensitivity to particle motion is more likely to be important for behavioural responses rather than injury (Hawkins 2009). However, the proposed criteria for fish species so far (e.g. Popper *et al.* 2006; Nedwell *et al.* 2007b) are all in terms of pressure rather than particle velocity. A recent COWRIE study by Cefas in the UK (Mueller-Blenkle *et al.* 2010) on the behavioural response of fish to pile driving did measure and consider the fish response to particle velocity as well as pressure.

226. It should be noted that, for a propagating acoustic wave in the water column, the particle velocity component will generally be related to the acoustic pressure i.e. as the acoustic pressure reduces with distance, the particle velocity component would be expected to reduce proportionally.

227. When considering vibration in the seabed it should be noted that little or no data exists for either the effect on seabed dwelling marine fauna or on the levels generated during marine impact piling. However, vibration generated in the seabed would be expected to decay more rapidly than the acoustic pressure component in the water, which is regarded as the prevalent component when considering impact of underwater noise on marine life.

Injury criteria for fish

228. Although the criteria proposed by US Marine Mammal Criteria Group has been adopted reasonably widely for mammals, there is a lack of similarly accepted criteria for fish species. A comprehensive review by Popper and Hastings (2009) on the effects of anthropogenic sound on fishes concluded that there are substantial gaps in the knowledge that need to be filled before meaningful noise exposure criteria can be developed.

229. As of August 2008, the Fisheries Hydroacoustic Working Group (FHWG) (established by California Department for Transportation in coordination with the US Federal Highways Administration and the departments of transportation in Oregon state and Washington state) have advised the use of interim dual injury criteria based on a peak pressure level of 206dB re 1 µPa for a single strike and an accumulated SEL (SEL dose) of 187dB re 1 $\mu Pa^2 \cdot s$ for all fish except those less than 2 grams in mass, for which an SEL dose of 183dB re 1 $\mu Pa^2 \cdot s$ was set (FHWG 2008). These interim criteria for fish injury are based on a white paper by Popper *et al.* (2006) to establish interim criteria for injury of fish exposed to pile driving operations, which previously advised the use of the same dual criteria but with a slightly higher peak pressure level threshold of 208dB re 1 µPa. The peak pressure level and SEL dose thresholds were dictated by the possible onset of auditory tissue damage, except for the latter case of fish of less than 2 grams where non-auditory tissue damage is considered to occur first (Carlson *et al.* 2007). Carlson *et al.* (2007) also recommended that the cumulative SEL (SEL dose criterion) for larger fish should be 197dB re 1 $\mu Pa^2 \cdot s$ for fish over 8 grams and 213dB re 1 $\mu Pa^2 \cdot s$ for fish over 200 grams. The FHWG dual criteria were also included in a technical guidance document for assessing the effects of pile driving on fish, issued by the California Department for Transportation (Oestman *et al.* 2009). Whilst the FHWG

dual criteria for fish injury are perhaps the most widely adopted criteria for fish, it should be noted that the findings are based on a limited number of studies and substantial variation between fish species, size, age and sex might be expected, in addition to variability due to the sound source, the environment and the activity of the fish being considered. New injury criteria for fish are expected either during 2012 or 2013 from an Acoustical Society of American standards working group created for this reason (Fay and Popper 2006) and recent publications by Halvorsen *et al.* (2011 and 2012) question the use of the equal energy hypothesis. The study by Halvorsen *et al.* (2011) proposes the use of a 1 to 10 response weighted index (RWI) based on the level of physiological significance of damage, where an RWI of 2 or less does not lead to physiological effects that reduce either the immediate or long-term performance and energetics. The cumulative SEL, or SEL dose, established in the study using 2000 pulses, which resulted in a RWI of 2, considered to be sub-onset of injury, was 211dB re 1 $\mu Pa^2 \cdot s$. These findings are based on juvenile Chinook salmon *Oncorhynchus tshawytscha* with a mean weight of 11.8 grams and generally result in a higher SEL dose threshold than those proposed by the FHWG, except for the case of fish over 200 grams in weight.

230. A recent study by IMARES (Bolle *et al.* 2011;2012) which exposed common sole larvae to piling noise observed no statistically significant effect on their survival rates for a piling sequence which resulted in a SEL dose of 206dB re 1 $\mu Pa^2 \cdot s$. Although the results should not be extrapolated to all species, the study does indicate that the injury criteria for small fish (less than 2 grams) of 183dB re 1 $\mu Pa^2 \cdot s$ SEL dose proposed by the FHWG may not be applicable for fish larvae.

Behavioural considerations for fish

231. Studies on the behavioural response of fish to underwater sound are very limited and currently, no criteria exist for assessing this. There is some observational evidence that fish behaviour is influenced by sound as a fall in fish catch rates has been observed following seismic surveying (Engås *et al.* 1996; Webb *et al.* 2008; Løkkeborg *et al.* 2010). However, this is difficult to quantify and only a handful of studies have attempted to study the behavioural response of fish to impulsive sounds such as seismic survey or pile driving activities. One study by Slotte *et al.* (2004) used sonar to observe the fish movement during a seismic survey, showing that the fish appeared to go to greater depths after exposure to a seismic airgun source and a study by Hassel *et al.* (2004) showed behavioural changes in sandeels *Ammodytes marinus* when exposed to a seismic airgun.

232. Experiments using confined fish offer a way of studying the behavioural response of fish when exposed to sound and Blaxter *et al.* (1981) observed a startle response in schooling herring when exposed to sound over a frequency range of 30Hz to 800Hz, although no received levels were stated. Although confined fish experiments offer a convenient way to observe behavioural reactions, the nature of the experiment and the likelihood of increased stress in the fish should be considered carefully when assessing the implications on potential impact. This has been stressed by Popper and Hastings (2009) who have extensively reviewed a number of other studies exposing caged fish to sound. A study in the UK by Nedwell *et al.* (2006) showed an increase in activity of caged salmonids (brown trout and salmon) around 50m from a pile driving activity, although responses in other cages were not consistent. Another study in the UK analysed the effectiveness of an acoustic fish deterrent used to discourage fish from entering intakes for a nuclear power plant cooling system (Maes *et al.* 2004). This work

showed a clear avoidance of some fish species to the deterrent which had a reported generated swept sinusoid from 20Hz to 600Hz with a measured sound pressure level (RMS) of 170dB re 1 μPa. A report assessing the same study by Nedwell *et al.* (2007b) proposed the use of a criterion for strong avoidance at 90dB above the hearing threshold of the fish and the possibility of traumatic hearing damage at 130dB above the hearing threshold of the fish. Hastings and Popper (2005) made a similar observation that hair cell damage appears to occur at around 120dB above auditory threshold at the most sensitive frequency range.

233. The drawback of using a criterion based on the threshold of hearing of fish is that they are usually based on the measured hearing response of a limited number of fish of a particular species, where the measured audiograms for a given individual of the same species can vary substantially. An example of this is cod, where a variation of over 30dB exist at the most sensitive frequencies of the three audiograms measured and reported in the literature (Nedwell *et al.* 2004). This could be due to both the method used to establish the hearing sensitivity and the natural variability between individual cod. In coastal waters where ambient noise levels are generally above the hearing threshold for fish it is perhaps the level of the sound above ambient, and not the threshold of hearing, which is more important. It is therefore preferable to state any criterion as an absolute sound level which can be compared with future criteria and assessed against the context of ambient noise *etc*. for the location and time in question.

234. A recent COWRIE funded project led by Cefas in the UK (Mueller-Blenkle *et al.* 2010) measured the behavioural response of both cod and sole to sounds representative of those produced during marine piling. These measurements were performed using a play back of a piling sound with the temporal characteristics of a sound to which fish might be exposed to at a distance of around 400m from a piling event but with a range of received levels typical for much greater distances. The confinement of the fish in cages might influence the response of the fish by increasing the overall stress levels in the fish and also by limiting its ability to swim away from the sound source. The observed reaction also depends on the age, sex and condition etc. of the fish. The report stated that there was considerable variation across subjects and that it was not possible to find an obvious relationship between the level of exposure and the extent of the behavioural response.

235. Despite these limitations, the study provided an indicator of the received levels which may provoke a behavioural response for both cod and sole, although this threshold should not be interpreted as the level at which an avoidance reaction will be elicited as the study was not able to show this. The identified thresholds of exposure in peak pressure level that lead to an observable behavioural response were 140 to 161dB re 1 μPa for cod and 144 to 156dB re 1 μPa for sole, although the stated particle velocity values would be more appropriate for sole.

236. The authors of the report also recommend that for the reporting of impact zones, a single number or range is not sufficient, hence the range of peak pressure level values over which a reaction might occur. These behavioural threshold levels can only be used to signify that a behavioural reaction may occur and is not necessarily indicative of an avoidance response which is perhaps more important for the purpose of this assessment. The reaction observed in the above study (Mueller-Blenkle *et al.* 2010) is perhaps more analogous to the 70/75dB above the hearing threshold criterion proposed by Nedwell

and Howell (2004) for a behavioural reaction which is not considered a strong avoidance response.

237. Although no behavioural disturbance criteria have been established, Washington State Department of Transportation, who do specify a requirement for the FHWG interim criteria for fish injury to be followed, also provide guidance in their Biological Assessment manual (WSDOT, 2011) for behaviour effects in the form of a disturbance threshold which is based on work by Hastings (2002). The recommended threshold is 150dB re 1 μPa RMS, where the RMS refers to the root-mean squared pressure over the duration of the pulse. From previous analysis of sound pulses from marine impact piling in shallow water, the pulse duration RMS is several dB (10 to 12dB) lower than the acoustic peak pressure measured for the same pulse (Robinson *et al.* 2007). It should be noted that this correlation between peak pressure level and RMS levels will actually depend on the propagation distance and so the peak pressure level can only be used as an approximate indicator. Following the guidance from the Washington State Department of Transportation Biological Assessment manual, and using the definition of peak pressure level this approximation would result in a peak pressure level disturbance threshold of around 160 to 162dB re 1 μPa. This value is similar in magnitude to the upper threshold stated by Mueller-Blenkle *et al.* (2010) for cod. Studies by Curtin University in Australia for the oil & gas industry by McCauley *et al.* (2000) exposed various fish species in large cages to seismic airgun and assessed behaviour, physiological and pathological changes. The study made the following observations:

- A general fish behaviour response to move to the bottom of the cage during periods of high level exposure (greater than RMS levels of around 156-161dB re 1 μPa);
- A greater startle response by small fish to the above levels;
- A return to normal behavioural patterns some 14 to 30 minutes after airgun operations ceased;
- No significant physiological stress increases attributed to air gun exposure; and
- Some preliminary evidence of damage to the hair cells when exposed to the highest levels, although it was determined that such damage would only likely occur at short range from the source.

238. Although, as pointed out by McCauley *et al.* (2000), it is not technically correct to convert RMS to peak pressure level units (as defined in this report) an approximate conversion was provided by the authors resulting in peak pressure level levels of around 168 to 173dB re 1 μPa. The authors do point out that any potential seismic effects on fish may not necessarily translate to population scale effect or disruption to fisheries and McCauley *et al.* (2000) show that caged fish experiments can lead to variable results. However, experimental studies by Engås *et al.* (1996) have shown catch rate reductions for cod and haddock both during and following a seismic survey, which could be caused by the fish leaving the immediate area or simply by the fish increasing their swim depth (water depth was >200m). Skalski *et al.* (1992) also experimentally demonstrated a reduction in rockfish catches during exposure to a seismic airgun where the peak acoustic pressure or peak pressure level was around 186dB re 1 μPa. Caged rockfish were also the subject of a study by Pearson *et al.* (1992) who observed a subtle behavioural response at a peak pressure level of 161dB re 1 μPa (mean) and an alarm response at a peak pressure level of 180dB re 1 μPa (mean) where the alarm response is defined as a general increase in activity and changes in schooling or position in the

water column. Pearson *et al.* (1992) also observed a startle or C-turn response at peak pressure levels beginning around 200dB re 1 μPa, although this was less common with the larger fish. This is higher than levels reported by McCauley *et al.* (2000) where C-turn responses were observed at a peak pressure level of 183 to 196dB re 1 μPa for small fish but it is consistent with the peak pressure level of 203dB re 1 μPa reported by McCauley *et al.* (2000) for larger fish.

239. Although there is insufficient evidence to determine a behaviour criterion for individual fish species, there is some broad consistency in the literature of the levels at which fish, across a broad range of species, respond to low frequency impulsive noise sources such as piling or seismic surveys. These levels range from around 161dB re 1 μPa (upper threshold proposed by Mueller-Blenkle *et al.* (2010) for cod) to around 200dB re 1 μPa (startle response observed by Pearson *et al.* (1992)).

Fish behavioural criteria adopted for this assessment

240. The Popper *et al.* (2006) and Carlson *et al.* (2007) criteria described above have been adopted for this assessment when considering fish injury. Based on the findings of the above studies by McCauley *et al.* (2000) and Pearson *et al.* (1992), in the absence of other evidence, guidance peak pressure levels for different levels of behavioural response have been defined for the purposes of this assessment:

i. *General change in swimming and schooling behaviour with possible moderate to strong avoidance* – 168 to 173dB re 1 μPa (McCauley *et al.* 2000)

ii. *Startle response/C-turn reaction and very strong avoidance* – 200dB re 1 μPa (Pearson *et al.* 1992)

241. These response levels are only indicative and the level of behavioural disturbance will depend on a number of factors such as the type of fish, its sex, age and condition, as well as other stressors to which the fish is or has been exposed. For example, it would be expected that smaller fish might undergo the above behavioural changes at slightly lower levels. In addition to this, the response of the fish will depend on the reasons and drivers for the fish being in the area. Foraging or spawning, for example, may increase the desire for the fish to remain in the area despite the elevated noise level. For the above threshold levels, it is assumed that the fish have hearing sensitivity over the frequency range of approximately 100 to 400Hz where the majority of the sound energy from a piling event would be contained. Fish species with particularly poor hearing sensitivity (some hearing generalist), such that the threshold of hearing is substantially above ambient noise levels, would be expected to have behavioural response thresholds which are of a higher level than those stated above and would therefore have reduced impact ranges. Also, fish species which are thought to respond primarily to acoustic particle velocity and not acoustic pressure may require special consideration.

APPENDIX C - REVIEW OF MITIGATION MEASURES FOR IMPACT PILING

Mitigation strategies

242. Mitigation strategies to reduce the impact of underwater noise from wind farm developments can be categorised as:
   i) Reduction of noise generated by the source;
   ii) Acoustic barriers to reduce the radiated noise; and
   iii) Controls to protect or deter animals out of the critical zone.

243. The following sections review potential methods for implementing the three strategies outlined above. It should be noted that some of the methods reviewed, whilst showing potential for noise reduction, may not be practically feasible or realisable at the present time.

i) Reduction of noise generated by the source

244. Reducing the level of noise generated by the source is the most effective way of reducing the potential impact of the noise on marine fauna. Suitable design choices and optimisation of engineering methods can, in some cases, result in an effective noise level reduction which will correlate directly with a reduced impact.

Choice of foundation type

245. The choice of foundation is likely to be the prevalent factor in the noise levels produced at the source. Generally, suction caissons (bucket foundations), floating foundations (assuming they are gravity anchored), gravity base foundations and screw-piles will result in much lower noise levels when compared to foundations which require the insertion of a pile into the seabed by means of impact pile driving, such as a monopole or a jacket foundation. Suction caissons, floating and gravity base foundations will not generate the loud, impulse sounds that are associated with impact pile driving, although noise will result from the installation of the foundation and the necessary seabed preparations. There are currently no data available in the public domain for the noise resulting from the installation of such foundation types, but it would be expected to be dominated by the noise of the installation vessel and any other support vessels. It should also be remembered that dredging may also be required to prepare the seabed. A study by Robinson *et al.* (2011) showed that aggregate extraction dredging resulted in noise levels which were similar to other large surface vessels, but with an increase in the level of higher frequency components. Although the noise levels would not be considered high enough to have a significant impact, they would be present for extended periods.

246. The noise levels generated by impact piling can be very high and there are many factors which might influence the radiated noise levels. There is some consensus (Nehls *et al.* 2007) that large scale monopole foundations requiring high energy hammers are likely to result in higher noise levels than foundations, such as jackets, which require installation of smaller pin-piles, with generally lower hammer energy. This will likely depend heavily on the substrate into which the pile is being driven, where the increased energy required for penetration of larger diameter piles will likely result in the radiation of more acoustic energy (the relationship between hammer energy and acoustic energy is considered further in this appendix). It should be remembered that, although the peak noise levels generated by the installation of jacket foundations are generally lower than monopole foundations, the total time required for installation is several times longer. The implication of this is that although the zone of impact is smaller, the disturbance is

present for a longer time period. Without a considerable body of observational evidence it is difficult to be certain which scenario has a lesser or greater impact on a given species or population. There is some indication that the duration of animal displacement away from the driven pile may exceed the interval between successive foundation installations. Recent findings by Brandt *et al.* (2011) demonstrated that the harbour porpoise density, which showed a decrease in response to impact piling, may take 24 to 72 hours to recover, which suggests the potential for harbour porpoise density reduction around pile driving activities for the entire period of construction. Compared to this, the time scales involved in the installation of any one foundation and the gaps between the foundation installations are generally relatively short (generally hours, rather than days) and the duration of disturbance resulting from wind farm construction may be similar for monopole or jacket foundations. On the other hand, the lower hammer energies associated with jacket foundations will likely result in a reduced area of impact and lower overall instantaneous sound level values. The use of jacket foundations that require lower hammer blow energies could, assuming that the total time to construct the wind farm is not increased significantly compared to the use of monopole foundations, could be considered to have a reduced impact on hearing sensitive marine life.

247. The overall time taken to complete construction of the wind farm should also be considered ensuring there is no overlap with any noise sensitive biological activity specific to the local area (e.g. mating, spawning etc.). Provided that there is no indication that the local populations' survival and reproduction are dependent on cessation of construction activity within the wind farm at certain times of the year, and that the animals can move to neighbouring areas without consequence, then the use of jacket foundation, even if this extends the construction time associated with each foundation, may still result in a lower impact than a large monopole foundation. This generalisation could be dependent on the species in question and does assume that the small diameter pin-piles generally used for jacket type foundations require substantially less energy to install than a large diameter monopole foundation capable of bearing the same load.

Reduction of impact hammer energy

248. The minimum hammer energy required will be dictated by the energy needed to overcome the resistive forces when penetrating the pile into the seabed. The impact energy used for each strike would be expected to have an influence on the sound energy in the propagated pulse if all other conditions remained the same. For measurements on the Dutch Q7 wind farm (de Jong and Ainslie 2008) it was inferred, using simple approximations, that just under 1% of the total hammer energy was converted into acoustic energy. It is sensible to assume that the majority of energy is spent overcoming frictional resistance around the surface of the pile and displacing and compressing seabed material around and below the pile. De Jong and Ainslie (2008) also postulate using the same approach that even if all the hammer energy (800kJ) were converted to sound energy in the water, the maximum SEL source level expected would be 230dB 1 re $\mu Pa^2 \cdot s \cdot m^2$. The corresponding maximum SEL source level associated with a 3,000kJ hammer would be around 5.7dB higher (i.e. around 3.75 times higher) than that for an 800kJ hammer energy with a hammer blow energy of 2,300kJ being around 4.6dB higher than that for an 800kJ hammer blow energy. This should be treated as an absolute theoretical maximum, which would not be possible to achieve in practice. The amount of the total energy converted into acoustic energy will depend on the frictional resistance during penetration and coupling of the acoustic energy into the

water. Based on measurement data, the amount of hammer impact energy converted into acoustic energy would be much less than 1% (Robinson *et al.* 2009b). Also, measurement data from the soft-start sequence of a 4.74m monopole show that the energy in the acoustic pulse correlates closely with the increasing hammer energy during the soft-start (Robinson *et al.* 2009b). Similar results were also shown in the underwater noise monitoring reports for the Greater Gabbard Offshore Wind Farm (Theobald *et al.* 2010), showing the entire piling sequence with an increase in received SEL during the soft-start. The implication of this is that a lower hammer energy achieving the required penetration depth would result in a reduced noise level and a smaller zone of impact. The potential for harbour porpoise abundance reduction in an area around a piling activity for 24 to 72 hours (Brandt *et al.* 2011) indicates that the small increase in time associated with a reduction in hammer energy would therefore have minimal effect on the period over which the abundance may be reduced, but would reduce the range over which a reduction in abundance might be expected.

249. The use of a soft-start involves a gradual ramping up of the hammer strike energy and is considered as a mitigation measure because it may enable animals to move away from the sound source before it reaches the maximum noise levels. The JNCC (JNCC 2010a) has recommended a minimum soft-start duration of 20 minutes, to provide adequate time for marine mammals to leave the area. The efficacy of this approach finds some support in previous studies. For example, Tougaard *et al.* (2011) reported a clear avoidance reaction of harbour porpoise to simulated pile driving noise and an animal farther away from the source will experience lower sound exposure levels, and a lower likelihood of suffering hearing damage, than one closer to the sound source.

250. As it is the SEL dose which is most likely to be the mechanism for auditory injury during marine piling operations, the soft-start is particularly important in providing the animal an opportunity to flee the area before becoming overexposed to the noise and suffering auditory damage or permanent threshold shift (PTS). In general, shorter piling times and overall reduced hammer energy will reduce the overall SEL noise dose, but if it is assumed that the animal swims away at the onset of piling and it is then exposed to a piling sequence of typical length, then it is the initial hammer strikes which are most critical, as the contribution to the SEL dose is largest at shorter ranges and contributes less to the total dose further away (Theobald *et al.* 2009; Lepper *et al.* 2011). In this case, once full energy piling commences the animal is exposed to lower noise levels due to its greater distance from the pile assuming it swims away from the source.

Use of an impact cushion

251. An impact cushion can be used between the hammer and the pile to change the stiffness of the contact, used to prevent pile fracture and pile head damage. The use of such cushions can also have an effect on the impact noise radiated into the water from the pile. A numerical simulation by Wood and Humphrey (2012) showed that a more compliant (i.e. softer) cushion can reduce the peak force transmitted through the pile and, as such, reduce the acoustic pressure peak and increase the pulse duration.

252. Work by Nehls *et al.* (2007) also considered the possibility of extending the hammer impact time on the pile through the use of a ‘cushion’ between the hammer and the pile. This was experimented with on the FINO 2 wind farm in Germany (Elmer 2007) but was not particularly successful, both in terms of implementation and in terms of noise reduction. The FINO 2 experiment, which used steel cable as a cushion, determined that effective and durable cushions are not feasible in practice. However, a similar

increase in impact time could be achieved through the use of a larger hammer than is necessary, operating at a lower energy. Because of the larger mass used in a larger hammer, the impact velocity is lower compared with a small hammer operating at an equivalent impact which has a lower mass. This could result in a reduction of the peak pressure level but would not reduce the SEL or acoustic energy in the pulse. Reducing the impact time of the hammer results in a loss of force and might in practice compromise the success of pile driving. In reality, the noise reduction would likely be small.

Vibration pile driving

253. Vibration pile driving involves the use of a pile driver vibrating at a frequency of 20Hz to 40Hz, inducing vertical vibrations on the pile, driving it into the seafloor. A comparison of vibration and impact pile driving at the FINO 2 wind farm indicated a difference in noise levels of several tens of dB at frequencies between 200Hz and 400Hz, with impact piling resulting in the highest noise levels (Matuschek and Betke 2009; Betke and Matuschek 2010). Vibration pile driving results in lower level continuous type noise and not the impulsive type noise with high peak levels associated with impact pile driving. However, construction at the FINO 2 offshore wind farm could not achieve full penetration depth with vibration piling alone.

254. Vibration pile driving has also been used in the USA for pier and pipeline constructions using relatively small piles (Reyff 2007). Depending on the conditions and location, *etc*., the level of underwater noise generated by the vibration pile driving varied substantially, although the noise level was substantially lower than impact pile driving, and, in most cases, was subject to considerable penetration resistance. This was mostly overcome with the use of a larger vibration hammer or with the subsequent use of impact piling.

255. The limited penetration depth generally achievable does limit its application. Nonetheless, the use of vibration piling can reduce noise levels significantly and even partial use may reduce the overall exposure to noise (i.e. the SEL dose). Reportedly, the additional use of a vibratory hammer for the initial pile stepping of pre-installed piles may be advantageous, ensuring pile verticality, removing the need for levelling equipment and consequently reducing installation time (Acteon 2013).

Drilling/Screw-piles

256. Drilling is sometimes applied in addition to impact piling and could be viewed as a noise reduction strategy, as it may account for some of the penetration that would otherwise be achieved by impact piling that radiates much higher noise levels into the surrounding water column. The drilling of pin-piles during the installation of a tidal turbine also resulted in noise levels and impact ranges which were substantially less than those associated with impact pile driving (Nedwell and Brooker 2008). A recent review has reported levels as low as 117dB 1 re $\mu Pa^2 \cdot s$ SEL for the drilling of monopole foundations (Verfuß 2012).

257. Screw-piles have also been considered in a review by Saleem (2011), which are likely to result in noise levels comparable to drilling methods. Screw-piles are commonly used for building foundations and it is not clear if they would be suitable for the ground conditions and load requirements for an offshore wind turbine.

ii) Acoustic barrier methods – reduction of radiated noise

258. Acoustic barriers can be deployed around the pile to reduce the level of noise which radiates into the surrounding water. The actual barrier can be implemented in a number of ways with varying degrees of noise reduction efficacy. These methods can include bubble curtains, coffer dams, sleeve type methods and mitigation screens. Barrier methods are perhaps the most difficult mitigation methods to implement and at present are likely to be too costly and logistically challenging to implement in an effective manner. However, significant research and development effort is being focussed on this area and it may be that a number of viable solutions become available in the future.

Bubble curtain

259. A bubble curtain is a layer of air bubbles produced in the water column surrounding the pile, which acts to reduce the radiated noise level. The air bubbles are typically released from a perforated tube as compressed air is forced through it so that the bubbles ascend to the surface. They can include multiple such tubes around the sound source to provide greater coverage. The use of air bubbles can be an effective way of attenuating sound in water with two mechanisms at work: i) bubble resonance effects/scattering; and ii) acoustic impedance mismatching. These effects are complex functions of frequency as they depend on the size of the bubble in the first case and on the size and number of the bubbles in the second case. In general, the acoustic wavelengths dominant during marine impact piling are several orders of magnitude larger than the bubble diameters achievable using the stated method of generating a bubble curtain. This limits the effectiveness of a bubble curtain for use as an acoustic barrier and means that it will generally act to provide a bulk acoustic impedance change. The effects of scattering and bubble resonance will only be effective at higher frequencies, which contribute much less to the overall noise levels generated during marine impact piling.

260. Several bubble curtain studies have been undertaken (e.g. Wursig *et al.* 2000; Reyff 2007; Lucke *et al.* 2011), including acoustic efficacy measurements at the FINO 3 wind farm site and Alpha Ventus in Germany (Matuschek and Betke 2009; Grießmann 2009; Betke and Matuschek 2010) and many of these are summarised in a 2007 COWRIE (Collaborative Offshore Windfarm Research Into the Environment) report by Nehls *et al.* (2007) that assessed engineering solutions for mitigating underwater construction noise. A recent programme of work in Germany, funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), employed both small and large diameter bubble curtains and reported consistent (current independent) acoustic energy reductions of up to about 12dB (Verfuß 2012).

261. In general, the reported noise reduction levels for bubble curtains range from negligible (between zero and 2dB) up to 35dB, with the largest reductions observed at higher frequencies. However, reductions of 5dB to over 15dB have been observed below 400Hz where the acoustic energy from piling is most prevalent (Matuschek and Betke 2009, Verfuß 2012). This reduction depended heavily on the bearing of the measurement position relative to the source, with some angles showing negligible or no reduction due to bubble drift (Matuschek and Betke 2009; Betke and Matuschek 2010; Verfuß 2012).

262. Thus, an important operational consideration when utilizing bubble curtains includes complete enclosure of the sound emission structure. However, this is frequently impracticable, as a total circumference of the bubble curtain would often have to exceed several hundred metres (Nehls *et al.* 2007). Confined bubble curtains have been used in

combination with a pile sleeve or a surrounding jacket by releasing air between the pile and the sleeve with varying success. A study for the State of California Department of Transportation (Caltrans) Pile Driving Installation Project (PDIP), summarised in Spence and Dreyer (2012), has shown that a confined air curtain has the potential to reduce sound levels by 10dB or more even at frequencies around 100Hz (third-octave band RMS values), however, this was only achieved when the barrier was seated on the sea floor. Gaps at the bottom of the barrier caused by the roughness of the sea floor lead to reduced effectiveness of this approach (about 5dB reduction or less at frequencies less than 1000Hz). Reyff (2007) reported a reduction of the broadband SEL of around 20dB, although this was only obtained for an experimental set up and was not implemented for the pipeline construction project due to excessive cost.

263. Bubble curtains, if implemented effectively, can provide a substantial reduction of the noise levels radiated into the water and can, therefore, reduce the potential for impact resulting from pile driving. However, the engineering solutions to achieve this in practice can be extremely challenging and many of the experiments undertaken to date have been implemented at significant expense, with limited success, on a limited number of test piles only. It is envisaged that in the North Sea, the water depth would compromise the effectiveness of a non-enclosed bubble curtain.

264. A potential solution to the tidal/current drift of the bubble curtain is to enclose the bubble curtain. Such a device is being developed by Bernhard Weyres (http://weyres-offshore.de/) and was tested as part of the ESRa Project under the name ‘little bubble curtain’ (LBC). The level of energy (SEL) reduction during the ESRa test was reported to be around 4dB for the broadband SEL (although the ESRa report also states that in practice these would be higher due to boundary conditions. It is understood that this refers to the pile already being at refusal during the ESRa tests), but further inspection shows that it achieves about 5dB or more energy reduction between 125 and 500Hz.

265. The current availability or current state of development of the LBC is unknown. It should be noted that the water depth at the ESRa site was only around 8.5m and so the maximum length of device tested was of this order. However, the LBC does appear to be one of the lighter of the commercial solutions tested during the ESRa Project and its weight should scale favourably with water depth due to the weight being dominated by the lower and upper rings. The device is also telescopic meaning it will not take up so much deck space as rigid solutions, but it will require a compressor to generate the required air bubbles.

Encapsulated bubble or hydro sound damper

266. The use of air filled cavities can be considered as an alternative to the air injection systems described above. In this case, the resonant scattering properties are exploited where the resonant scattering frequency is inversely proportional to the diameter of the bubble. Research at the University of Texas (Lee *et al.* 2011) has been considering the use of encapsulated bubbles controlled in size to offer maximum scattering at the frequencies associated with piling. These can be distributed as a net around the pile and have demonstrated the potential in controlled experiments to reduce the transmission of sound by over 20dB at 200Hz. More recently, Spence and Dreyer (2012) described the attenuation efficiency test of hard bubbles (about 4cm, 7cm and 40cm in diameter, each bubble size forming its own layer) attached to a strong fabric blanket and concluded that the approach has potential for sound attenuation exceeding 10dB at frequencies above 100Hz. Removal of smaller size bubbles reduced the effectiveness, mainly at 500Hz and

above. At lower frequencies, resonant bubble properties and the barrier size (about 7x11m in water depths of 100m) were believed to have limited the effectiveness. This is similar in principle to the Hydro Sounds Dampers (HSD) developed in Germany by Braunschweig University /Dr. Elmer and described by Elmer (2010), Elmer *et al.* (2012) and Koschinski and Ludemann (2011).

267. An important consideration when using encapsulated air for noise mitigation is the effect of hydrostatic pressure on the bubble case, which may lead to stiffer bubble-encapsulating materials (and hence poorer acoustic impedance matching) or burst bubble cases constructed from softer materials. Elmer *et al.* (2012) achieved the required bubble size by using gas-filled thin walled balloons, used in combination with PE-foam elements. These were tuned to a resonant scattering frequency of 120Hz to achieve maximum noise reduction at frequencies where piling contains most energy. Offshore trials have demonstrated underwater acoustic energy reductions of up to 23dB, between 100 and 600Hz (Elmer *et al.* 2012). This type of mitigation solution does not require compressed air and is considered to be less costly than implementing a bubble curtain (Elmer 2010). They are also potentially more reliable than unconfined bubble curtains under variable tidal flow conditions.

268. The HSD solution was tested as part of the ESRa Project and has additionally been tested at the London Array offshore wind farm. During the ESRa Project an energy reduction of about 4.0 to 5.5dB (broadband SEL) was reported (caveats apply to all ESRa – see the LBC description). The dimensions of the HSD ‘bubbles’ have been designed to provide effective reduction over the frequency range where most acoustic energy is propagated from pile driving and results in an energy reduction of 5dB and higher between 100 and 500Hz. At London Array, the device was deployed in relatively deeper water, with an effective depth of around 28m. The reported reduction for London Array was generally better than that during the ESRa Project which may be due to the pile at London Array actually undergoing penetration compared with the pile used for the ESRa Project which had previous been piled to refusal. The reduction between 125 and 500Hz was generally better than 5dB and better than 10dB between around 200Hz and 500Hz. The additional time associated with the use of the HSD was reported to be 245 minutes for each monopole. The device also had a reported weight of only 17 tonnes.

Coffer dam

269. Coffer dams potentially offer the best noise reduction into the water from marine impact piling and have been used for bridge building projects in the USA (Reyff 2007). They have the potential to substantially reduce the waterborne component of the noise. However, the time taken to install them means they entail excessive cost and they have generally not been deemed a practical solution for offshore wind farm construction. A simplified method was tested during the Benicia-Martinez Bridge construction, where a metal tube/jacket with a diameter several meters larger than the diameter of the pile was dropped over the pile foundation. The water between the jacket and the pile was then filled with bubbles using a compressor to create a coffer dam. This provided a substantial reduction of the radiated sound, with an approximate 20dB decrease for the broadband/pulse SEL. However, the method was too costly to implement for the construction of the bridge.

270. More recently (end of 2011) tests with cofferdams were carried out in Denmark at the request of the German Federal Marine and Hydrographic Agency (BSH), which

concluded them successful. Reportedly, the approach will be implemented at two offshore projects in the German North Sea (Wind power monthly 2012 and Verfuß 2012). Another mitigation solution, 'Lo-Noise', advertised by OSK Shiptech A/S also appears to be a coffer dam and further claims significant reductions in noise level (http://www.osk-shiptech.com/Default.aspx?ID=6#3558). However, no other information is available and so the performance of the device cannot be confirmed neither can its practicality for deployment.

271. Whilst the potential noise reduction associated with coffer dams is substantial, there are potentially more practical methods which might offer similar reduction in the future, such as the encapsulated bubble distribution described above or some of the sleeve solutions discussed below.

Pile sleeve

272. A pile sleeve refers to a barrier method that involves coating or wrapping the pile in a material that has the potential to reduce the transmission of sound into the water. These materials are typically air filled foams, with an acoustic impedance different to that of water. The impedance difference reduces the sound transmission between the pile and the water, leading to reduced noise levels. As with the bubble curtain, the efficacy of this approach depends on whether a complete enclosure of the sound source can be achieved (Nehls *et al.* 2007). The transmission reduction realised during testing in Germany and reviewed by Nehls *et al.* (2007), is primarily effective at frequencies above 1 kHz, which are less crucial to reducing the radiated noise from piling that has most energy below 400Hz. At frequencies of 400Hz and below, where most of the acoustic energy is radiated during piling, the transmission reduction was relatively small, typically less than 5dB. At these low frequencies, the long wavelength of the sound (approximately 6.5m at 200Hz in water) reduces the efficacy of a relatively thin barrier material, even if there is a substantial impedance difference. The difficulties associated with the installation and removal of the sleeve also limit its practicality and make it costly to implement (Matuschek and Betke 2009).

273. More recently, a double walled sound shield filled with a sound absorbing material was tested off Seattle, USA, using a vertical hydrophone array. Reductions of 10 to 15dB in the peak pressure and around 5dB in the SEL or acoustic energy were reported (Reinhall and Dahl 2012). The study did not explore frequency dependant losses, as the analysis was done in the time domain. However, the acoustic energy measured at the hydrophones with and without the shield in place suggests that the shield, whilst effective in dampening the noise radiated directly from the pile, does not block any later arrivals that originate from the seabed.

274. Another variant of the pile sleeve is the use of vertical air filled fire hoses surrounding the pile. This air layer causes a change in acoustic impedance which has the potential to reduce sound transmission between the pile and water. This potentially provides greater capacity for reducing the radiated sound but, so far, only laboratory scale results have been reported and no data are available for frequencies below 800Hz. Above 800Hz, the noise level reduction was between 10dB and 30dB (Koschinski and Lüdemann, 2011). The noise level reduction below 800Hz would presumably be less effective as the acoustic wavelength becomes larger compared with the diameter of the fire hoses.

Commercial pile sleeve solutions

275. A commercial implementation of the fire hose system was deployed during the ESRa Project by Menck. This system comprises a number of vertically aligned fire hoses, filled with air, which completely surround the pile. As with a bubble curtain, this system requires a compressor to inflate the fire hoses once the system is deployed. The broadband SEL reduction reported in the ESRa Project report was between 4.4 and 5.0dB, with a 5.0dB or better reduction being achieved above 500Hz. The highest reduction was achieved at 2,000Hz and is assumed that this was due to the diameter of the fire hoses. The fire hose diameter would need to be increased to achieve an improved reduction below 500Hz.

276. Menck also advertise the ‘Noise Reduction Skirt on their website. The noise reduction numbers stated by the manufacturer state the airborne noise reduction so its effectiveness in water cannot be determined. The Noise Reduction Skirt is a concertina construction which can extend to a depth of 30m and can fit piles with a diameter of 5m. The material appears to be a type of sound absorber which would perhaps be more effective at reduction of sound in air. The system has been under evaluation on the BARD Offshore 1 Project in the North Sea (Mertschat, L. Personal email, 19 June 2012).

277. Another commercial mitigation solution is the IHC Merwede Noise Mitigation System (NMS). This is a twin layer (with an air cavity) metal tubular construction which can be lowered in to the water around the pile. The design is such that a confined bubble curtain can be implemented, if desired, between the pile and sleeve. Measurements assessing the performance of the IHC noise mitigation solution were carried out by TNO, Netherlands. Initial measurements were undertaken on a small test pile in Kinderdijk harbour in relatively shallow water and demonstrated reductions typically higher than 20dB above 160Hz. The level of reduction was much less (less than 10dB) below 160Hz and negligible below 100Hz. Later experiments were conducted on a pile in Germany and the Netherlands, both in deeper water (about 25 m) (Jansen *et al*. 2012). The broadband SEL reduction was observed to be between 8 and 11dB, showed frequency dependency and had the smallest effect at lower frequencies, where most piling energy occurs. The effect of bubbles in conjunction with the sleeve was also tested and shown to help dampen noise at higher frequencies, but had little or no contribution to noise reduction at frequencies <160Hz. The IHC NMS was planned for use at the Riffgat wind farm in Germany (IHC Merwede April 2012 brochure), with significant noise reduction predicted, although the results of this test are not currently available.

278. Results of the IHC NMS when tested as part of the ESRa Project were comparable, between 100 and 500Hz, with the other mitigation systems tested as part of the ESRa Project. The IHC NMS was also designed to be used with an enclosed bubble curtain but this, and the ESRa Project results indicate, only improves its reduction performance above around 500Hz, which whilst useful, is arguably less important for marine impact pile driving. When used without the bubble curtain, the IHC NMS, is a very simple solution which has the potential for easy installation and removal. However, it was one of the heavier solutions tested during the ESRa Project and this weight will be significant for larger diameter piles or deeper water. IHC’s current brochure (2012-11 NMS&TiNS IHC HH version L.pdf) indicates that as of 2012 a commercial device was

available suitable for use with a 6.5m monopole foundation in water depths of less than 30 m. This would be expected to have a weight in excess of 360 tonnes.

279. At present, the IHC NMS does not appear to be compatible with jacket templates. However, IHC have confirmed that they are currently developing a system for use with pre-install jacket piles to speed up installation time (Tim van Erkel, Personal email, 09 January 2013).

280. Bernhard Weyres (http://weyres-offshore.de/), the company that developed the LBC solution tested for ESRa, also offer a commercial solution. The system comprises two steel half-shells and industrial sound dampers, with two internal bubble curtains. This solution was also tested as part of the ESRa Project and showed reduction performance comparable to that of the IHC NMS (with internal bubble curtain). It was the heaviest solution tested during the ESRa Project and at present it is capable of 30m water depth for up to 6.5m diameter piles.

iii) Use of mitigation zones

281. A marine mammal exclusion zone or mitigation zone can be employed during impact piling to reduce the risk of injury to marine fauna, particularly marine mammals, the implementation of which is outlined in a JNCC guidance document (JNCC 2010a). The implementation of a mitigation zone consists of a survey programme to check for absence of marine mammals in the zone where injuries may be expected and has in the past been considered best practice for piling operations (JNCC 2010a). In UK waters, this has generally consisted of a 30 minute pre-piling survey within no less than a 500m radius from the sound source. This mitigation zone can be realised using either passive techniques, relying on visual and acoustic observations, or actively, using acoustic mitigation devices (AMDs) to repel marine mammals from the area prior to piling.

Observation/passive mitigation measures (Marine mammal monitoring and passive acoustic monitoring)

282. The passive methods for implementing a mitigation zone currently rely on two main methods: a visual watch for marine mammals conducted using marine mammal observers; and passive acoustic monitoring (PAM) which includes the use of hydrophones to detect marine mammal vocalisations, carried out by a PAM operative. The primary role of marine mammal observers and PAM operatives is to detect marine mammals and to potentially recommend a delay in the commencement of piling activity if marine mammals are detected within the mitigation zone during the pre-piling survey. Marine mammal observers/PAM operatives often then continue surveying the area to inform of any marine mammal presence during the soft-start and when piling at full energy. In the UK, if a break in piling activity exceeds 10 minutes, the pre-piling search and soft-start should be repeated (JNCC 2010a), thus continuous monitoring of the mitigation zone can reduce the pre-piling watch duration if no marine mammals have been sighted prior to the break in piling, enabling an imminent commencement of the soft-start. The response to marine mammal presence during a piling operation will depend on the agreement with the relevant agency or regulator, but JNCC (2010a) recommend that if a marine mammal enters the mitigation zone during the soft-start, whenever possible, the piling operation should cease or at least hammer energy should not increase. There is no requirement to cease piling or reduce energy if the marine mammal is detected within the mitigation zone when piling at full energy. It is usually assumed that if a marine mammal enters the area when full energy piling is taking place it is because it has not been deterred by piling, possibly in response to a stronger

biological factor (e.g. foraging , JNCC 2010a). There is also a risk that the animal has already suffered a temporary threshold shift (TTS) in hearing and is not responding in the same way to the noise. Continued exposure could then result in the onset of PTS or auditory injury.

283. Vessel deployed PAM systems can sometimes have limited effectiveness, e.g be limited by propeller/engine noise and the location of the PAM vessel at a given time) and static, autonomous PAM systems may be considered as an alternative, being less limiting in this way.

284. The JNCC (JNCC 2010a) also provide guidance on the use of marine mammal observers for pile driving during the hours of darkness or during periods of poor visibility. Solutions to this could include an increased PAM effectiveness and/or the use of AMDs, which are discussed further below.

285. The use of a mitigation zone implemented using marine mammal observers can also apply to other protected fauna, such as turtles and basking sharks *Cetorhinus maximus*, however, it does not address mitigating pile driving impact on fish. It should, therefore, be considered alongside other noise reduction measures.

286. Based on the marine mammal injury criteria published by the Marine Mammal Criteria Group of the NMFS (National Marine Fisheries Service part of NOAA) (Southall *et al.* 2007), a 500m mitigation zone should be sufficient for most cetaceans. However, recent published work by Lucke *et al.* (2009) indicates that a more precautionary approach may be required for harbour porpoise, although generally, the lower hammer energies during a soft-start would usually reduce the range of risk to within the a 500m mitigation zone. It should also be noted that an animal travelling at the surface will generally be exposed to lower noise levels compared to the mid-water levels at distances exceeding only a few hundred metres from the pile. This would result in a reduced exposure of any animal and the impact area will be smaller.

287. It is also possible that a 500m mitigation zone is not necessarily sufficient for pinnipeds in water based on the injury criteria outlined by Southall *et al.* (2007) when considering their SEL noise dose. However, this does not account for the time that they would spend above the surface which would substantially reduce their SEL noise dose, whilst allowing their hearing sensitivity to recover and allow them to safely swim closer to the pile than noise dose predictions suggest.

288. Whilst an exclusion zone for explosives mitigation in the UK is 1,000m (JNCC 2010b), it is not clear that this could be achieved using marine mammal observers due to the reduced chances of observations with range, particularly in reduced visibility or higher sea-states.

Active acoustic mitigation (Acoustic mitigation devices)

289. The principle behind the use of AMDs is similar to a soft-start. They are intended to produce a warning sound, allowing marine mammals to move further away from the noise source, thus reducing the likelihood of exposing the animal to sounds that may cause injury. AMDs can be deployed before piling operations commence and guidance by JNCC suggests that should be used in conjunction with visual observations and/or passive acoustic monitoring (JNCC 2010a). If being used in conjunction with passive acoustic monitoring, then any potential impact on the effectiveness of passive acoustic

monitoring survey should be evaluated. AMDs include ADDs (Acoustic Deterrent Devices) and AHDs (Acoustic Harassment Devices), also known as Pingers and Seal Scarers, respectively. Pingers were originally developed to prevent cetacean bycatch, while Seal Scarers were initially intended to deter seals from fish farms. The effectiveness of a number of commercial devices for deterring harbour porpoise and harbour seal *Phoca vitulina* have been reviewed by Kastelein *et al.* (2010), indicating that they can be effective over relatively large distances. A recent study by Hoeschle *et al.* (2011) reported a reduction in visual and acoustic detections of harbour porpoise in an area exceeding 1km around an AMD, indicating a clear avoidance reaction. Similarly, Brandt *et al.* (2012) reported a significant deterring effect of a Seal Scarer on wild harbour porpoise at two distinct locations. Both studies showed a significant detection reduction in harbour porpoise for areas close to the source (<500 m), corresponding to an estimated 119dB re 1µPa (RMS) received level or higher. However, in both instances some animals were detected at ranges closer to the source where sound levels exceeded the deterring level.

290. It could be argued that AMDs have the potential to increase the total sound energy to which an animal is exposed, however, they can also be assumed to provide a warning, allowing the animal to move away to a safe distance before piling commences. As such, the use of AMDs has the potential to reduce the overall exposure of a marine mammal to piling noise and thus reduce the risk of hearing damage, assuming the animal does in fact flee the sound. When deploying AMDs the risk of habituation should be considered along with the risk that the devices themselves pose to the animal. To avoid habituation (decreased responsiveness), the use of such devices should be kept to a minimum and used for a short period only prior to piling (Gordon *et al.* 2007).

291. While pinnipeds have been reported to habituate and be attracted to AMDs (e.g. Reeves *et al.* 1996; Shapiro *et al.* 2009) this was likely in response to food rewards, as most Seal Scarers are used in the context of fish farms. Most studies of harbour porpoise response to Seal Scarers show that AMDs have a clear deterring effect (e.g. Hoeschle *et al.* 2011; Brandt *et al.* 2012; 2013) and could therefore be an effective way to deter this species from piling sites, reducing the potential for injury due to noise exposure.