Norfolk Boreas Offshore Wind Farm

Appendix 5.4

Underwater Noise Assessment

Environmental Statement

Volume 3

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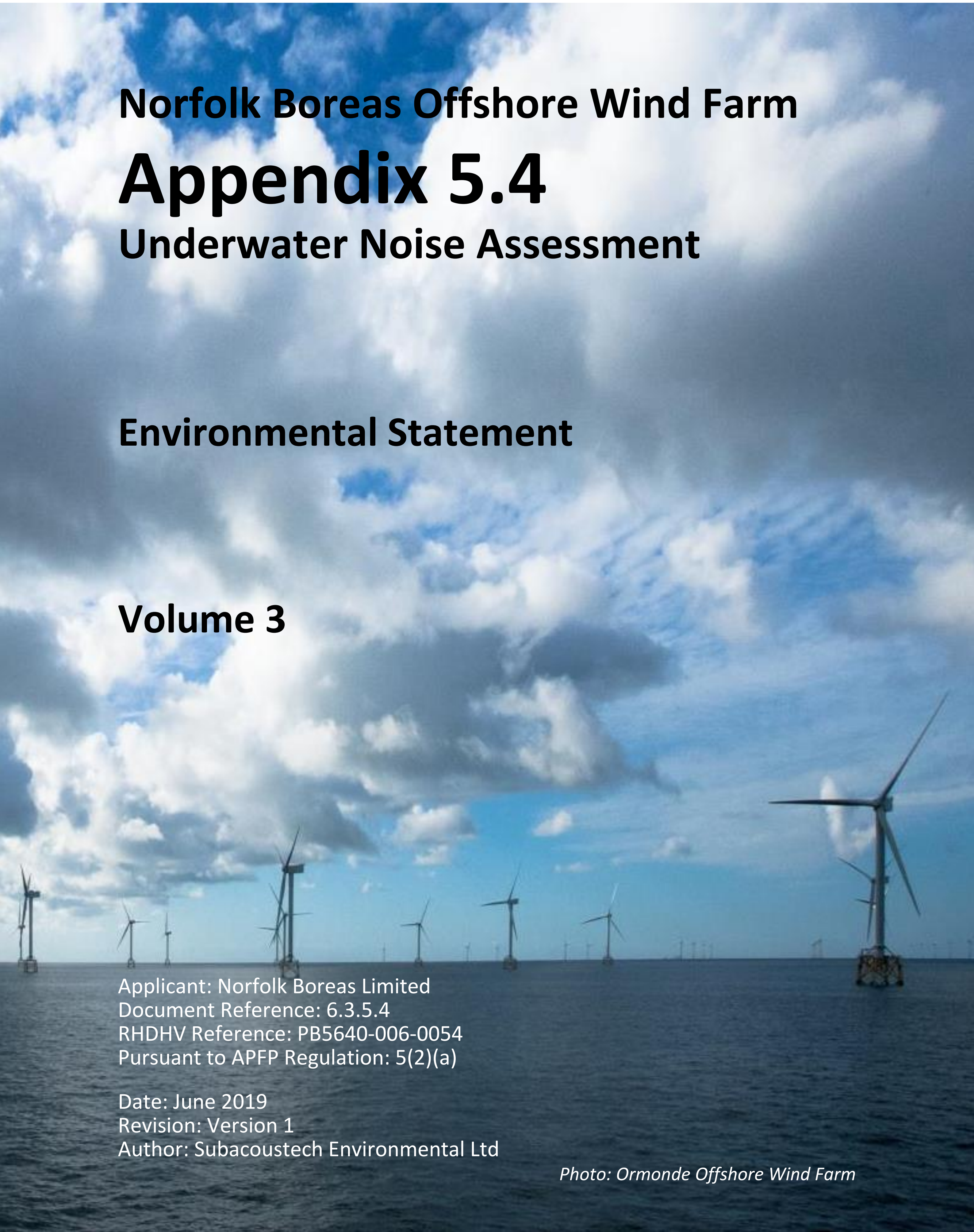

Photo: Ormonde Offshore Wind Farm

1. This appendix comprises:

- The main underwater noise report for the Norfolk Boreas site; and
- Annex 1 to the main report which contains the results of additional modelling which were carried out follow consultation on the main report.

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Norfolk Boreas Offshore Wind Farm: Underwater noise assessment

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List of contents

1 Introduction

This report has been prepared by Subacoustech Environmental Ltd for Royal HaskoningDHV and Norfolk Boreas Limited and presents the underwater noise modelling results for impact piling at the proposed Norfolk Boreas Offshore Wind Farm development.

1.1 Norfolk Boreas Offshore Wind Farm

Norfolk Boreas is a proposed wind farm in development in the North Sea, located approximately 72 km off the coast of Norfolk at the nearest point to shore. The location is shown in Figure 1-1. The proposed project would have a potential capacity of up to 1800 MW.

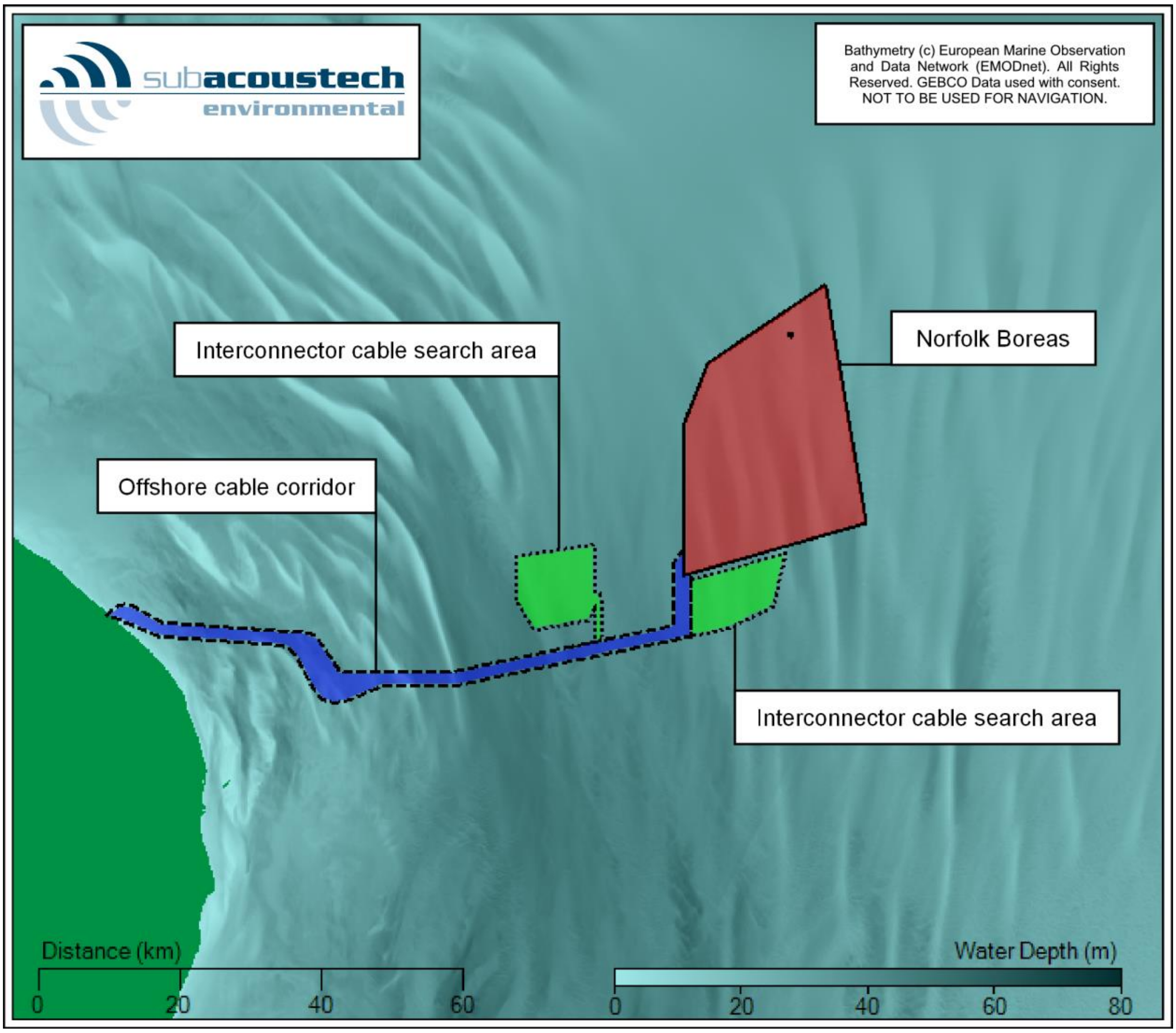

Figure 1-1 Map showing the boundaries of the Norfolk Boreas Offshore Wind Farm Project

1.2 Noise assessment

This report focusses on pile driving activities during construction at the Norfolk Boreas site, and also considers other noise sources that are likely to be present during the development. Underwater noise modelling has been carried out in two parts. Impact piling has been considered using Subacoustech's INSPIRE subsea noise propagation and prediction software, which including the effect of bathymetry and frequency content of noise when calculating noise levels. Other noise sources have been considered using a high-level, simple modelling approach.

1.2.1 Impact piling

As part of a series of construction options, impact piling has been proposed as a method for installing foundation piles for wind turbines into the seabed. Impact piling could be used to install either monopile or pin pile (jacket) foundation options.

The impact piling technique involves a large weight or "ram" being dropped or driven onto the top of the pile, forcing it into the seabed. Usually, double-acting hammers are used in which a downward force on the ram is applied, exerting a larger force than would be the case if it were only dropped under the action of gravity. Impact piling has been established as a source of high level underwater noise (Würsig *et al.*, 2000; Caltrans, 2001; Nedwell *et al.*, 2003b and 2007; Parvin *et al.*, 2006; and Thomsen *et al.*, 2006).

Noise is created in air by the hammer as a direct result of the impact of the hammer with the pile and some of this airborne noise is transmitted into the water. Of more significance to the underwater noise is the direct radiation of noise from the pile into the water because of the compressional, flexural or other complex structural waves that travel down the pile following the impact of the hammer on the top. Structural pressure waves in the submerged section of the pile transmit sound efficiently into the surrounding water. These waterborne pressure waves will radiate outwards, usually providing the greatest contribution to the underwater noise.

1.2.2 Other source of noise

Although impact piling is expected to be the greatest noise source of noise during construction (Bailey *et al.* 2014, Bergström *et al.* 2014), several other noise sources will also be present. These include, dredging, drilling, cable laying, rock placement, trenching, vessel noise and noise from operational wind turbines. These noise sources have been considered using a simple modelling approach due to the relative level of noise from these activities being much lower than impact piling.

1.3 Scope of work

This report presents a detailed assessment of the potential underwater noise from impact piling at Norfolk Boreas and covers the following:

- A review of information on the units for measuring and assessing underwater noise and a review of underwater noise metrics and criteria that have been used to assess possible environmental effects in marine receptors (Section 2).
- A brief discussion of baseline ambient noise (Section 3).
- Discussion of the approach, input parameters and assumptions for the impact piling noise modelling undertaken (Section 4).
- Presentation of detailed subsea noise modelling using unweighted metrics (Section 5.1) and interpretation of the subsea noise modelling results with regards to injury and behavioural effects in marine mammals and fish using various noise metrics and criteria (Section 5.2).
- Summary of the predicted noise levels from the simple modelling approach for dredging, drilling, cable laying, rock placement, trenching, vessel noise and noise from operational wind turbines (Section 6).
- Summary and conclusions (Section 7).

2 Measurement of noise

2.1 Underwater noise

Sound travels much faster in water (approximately 1,500 ms^{-1}) than in air (340 ms^{-1}). Since water is a relatively incompressible, dense medium, the pressures associated with underwater sound tend to be much higher than in air. As an example, background noise levels in the sea of 130 dB re 1 µPa for UK coastal waters are not uncommon (Nedwell *et al.*, 2003a and 2007). It should be noted that stated underwater noise levels should not be confused with the noise levels in air, which use a different scale.

2.1.1 Units of measurement

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

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

$$Level = 10 \times \log_{10}\left(\frac{Q}{Q_{ref}}\right)$$

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

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

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

$$Sound\ Pressure\ Level = 20 \times \log_{10}\left(\frac{P_{RMS}}{P_{ref}}\right)$$

For underwater sound, typically a unit of one micropascal (1 µPa) is used as the reference unit; a Pascal is equal to the pressure exerted by one Newton over one square metre; one micropascal equals one millionth of this.

Unless otherwise defined, all noise levels in this report are referenced to 1 µPa.

2.1.2 Sound pressure level (SPL)

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

Where SPL is used to characterise transient pressure waves such as that from seismic airguns, underwater blasting or impact piling, it is critical that the period over which the RMS level is calculated is quoted. For instance, in the case of a pile strike lasting, say, a tenth of a second, the mean taken over a tenth of a second will be ten times higher than the mean spread over one second. Often, transient sounds such as these are quantified using "peak" SPLs.

2.1.3 Peak sound pressure level (SPL_{peak})

Peak SPLs are often used to characterise sound transients from impulsive sources, such as percussive impact piling and seismic airgun sources. A peak SPL is calculated using the maximum variation of the pressure from positive to zero within the wave. This represents the maximum change in positive pressure (differential pressure from positive to zero) as the transient pressure wave propagates.

A further variation of this is the peak-to-peak SPL where the maximum variation of the pressure from positive to negative within the wave is considered. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak level will be twice the peak level, or 6 dB higher (see 2.1.1).

2.1.4 Sound exposure level (SEL)

When assessing the noise from transient sources such as blast waves, impact piling or seismic airgun noise, the issue of the duration of the pressure wave is often addressed by measuring the total acoustic energy (energy flux density) of the wave. This form of analysis was used by Bebb and Wright (1953, 1954a, 1954b and 1955) and later by Rawlins (1987) to explain the apparent discrepancies in the biological effect of short and long-range blast waves on human divers. More recently, this form of analysis has been used to develop criteria for assessing the injury range from fish for various noise sources (Popper *et al.*, 2014).

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

$$SE = \int_0^T p^2(t)dt$$

where p is the acoustic pressure in Pascals, T is the duration of the sound in seconds, and t is the time in seconds. The SE is a measure of acoustic energy and has units of Pascal squared seconds (Pa^2s).

To express the SE on a logarithmic scale by means of a dB, it is compared with a reference acoustic energy level (${p^2}_{ref}$) and a reference time (T_{ref}). The SEL is then defined by:

$$SEL = 10 \times \log_{10}\left(\frac{\int_0^T p^2(t)dt}{{P^2}_{ref}T_{ref}}\right)$$

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

$$SEL = SPL + 10 \times \log_{10} T$$

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

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

Weighted metrics for marine mammals have been proposed by the National Marine Fisheries Service (NMFS) 2016 and Southall *et al.,* 2007. These assign a frequency response to groups of marine mammals and are discussed in detail in the following section.

2.2 Analysis of environmental effects

2.2.1 Background

Over the past 20 years it has become increasingly evident that noise from human activities in and around underwater environments can have an impact on the marine species in the area. The extent to which intense underwater sound might cause an adverse impact in a species is dependent upon the incident sound level, sound frequency, duration of exposure and/or repetition rate of an impulsive sound (see for example Hastings and Popper, 2005). As a result, scientific interest in the hearing abilities of aquatic species has increased. Studies are primarily based on evidence from high level sources of underwater noise such as blasting or impact piling, as these sources are likely to have the greatest immediate environmental impact and therefore the clearest observable effects, although there has been more interest in chronic noise exposure over the last five years.

The impacts of underwater sound on marine species can be broadly summarised as follows:

- Physical traumatic injury and fatality;
- Auditory injury (either permanent or temporary); and
- Disturbance.

The following sections discuss the agreed criteria for assessing these impacts in species of marine mammal and fish at Norfolk Boreas.

2.2.2 Criteria to be used

The main metrics and criteria that have been used in this study to assess environmental effect come from several key papers covering underwater noise and its effects:

- The marine mammal noise exposure criteria from Southall *et al.* (2007);
- Data from Lucke *et al.* (2009) regarding harbour porpoise response to underwater noise;
- The National Marine Fisheries Service guidance (NMFS, 2016) for marine mammals generally; and
- Sound exposure guidelines for fishes by Popper *et al.* (2014).

At the time of writing, these include the most up to date and authoritative criteria for assessing environmental effects for use in impact assessments. The NMFS (2016) document effectively updates Southall *et al.* (2007) but for completeness, both sets of criteria have been used. These are described in the following section.

2.2.2.1 Marine mammals

This assessment considers three sets of criteria to assess the effects of impact piling noise on marine mammals: Southall *et al.* (2007), Lucke *et al.* (2009) and NMFS (2016).

Southall *et al.* (2007) has been the source of the most widely used criteria to assess the effects of noise on marine mammals since it was published, although has largely been updated by NMFS (2016). The criteria from Southall *et al.* (2007) are based on M-Weighted SELs, which are generalised frequency weighting functions to adjust underwater noise data to better represent the levels of underwater noise that various marine species are likely to be able to hear. The authors group marine mammals into five groups, four of which are relevant to underwater noise (the fifth is for pinnipeds in air). For each group, an approximate frequency range of hearing is proposed based on known audiogram data, where available, or inferred from other information such as auditory morphology. The M-Weighting filters are summarised in Table 2-1.

Functional hearing group	Established auditory bandwidth	Genera represented	Example species
Low frequency (LF) cetaceans	7 Hz to 22 kHz	*Balaena, Caperea, Eschrichtius, Megaptera, Balaenoptera* (13 species/subspecies)	Grey whale, right whale, humpback whale, minke whale
Mid frequency (MF) cetaceans	150 Hz to 160 kHz	*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)	Bottlenose dolphin, striped dolphin, killer whale, sperm whale
High frequency (HF) cetaceans	200 Hz to 180 kHz	*Phocoena, Neophocaena, Phocoenoides, Platanista, Inia, Kogia, Lipotes, Pontoporia, Cephalorhynchus* (20 species/subspecies)	Harbour porpoise, river dolphins, Hector's dolphin
Pinnipeds (in water)	75 Hz to 75 kHz	*Arctocephalus, Callorhinus, Zalophus, Eumetopias, Neophoca, Phocarctos, Otaria, Erignathus, Phoca, Pusa, Halichoerus, Histriophoca, Pagophilus, Cystophora, Monachus, Mirounga, Leptonychotes, Ommatophoca, Lobodon, Hydrurga, Odobenus* (41 species/subspecies)	Fur seal, harbour (common) seal, grey seal

Table 2-1 Functional marine mammal groups, their assumed auditory bandwidth of hearing and genera presented in each group (from Southall et al., 2007)

The unweighted SPL_{peak} and M-Weighted SEL criteria used in this study are summarised in Table 2-2 to Table 2-4, covering auditory injury, TTS (temporary threshold shift, a short-term reduction in hearing acuity) and behavioural avoidance. It should be noted that where multiple pulse criteria (SEL_{cum}) are unavailable single pulse criteria (SEL_{ss}) have been used in their place.

Southall *et al* (2007)	**Auditory Injury (Unweighted SPL_{peak} dB re 1 µPa)**	**TTS (Unweighted SPL_{peak} dB re 1 µPa)**
Low Frequency (LF) Cetaceans	230	224
Mid Frequency (MF) Cetaceans	230	224
High Frequency (HF) Cetaceans	230	224
Pinnipeds (in water) (PW)	218	212

Table 2-2 SPL_{peak} criteria for assessment of auditory injury and TTS in marine mammals (Southall et al, 2007)

Southall *et al.* (2007)	**Auditory Injury (M-Weighted SEL_{ss} dB re 1 µPa^{2}s)**	**Auditory Injury (M-Weighted SEL_{cum} dB re 1 µPa^{2}s)**	**TTS (M-Weighted SEL_{ss} dB re 1 µPa^{2}s)**
Low Frequency (LF) Cetaceans	198	198	183
Mid Frequency (MF) Cetaceans	198	198	183
High Frequency (HF) Cetaceans	198	198	183
Pinnipeds (in water) (PW)	186	186	171

Table 2-3 SEL criteria for assessment of auditory injury and TTS in marine mammals (Southall et al, 2007)

Southall *et al.* (2007)	**Likely Avoidance (M-Weighted SEL_{ss} dB re 1 µPa^{2}s)**	**Possible Avoidance (M-Weighted SEL_{ss} dB re 1 µPa^{2}s)**
Low Frequency (LF) Cetaceans	152	142
Mid Frequency (MF) Cetaceans	170	160

Table 2-4 Criteria for assessment of behavioural avoidance in marine mammals (Southall et al, 2007)

In addition to Southall *et al.* (2007), criteria from Lucke *et al.* (2009) have been used to further assess the effects of noise on harbour porpoise. The criteria from Lucke *et al.* (2009) are derived from testing harbour porpoise hearing thresholds before and after being exposed to seismic airgun stimuli (a pulsed noise like impact piling). All the criteria used unweighted single strike SELs. These are summarised in Table 2-5.

Lucke *et al.* (2009)	**Unweighted SEL_{ss} (dB re 1 µPa^{2}s)**		
	Auditory Injury	**TTS**	**Behavioural**
Harbour Porpoise	179	164	145

Table 2-5 Criteria for assessment of auditory injury, TTS and behavioural response in harbour porpoise (Lucke et al, 2009)

NMFS (2016) was co-authored by many of the same authors from the Southall *et al.* (2007) paper, and effectively updates its criteria for assessing the risk of auditory injury.

Similarly to Southall *et al.* (2007), the NMFS (2016) guidance groups marine mammals into groups of similar species and applies filters to the unweighted noise to approximate the hearing sensitivity of the receptor. The weightings are different to the “M-weightings” used in Southall *et al*. The hearing groups given in the NMFS (2016) are summarised in Table 2-6 and Figure 2-1. A further group for Otariid Pinnipeds is also given in the guidance for sea lions and fur seals but this has not been used in this study as those species of pinnipeds are not found in the North Sea.

Hearing group	**Example species**	**Generalised hearing range**
Low Frequency (LF) Cetaceans	Baleen Whales	7 Hz to 35 kHz
Mid Frequency (MF) Cetaceans	Dolphins, Toothed Whales, Beaked Whales, Bottlenose Whales (including Bottlenose Dolphin)	150 Hz to 160 kHz
High Frequency (HF) Cetaceans	True Porpoises (including Harbour Porpoise	275 Hz to 160 kHz
Phocid Pinnipeds (PW) (underwater)	True Seals (including Harbour Seal)	50 Hz to 86 kHz

Table 2-6 Marine mammal hearing groups (from NMFS, 2016)

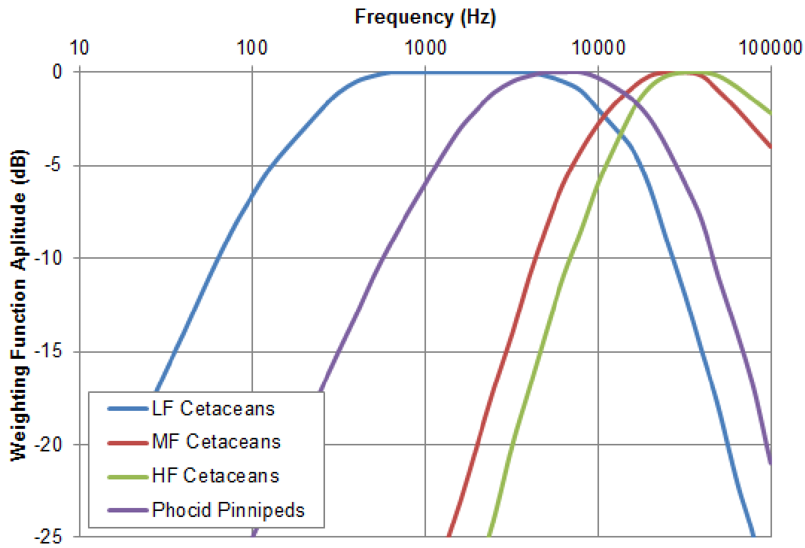

Figure 2-1 Auditory weighting functions for low frequency (LF) cetaceans, mid frequency (MF) cetaceans, high frequency (HF) cetaceans, and phocid pinnipeds (PW) (underwater) (from NMFS, 2016)

NMFS (2016) presents single strike, unweighted peak criteria (SPL_{peak}) and cumulative (i.e. more than a single sound impulse), weighted sound exposure criteria (SEL_{cum}) for both permanent threshold shift (PTS) where unrecoverable hearing damage may occur and temporary threshold shift (TTS) where a temporary reduction in hearing sensitivity may occur in individual receptors.

Table 2-7 and Table 2-8 presents the NMFS (2016) criteria for onset of risk of PTS and TTS for each of the key marine mammal hearing groups.

NMFS (2016)	**Unweighted SPL_{peak} (dB re 1 µPa)**	
	Auditory Injury	**TTS (Temporary Threshold Shift)**
Low Frequency (LF) Cetaceans	219	213
Mid Frequency (MF) Cetaceans	230	224
High Frequency (HF) Cetaceans	202	196
Phocid Pinnipeds (PW) (underwater)	218	212

Table 2-7 SPL_{peak} criteria for assessment of auditory injury and TTS in marine mammals (NMFS, 2016)

NMFS (2016)	**Weighted SEL_{cum} (dB re 1 µPa^{2}s)**	
	Auditory Injury	**TTS (Temporary Threshold Shift)**
Low Frequency (LF) Cetaceans	183	168
Mid Frequency (MF) Cetaceans	185	170
High Frequency (HF) Cetaceans	155	140
Phocid Pinnipeds (PW) (underwater)	185	170

Table 2-8 SEL criteria for assessment of auditory injury and TTS in marine mammals (NMFS, 2016)

Where SEL_{cum} are required, a fleeing animal model has been used. This assumes that the animal exposed to high noise levels will swim away from the noise source. For this a constant fleeing speed of 3.25 ms^{-1} has been assumed for the low frequency (LF) cetaceans group (Blix and Folkow, 1995), based on data for minke whale, and for other receptors a constant rate of 1.5 ms^{-1} has been assumed, which is a cruising speed for a harbour porpoise (Otani *et al.*, 2000). These are considered 'worst case' as marine mammals are expected to be able to swim much faster under stress conditions. The model assumes that when a fleeing receptor reaches the coast it receives no more noise, as it is likely that the receptor will flee along the coast, and at this stage at Norfolk Boreas site it will be so far from the piling that it will have received the majority of the noise exposure.

This assessment is comprehensive in its application of the older Southall *et al.* and Lucke *et al.* (2009) criteria, as well as the up to date criteria from NMFS (2016).

2.2.2.2 Fish

The large variation in fish species leads to a greater challenge in production of a generic noise criterion, or range of criteria, for the assessment of noise impacts. Whereas previous assessments applied broad criteria based on limited studies of fish not present in UK waters (e.g. McCauley *et al.*, 2000), the publication of Popper *et al.* (2014) provides an authoritative summary of the latest research and guidelines for the assessment of fish exposure to sound, and uses categories for fish that are representative of the species present in UK waters.

The Popper *et al* (2014) study groups species of fish into whether they possess a swim bladder, and whether it is involved in its hearing. The guidance also gives specific criteria (as both SPL_{peak} and SEL_{cum} values) for a variety of noise sources. This assessment has used the criteria given for pile driving noise on fish where their swim bladder is involved in hearing, as these are the most sensitive. The modelled criteria are summarised in Table 2-9. In a similar fashion to marine mammals for SEL_{cum} results, a fleeing animal model has been used assuming a fish flees from the source at a constant rate of 1.5 ms^{-1}, based on data from Hirata (1999).

Type of animal	Mortality and potential mortal injury	Impairment	
		Recoverable injury	TTS (Temporary Threshold Shift)
Fish: no swim bladder	>219 dB SEL_{cum} or >213 dB SPL_{peak}	>216 dB SEL_{cum} or >213 dB SPL_{peak}	>>186 dB SEL_{cum}
Fish: swim bladder is not involved in hearing	210 dB SEL_{cum} or >207 dB SPL_{peak}	203 dB SEL_{cum} or >207 dB SPL_{peak}	>186 dB SEL_{cum}
Fish: swim bladder involved in hearing	207 dB SEL_{cum} or >207 dB SPL_{peak}	203 dB SEL_{cum} or >207 dB SPL_{peak}	186 dB SEL_{cum}

Table 2-9 Criteria for assessment of mortality and potential mortal injury, recoverable injury and TTS in species of fish (Popper et al, 2014)

A set of criteria also exists for fish eggs and larvae, with a numerical mortality and potential mortality threshold at the same level as fish (swim bladder not involved in hearing). Hearing impairment and disturbance thresholds are not relevant.

3 Baseline Ambient Noise

The baseline noise level in open water, in the absence of any specific anthropogenic noise source, is generally dependent on a mix of the movement of the water and sediment, weather conditions and shipping. There is a component of biological noise from marine mammal and fish vocalisation, as well as an element from invertebrates.

Outside of the naturally occurring ambient noise, man-made noise dominates the background. The North Sea is heavily shipped by fishing, cargo and passenger vessels, which contribute to the ambient noise in the water. The larger vessels are not only louder but the noise tends to have a lower frequency, which travels more readily, especially in the deeper open water. Other vessels such as dredgers and small fishing boats have a lower overall contribution. There are no dredging areas, Active Dredge Zones or Dredging Application Option and Prospecting Areas within the Norfolk Boreas offshore project area.

Other sources of anthropogenic noise include oil and gas platforms and other drilling activity, clearance of unexploded ordnance (UXO) and military exercises. Drilling may contribute some low frequency noise in the Norfolk Boreas site, although due to its low-level nature (see section 6) this is unlikely to contribute to the overall ambient noise. Clearance of UXO contributes high but infrequent noise. Little information is available on the scope and timing of military exercises, but they are not expected to last for an extended period, and so would have little contribution to the long-term ambient noise in the area.

The Marine Strategy Framework Directive requires European Union members to ascertain baseline noise levels by 2020, and monitoring processes are being put into place for this around Europe. Good quality, long-term underwater noise data for the region around Norfolk Boreas is not currently available.

Typical underwater noise levels show a frequency dependency in relation to different noise sources; the classic curves are given in Wenz (1962) and are reproduced in Figure 3-1 below. Figure 3-1 shows that any unweighted overall (i.e. single-figure non-frequency-dependent) noise level is typically dependent on the very low frequency element of the noise. The introduction of a nearby anthropogenic noise source (such as piling or sources involving engines) will tend to increase the noise levels in the 100-1000 Hz region, but to a lesser extent will also extend into higher and lower frequencies.

In 2011, around the time of the met-mast installation in the former Hornsea zone, in broadly the same region as Norfolk Boreas, snapshot baseline underwater noise levels were sampled as part of the met-mast installation noise survey (Nedwell and Cheesman, 2011). Measurements were taken outside of the installation activity and in the absence of any nearby vessel noise. This survey sampled noise levels of 112 to 122 dB re 1 µPa RMS over two days and were described as not unusual for the area. The higher figure was due to higher sea state on that day. Unweighted overall noise levels of this type should be used with caution without access to more detail regarding the duration, frequency content and conditions under which the sound was recorded, although they do demonstrate an indication of the natural variation in background noise levels.

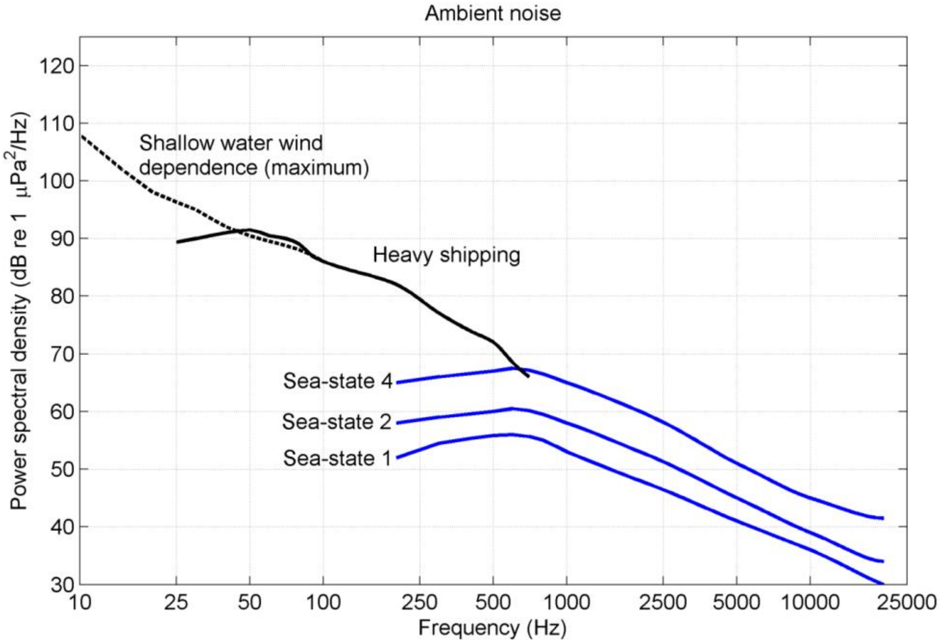

Figure 3-1 Ambient underwater noise as shown in Wenz (1962) showing frequency dependency from different noise sources.

There is little additional, documented ambient noise data publicly available for the region. Merchant *et al*. (2014) measured underwater ambient noise in the Moray Firth, acquiring measurements of a similar order to the baseline snapshot levels noted above, and which showed significant variation (i.e. a 60 dB spread) in daily average noise levels. Although this is outside of the region and in a much more coastal and heavily shipped location, it demonstrates that the snapshot noted above gives only limited information as the average daily noise levels are so dependent on weather and local activity. However, the snapshot measurements taken do show noise levels that are of the same order as baseline noise levels sampled elsewhere in the North Sea (Nedwell *et al*., 2003a) and so are considered to be realistic.

In principle, when noise introduced by anthropogenic sources propagates far enough it will reduce to the level of ambient noise, at which point it can be considered negligible. In practice, as the underwater noise thresholds defined in section 2.2.2 are all considerably above the level of background noise, any noise baseline would not feature in an assessment to these criteria.

4 Impact piling modelling methodology

4.1 Modelling introduction

To estimate the underwater noise levels likely to arise during construction of Norfolk Boreas, predictive noise modelling has been undertaken. The methods described in this section, and utilised within this report, meet the requirements set by the NPL Good Practice Guide 133 for underwater noise measurement (Robinson *et al.*, 2014).

The modelling has been undertaken using the INSPIRE noise model. The INSPIRE model (currently version 3.5) is a semi-empirical underwater noise propagation model based around a combination of numerical modelling and actual measured data. It is designed to calculate the propagation of noise in shallow, mixed water, typical of the conditions around the UK and very well suited to the Norfolk Boreas site. The model has been tuned for accuracy using over 50 datasets of underwater noise propagation around offshore piling.

The model provides estimates of unweighted SPL_{peak}, SEL_{ss}, and SEL_{cum} noise levels as well as various other weighted noise metrics. Calculations are made along 180 equally spaced radial transects (one every 2°). For each modelling run a criterion level can be specified allowing a contour to be drawn, within which a given effect may occur. These results are then plotted over digital bathymetry data so that impact ranges can be clearly visualised and assessed as necessary.

INSPIRE considers a wide array of input parameters, including variations in bathymetry and source frequency content to ensure accurate results for the circumstances. It should also be noted that the results presented in this study should be considered highly precautionary as the worst-case parameters have been selected for:

- Piling hammer blow energies;
- Soft start ramp-up profile and strike rate;
- Duration of piling; and
- Receptor swim speeds.

The input parameters for the modelling are detailed in the following section.

4.2 Locations

Modelling has been undertaken at two representative locations, covering the position closest to land (SW), which also happens to be one of the deepest locations on the site, and the furthest position from this location (NE) situated in shallower water. The chosen locations are shown in Figure 4-1 and summarised in Table 4-1, below.

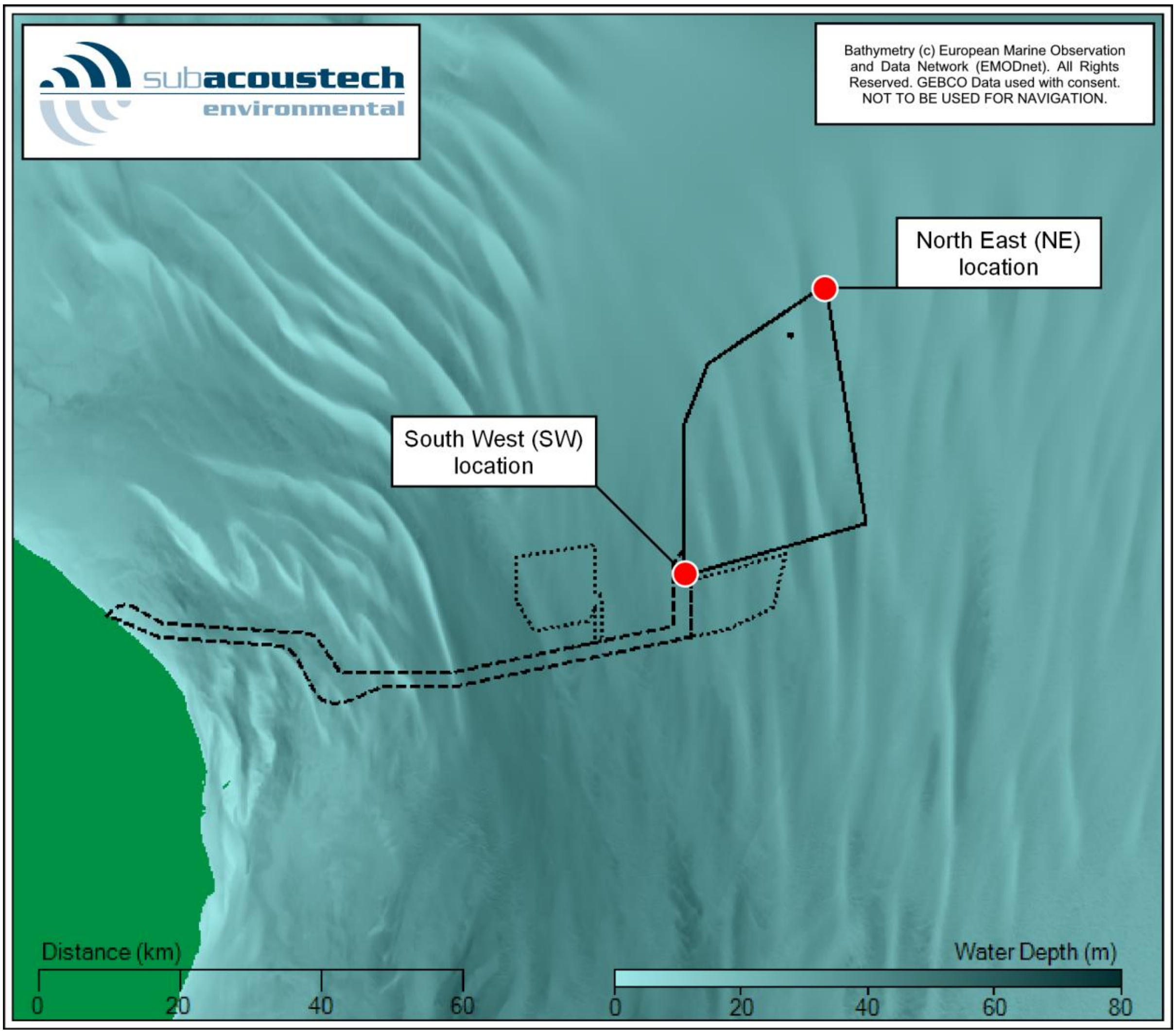

Figure 4-1 Map showing the underwater noise modelling locations in the Norfolk Boreas OWF site

	South West (SW)	North East (NE)
Latitude	52.8708°N	53.2412°N
Longitude	002.7596°E	003.0586°E
Water depth	38 m	28 m

Table 4-1 Summary of the underwater noise modelling locations and associated water depths (mean tide)

4.3 Input parameters

The modelling takes full account of the environmental parameters within the study area and the characteristics of the noise source. The following parameters have been assumed for modelling.

4.3.1 Impact piling

Two piling source scenarios have been modelled to include monopile and pin pile (jacket) WTG foundations across the Norfolk Boreas OWF farm site. These are:

- Monopiles installed using a maximum hammer blow energy of 5000 kJ; and
- Pin piles installed using a maximum hammer blow energy of 2700 kJ.

For cumulative SELs, the soft start and ramp up of blow energies along with total duration and strike rate of the piling have also been considered. These are summarised in Table 4-2 to Table 4-3, below.

The ramp up takes place over the first half-hour of piling, starting at ten percent of maximum and gradually increasing in blow energy and strike rate until reaching the maximum energy, where it stays for the remaining time.

The monopile scenario contains 10,350 pile strikes over 360 minutes (6 hours, inclusive of soft start and ramp up). Two pin pile scenarios have been considered and both include 4 individual piles installed consecutively. One scenario assumes a total of 9,000 strikes over 6 hours (1 hour 30 minutes for each pin pile), and the other assumes a total of 19,800 strikes over 12 hours (3 hours for each pin pile). For the purposes of noise modelling, it is assumed that there is no pause between each individual pin pile, and there is continuous exposure.

	10%	**Ramp up**	**100%**
Monopile blow energy	500 kJ	Gradual increase	5000 kJ
Number of strikes	150 strikes	300 strikes	9900 strikes
Duration	10 minutes	20 minutes	330 minutes

Table 4-2 Summary of the ramp up scenario used for calculating cumulative SELs for monopiles

	10%	**Ramp up**	**100%**
Pin pile blow energy	270 kJ	Gradual increase	2700 kJ
Number of strikes (6h)	150 strikes	300 strikes	1800 strikes
Duration (6h)	10 minutes	20 minutes	60 minutes
Number of strikes (12h)	150 strikes	300 strikes	4500 strikes
Duration (12h)	10 minutes	20 minutes	150 minutes

Table 4-3 Summary of the ramp up scenario used for calculating cumulative SELs for a single pin pile for both duration assumptions (modelling assumes four consecutive piles installed at the same location)

4.3.2 Source levels

Modelling requires knowledge of the source level, which is the theoretical noise level at 1 m from the noise source.

The INSPIRE noise propagation model assumes that the noise acts as a single point source. This is adjusted to take into account the water depth at the noise source location to allow for the length of pile in contact with the water, which affects the amount of noise that is transmitted from the pile into its surroundings.

The unweighted SPL_{peak} and SEL_{ss} source levels estimated for this project are provided in Table 4-4 and Table 4-5.

		Monopile source level (500 kJ)	**Pin pile source level (270 kJ)**
SPL_{peak}	SW	231.2 dB re 1 µPa @ 1 m	226.9 dB re 1 µPa @ 1 m
	NE	226.4 dB re 1 µPa @ 1 m	222.0 dB re 1 µPa @ 1 m
SEL_{ss}	SW	212.2 dB re 1 µPa²s @ 1 m	207.9 dB re 1 µPa²s @ 1 m
	NE	207.4 dB re 1 µPa²s @ 1 m	203.0 dB re 1 µPa²s @ 1 m

Table 4-4 Summary of the unweighted source levels used for starting energy modelling in this study

		Monopile source level (5000 kJ)	**Pin pile source level (2700 kJ)**
SPL_{peak}	SW	242.6 dB re 1 µPa @ 1 m	240.3 dB re 1 µPa @ 1 m
	NE	238.4 dB re 1 µPa @ 1 m	235.8 dB re 1 µPa @ 1 m
SEL_{ss}	SW	223.6 dB re 1 µPa²s @ 1 m	221.3 dB re 1 µPa²s @ 1 m
	NE	219.4 dB re 1 µPa²s @ 1 m	216.8 dB re 1 µPa²s @ 1 m

Table 4-5 Summary of the unweighted source levels used for full energy modelling in this study

4.3.3 Frequency content

The size of the pile being installed affects the frequency content of the noise it produces. For this modelling, frequency data has been sourced from Subacoustech's noise measurement database and an average taken to obtain representative third-octave band levels for installing monopiles and pin piles, which is a method for describing the frequency break-down of a noise level. The third-octave band frequency spectrum levels used for modelling the SW location are illustrated in Figure 4-2 as an example; the shape of each spectrum is the same for all the other locations and blow energies, with the overall source levels adjusted depending on these parameters. This becomes important when considering marine mammal species that are sensitive to a particular frequency of sound.

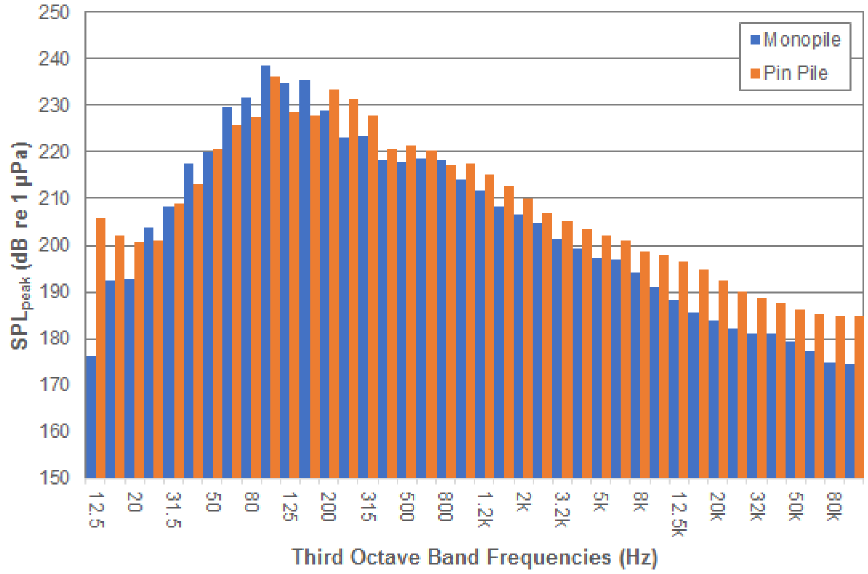

Figure 4-2 Third-octave source level frequency spectra for the south west location, maximum blow energy

Frequency spectra for piles more than 7 m in diameter, the largest where measured data is available, has been used for the monopile modelling and piles of approximately 4 m in diameter (mid-way between the 3 m and 5 m pin pile options currently under consideration) have been used for pin pile modelling. It is worth noting that the monopiles contain more low frequency content and the pin piles contain more high frequency content, due to the acoustics related to the dimensions of the pile. This trend would be expected to continue to larger piles under consideration for the monopiles at Norfolk Boreas. A larger diameter would be expected to move the dominant frequency of the sound (i.e. the frequency where the highest levels are present) produced lower, further below the frequencies of greatest hearing sensitivity of marine mammals. Thus the sound would appear slightly quieter to a receptor more sensitive to higher frequencies, such as dolphins and porpoises (MF and HF cetaceans). Marine mammal hearing sensitivity is covered in section 2.2.

4.3.4 Environmental conditions

Accurate modelling of underwater noise propagation requires knowledge of the sea and seabed conditions. The semi-empirical nature of the INSPIRE model considers the seabed type and speed of sound in water for the mixed conditions around the Norfolk Boreas site as it is based on over 50 datasets taken of impact piling noise around the UK.

Mean tidal depth has been used for the bathymetry as the tidal state will fluctuate throughout installation of foundations.

5 Impact piling noise modelling outputs

5.1 Unweighted subsea noise modelling

This section presents the unweighted (i.e. in the absence of any weighting for marine mammal hearing sensitivity) noise level results from the modelling undertaken for impact piling operations using the modelling parameters detailed in section 4.

The following figures present unweighted SPL_{peak} noise levels from impact piling operations at Norfolk Boreas. Figure 5-1 to Figure 5-4 show the unweighted SPL_{peak} noise levels for monopiles (installed using a maximum blow energy of 5000 kJ) and the unweighted SPL_{peak} noise levels for pin piles (installed using a maximum blow energy of 2700 kJ).

Comparing these plots shows that the greatest distribution of increased noise levels, with no weighting applied, occurs in deeper water. The effect of the deep water on noise transmission is also shown when considering the ridges to the south and northwest of the site, where a more 'jagged' contour occurs between the ridges as a consequence of the differences in water depth. The noise will propagate further when produced at the SW location.

The lower extent of the noise levels on these plots, denoted in dB SPL_{peak}, should not be confused with background or ambient noise levels, which are typically described in terms of dB SPL_{RMS}. The two metrics are not directly comparable.

The impulsive noise introduced to the water will return to background levels within seconds of the impulse passing.

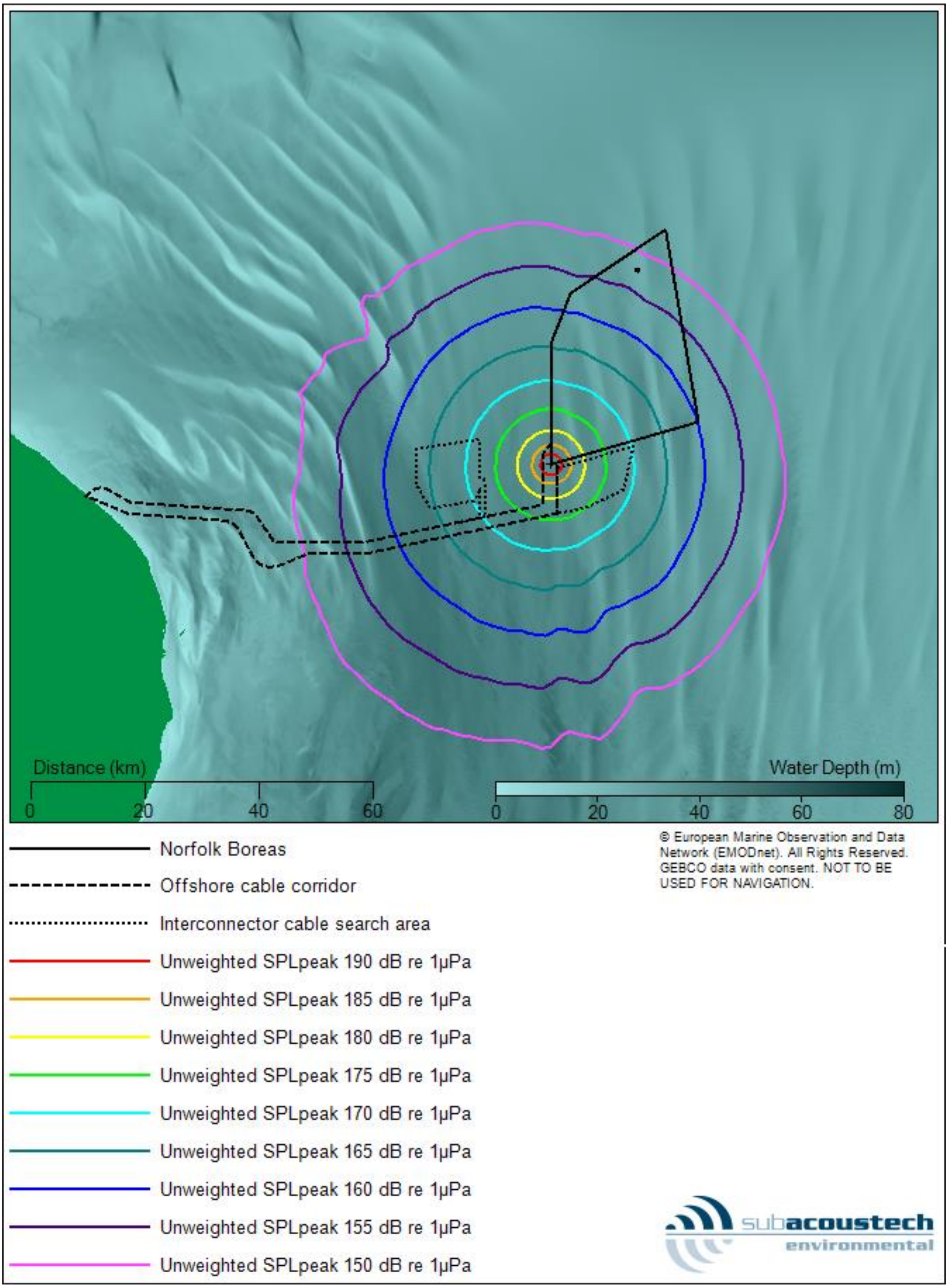

Figure 5-1 Noise level plot showing the predicted SPL_{peak} noise levels predicted for installing a monopile at the SW location

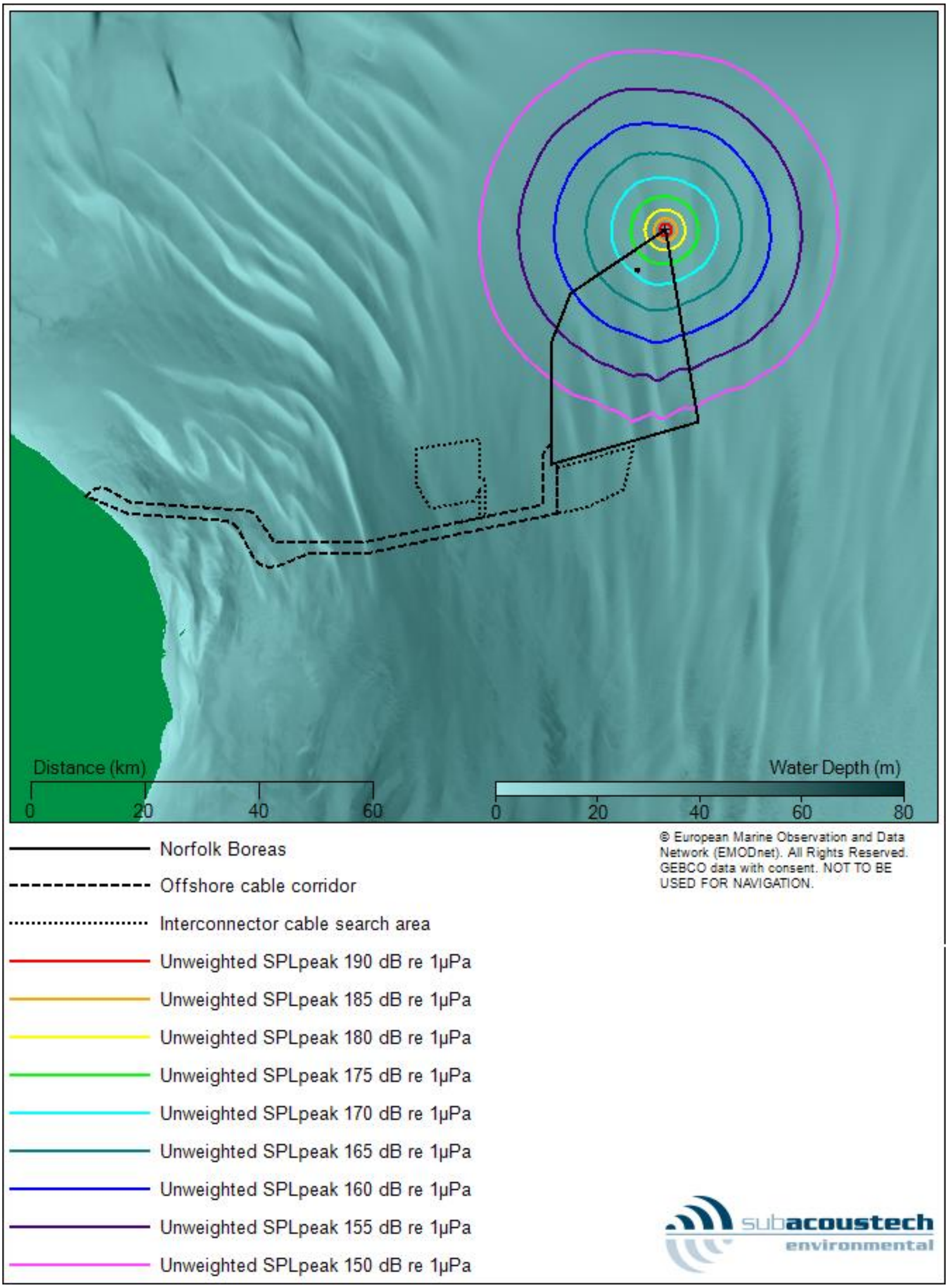

Figure 5-2 Noise level plot showing the predicted SPL_{peak} noise levels predicted for installing a monopile at the NE location

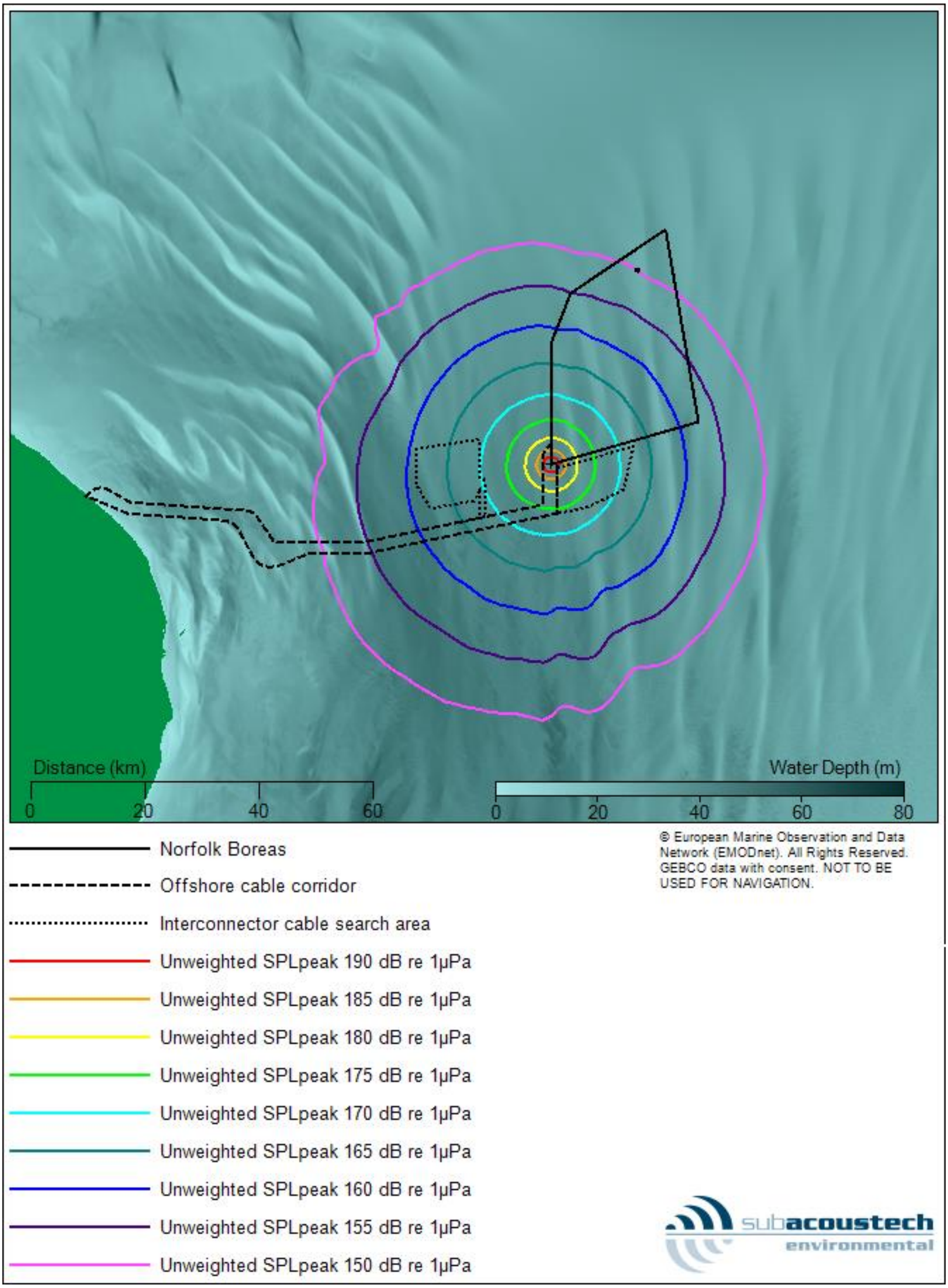

Figure 5-3 Noise level plot showing the predicted SPL_{peak} noise levels predicted for installing a pin pile at the SW location

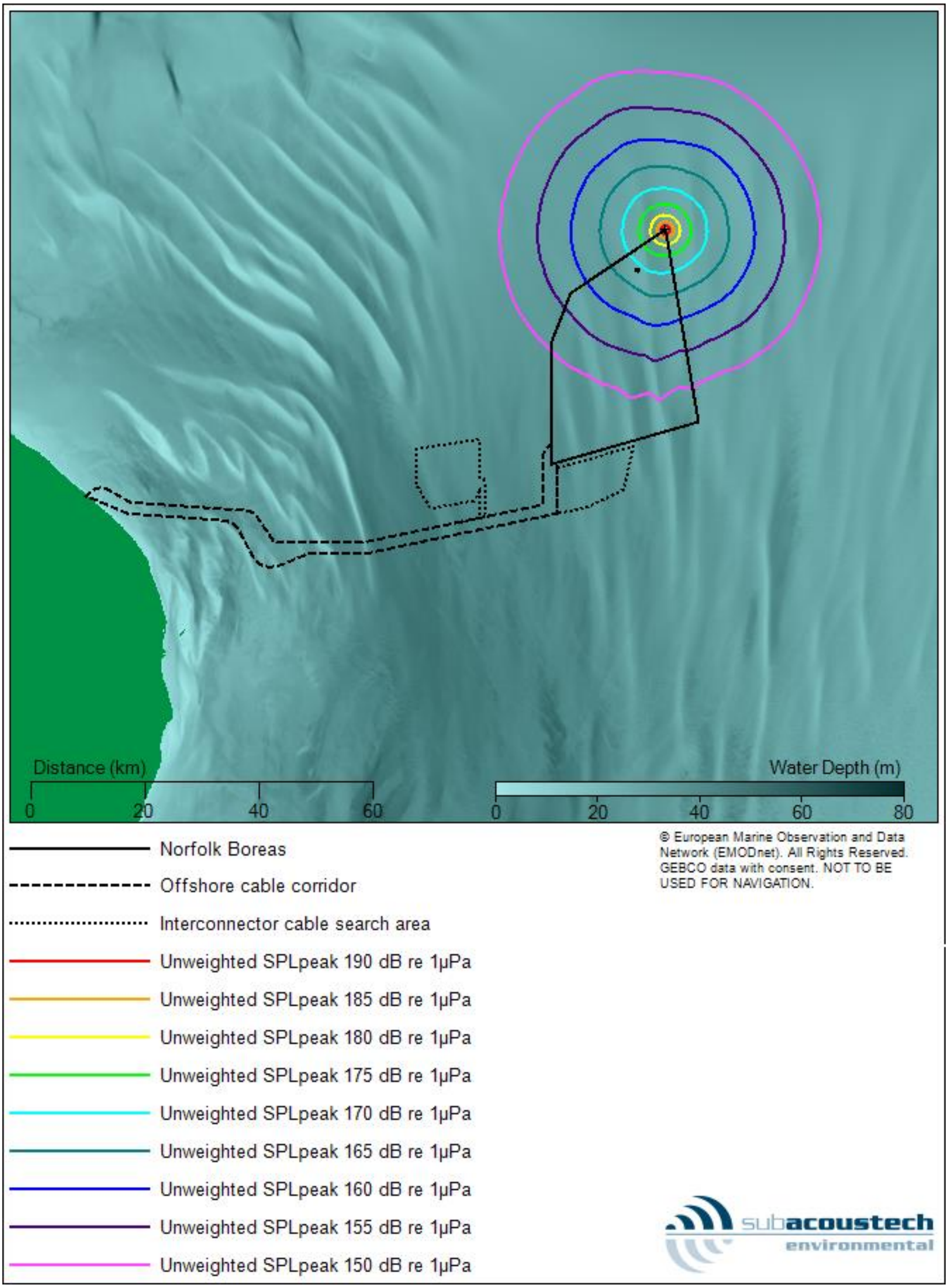

Figure 5-4 Noise level plot showing the predicted SPL_{peak} noise levels predicted for installing a pin pile at the NE location

5.1.1 Proximity to spawning grounds

Herring and sole spawning grounds (Coull *et al*., 1998; Ellis *et al*., 2010) are located close to the boundary of the Norfolk Boreas site. The main spawning grounds in the vicinity are shown below in Figure 5-5.

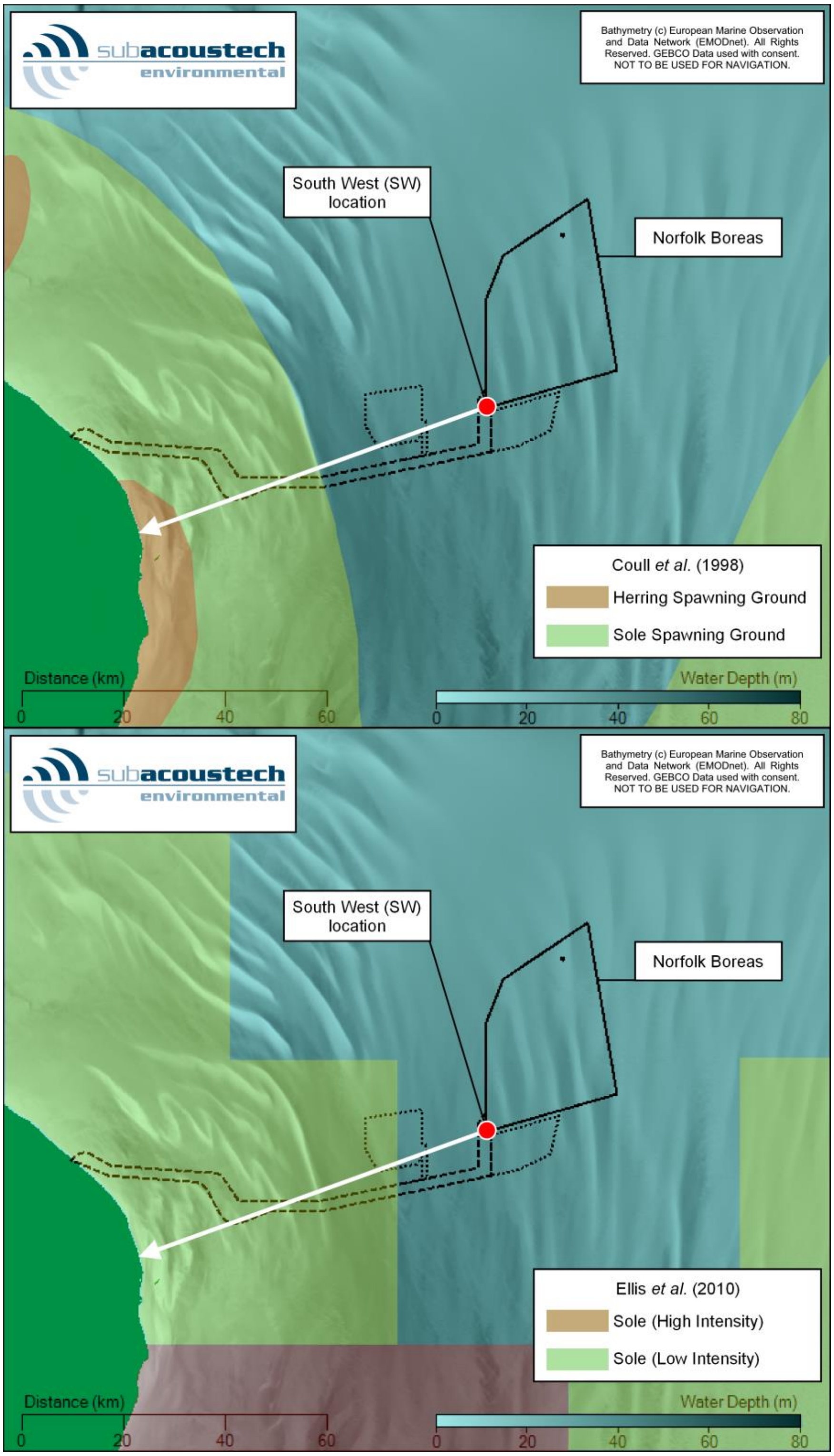

Figure 5-5 Map showing the extents of the herring and sole spawning grounds from Coull et al. (1998) and Ellis et al. (2010) along with the transect (shown as a white arrow) used in Figure 5-6

Figure 5-6 presents an SEL_{ss} level against range plot along a single transect from the worst-case SW location toward the herring and sole spawning grounds shown in Figure 5-5 along a bearing of 250°. Table 5-1 summarised the modelled noise levels at the points the transect intersects each spawning ground

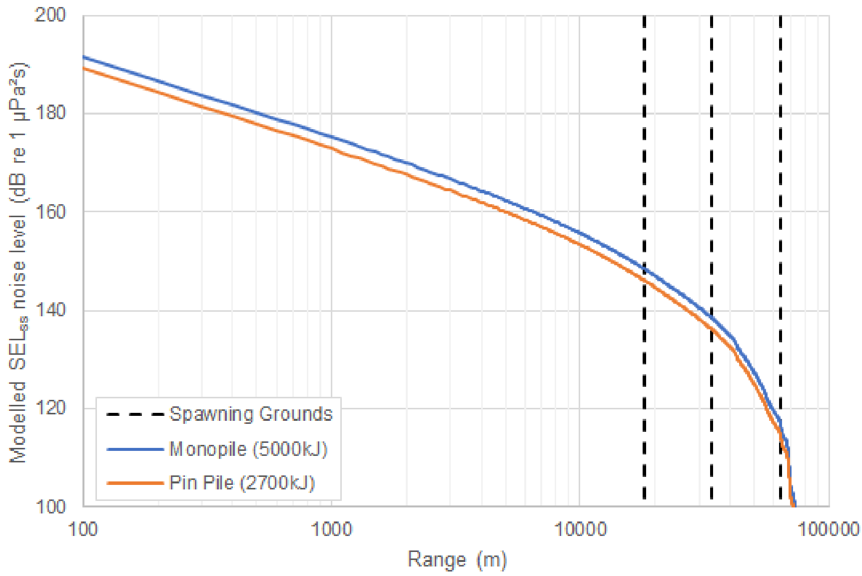

Figure 5-6 SEL_{ss} level against range plot showing the modelled noise level along a 250° transect from the SW modelling location and the locations of intersecting spawning grounds

Spawning ground	Range to SW location along 250° bearing	Modelled unweighted noise level (SEL_{ss})	
		Monopile (5000 kJ)	Pin Pile (2700 kJ)
Herring (Coull *et al*. 1998)	64 km	116.8 dB re 1 µPa²s	114.5 dB re 1 µPa²s
Sole (Coull *et al*. 1998)	34 km	138.5 dB re 1 µPa²s	136.2 dB re 1 µPa²s
Sole (low intensity) (Ellis *et al. (2010)*	18 km	148.6 dB re 1 µPa²s	146.3 dB re 1 µPa²s

Table 5-1 Summary of the modelled unweighted SEL_{ss} noise levels at the nearest spawning grounds

5.2 Interpretation of results

This section presents the modelling results in terms of the noise metrics and criteria covered in section 2.2. This discussion will guide the assessment of environmental impact to marine species from the proposed impact piling noise.

5.2.1 Impacts on marine mammals

The following sections present the modelling results in biological terms for various species of marine mammal split up by the source of the guidance: Southall *et al.* (2007), Lucke *et al.* (2009) and NMFS (2016).

5.2.1.1 Southall et al. (2007) results

Table 5-2 to Table 5-9 present the predicted auditory injury and TTS impact ranges for various cetaceans and pinniped hearing groups based on the Southall *et al.* (2007) thresholds. Behavioural avoidance results for low and mid frequency cetaceans are given in Table 5-10 to Table 5-13. The criteria from Southall *et al.* (2007) are given as unweighted SPL_{peak} or M-Weighted SELs, either as single or multiple pulse. Multiple pulse results include the noise exposure to an animal receptor over an entire installation period (as described in Table 4-2 and Table 4-3). In line with the unweighted results in section 5.1, maximum ranges were predicted for monopiles installed at the deeper SW location. In general, the pinnipeds have the greatest effect range due to the stricter criteria applied to this species hearing group.

When considering the two multiple pulse scenarios for pin piles, the 12-hour scenario results in slightly increased SEL_{cum} impact ranges compared to the 6-hour scenario.

Detail for ranges calculated to be less than 50 m for single strike criteria and 100 m for cumulative criteria have not been included as confidence cannot be given to the accuracy of the results at such close range.

Results for the initial impact ranges at soft start (500 kJ and 270 kJ for monopile and pin pile, respectively) and for the maximum energy, including exposure over the entire pile sequence, are given in separate tables.

Southall *et al.* (2007) - Auditory Injury				Monopile (500 kJ)		
				Maximum	Mean	Minimum
SW location	Unweighted SPL_{peak}	Cetaceans	230 dB	< 50 m	< 50 m	< 50 m
		Pinnipeds	218 dB	< 50 m	< 50 m	< 50 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		PW Pinnipeds	186 dB	< 50 m	< 50 m	< 50 m
NE location	Unweighted SPL_{peak}	Cetaceans	230 dB	< 50 m	< 50 m	< 50 m
		Pinnipeds	218 dB	< 50 m	< 50 m	< 50 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		PW Pinnipeds	186 dB	< 50 m	< 50 m	< 50 m

Table 5-2 Summary of the single strike impact ranges for auditory injury criteria from Southall et al (2007) for installation of a monopile using the soft start blow energy of 500 kJ

Southall *et al.* (2007) - Auditory Injury				Monopile (5000 kJ)		
				Maximum	Mean	Minimum
SW location	Unweighted SPL_{peak}	Cetaceans	230 dB	< 50 m	< 50 m	< 50 m
		Pinnipeds	218 dB	< 50 m	< 50 m	< 50 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	198 dB	50 m	< 50 m	< 50 m
		MF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		PW Pinnipeds	186 dB	150 m	150 m	140 m
	M-Weighted multiple pulse (SEL_{cum})	LF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		MF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		PW Pinnipeds	186 dB	3.1 km	2.9 km	2.8 km
NE location	Unweighted SPL_{peak}	Cetaceans	230 dB	< 50 m	< 50 m	< 50 m
		Pinnipeds	218 dB	< 50 m	< 50 m	< 50 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		PW Pinnipeds	186 dB	90 m	90 m	80 m
	M-Weighted multiple pulse (SEL_{cum})	LF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		MF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		PW Pinnipeds	186 dB	300 m	200 m	200 m

Table 5-3 Summary of the impact ranges for auditory injury criteria from Southall et al (2007) for installation of a monopile with a maximum blow energy of 5000 kJ

In these results and in the following tables, where the ranges are defined (i.e. above 50 m and 100 m), the calculated to be greater for the SW than the NE location. This is due to the higher source level at the SW location, which in turn is due to the deeper water in this location.

Southall *et al.* (2007) - Auditory Injury				Pin Pile (270 kJ)		
				Maximum	**Mean**	**Minimum**
SW location	**Unweighted SPL_{peak}**	Cetaceans	230 dB	< 50 m	< 50 m	< 50 m
		Pinnipeds	218 dB	< 50 m	< 50 m	< 50 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		PW Pinnipeds	186 dB	< 50 m	< 50 m	< 50 m
NE location	**Unweighted SPL_{peak}**	Cetaceans	230 dB	< 50 m	< 50 m	< 50 m
		Pinnipeds	218 dB	< 50 m	< 50 m	< 50 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		PW Pinnipeds	186 dB	< 50 m	< 50 m	< 50 m

Table 5-4 Summary of the single strike impact ranges for auditory injury criteria from Southall et al (2007) for installation of pin piles using the soft start blow energy of 270 kJ

Southall *et al.* (2007) - Auditory Injury				Pin Pile (2700 kJ)		
				Maximum	**Mean**	**Minimum**
SW location	**Unweighted SPL_{peak}**	Cetaceans	230 dB	< 50 m	< 50 m	< 50 m
		Pinnipeds	218 dB	< 50 m	< 50 m	< 50 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		PW Pinnipeds	186 dB	130 m	130 m	120 m
	M-Weighted multiple pulse (SEL_{cum}) (6 hours)	LF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		MF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		PW Pinnipeds	186 dB	2.0 km	1.9 km	1.8 km
	M-Weighted multiple pulse (SEL_{cum}) (12 hours)	LF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		MF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		PW Pinnipeds	186 dB	2.3 km	2.2 km	2.0 km
NE location	**Unweighted SPL_{peak}**	Cetaceans	230 dB	< 50 m	< 50 m	< 50 m
		Pinnipeds	218 dB	< 50 m	< 50 m	< 50 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	198 dB	< 50 m	< 50 m	< 50 m
		PW Pinnipeds	186 dB	80 m	80 m	70 m
	M-Weighted multiple pulse (SEL_{cum}) (6 hours)	LF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		MF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		PW Pinnipeds	186 dB	< 100 m	< 100 m	< 100 m
	M-Weighted multiple pulse (SEL_{cum}) (12 hours)	LF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		MF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	198 dB	< 100 m	< 100 m	< 100 m
		PW Pinnipeds	186 dB	< 100 m	< 100 m	< 100 m

Table 5-5 Summary of the impact ranges for auditory injury criteria from Southall et al (2007) for installation of pin piles with a maximum blow energy of 2700 kJ

Southall *et al.* (2007) - TTS				Monopile (500 kJ)		
				Maximum	**Mean**	**Minimum**
SW location	**Unweighted SPL_{peak}**	Cetaceans	224 dB	< 50 m	< 50 m	< 50 m
		Pinnipeds	212 dB	< 50 m	< 50 m	< 50 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	183 dB	70 m	70 m	70 m
		MF Cetaceans	183 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	183 dB	< 50 m	< 50 m	< 50 m
		PW Pinnipeds	171 dB	220 m	220 m	220 m
NE location	**Unweighted SPL_{peak}**	Cetaceans	224 dB	< 50 m	< 50 m	< 50 m
		Pinnipeds	212 dB	< 50 m	< 50 m	< 50 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	183 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	183 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	183 dB	< 50 m	< 50 m	< 50 m
		PW Pinnipeds	171 dB	110 m	110 m	110 m

Table 5-6 Summary of the single strike impact ranges for TTS criteria from Southall et al (2007) for installation of a monopile using the soft start blow energy of 500 kJ

Southall *et al.* (2007) - TTS				Monopile (5000 kJ)		
				Maximum	**Mean**	**Minimum**
SW location	**Unweighted SPL_{peak}**	Cetaceans	224 dB	< 50 m	< 50 m	< 50 m
		Pinnipeds	212 dB	80 m	80 m	80 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	183 dB	350 m	350 m	340 m
		MF Cetaceans	183 dB	140 m	140 m	130 m
		HF Cetaceans	183 dB	120 m	120 m	110 m
		PW Pinnipeds	171 dB	1.1 km	1.1 km	1.1 km
NE location	**Unweighted SPL_{peak}**	Cetaceans	224 dB	< 50 m	< 50 m	< 50 m
		Pinnipeds	212 dB	< 50 m	< 50 m	< 50 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	183 dB	200 m	200 m	190 m
		MF Cetaceans	183 dB	80 m	80 m	70 m
		HF Cetaceans	183 dB	70 m	70 m	60 m
		PW Pinnipeds	171 dB	610 m	610 m	600 m

Table 5-7 Summary of the impact ranges for TTS criteria from Southall et al (2007) for installation of a monopile with a maximum blow energy of 5000 kJ

Southall *et al.* (2007) - TTS				Pin Pile (270 kJ)		
				Maximum	**Mean**	**Minimum**
SW location	**Unweighted SPL_{peak}**	Cetaceans	224 dB	< 50 m	< 50 m	< 50 m
		Pinnipeds	212 dB	< 50 m	< 50 m	< 50 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	183 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	183 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	183 dB	< 50 m	< 50 m	< 50 m
		PW Pinnipeds	171 dB	150 m	150 m	150 m
NE location	**Unweighted SPL_{peak}**	Cetaceans	224 dB	< 50 m	< 50 m	< 50 m
		Pinnipeds	212 dB	< 50 m	< 50 m	< 50 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	183 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	183 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	183 dB	< 50 m	< 50 m	< 50 m
		PW Pinnipeds	171 dB	70 m	70 m	70 m

Table 5-8 Summary of the single strike impact ranges for TTS criteria from Southall et al (2007) for installation of pin piles using the soft start blow energy of 2700 kJ

Southall *et al.* (2007) - TTS				Pin Pile (2700 kJ)		
				Maximum	**Mean**	**Minimum**
SW location	**Unweighted SPL_{peak}**	Cetaceans	224 dB	< 50 m	< 50 m	< 50 m
		Pinnipeds	212 dB	60 m	60 m	60 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	183 dB	260 m	260 m	250 m
		MF Cetaceans	183 dB	130 m	130 m	120 m
		HF Cetaceans	183 dB	100 m	100 m	90 m
		PW Pinnipeds	171 dB	970 m	970 m	960 m
NE location	**Unweighted SPL_{peak}**	Cetaceans	224 dB	< 50 m	< 50 m	< 50 m
		Pinnipeds	212 dB	< 50 m	< 50 m	< 50 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	183 dB	140 m	140 m	130 m
		MF Cetaceans	183 dB	70 m	70 m	60 m
		HF Cetaceans	183 dB	60 m	60 m	50 m
		PW Pinnipeds	171 dB	520 m	520 m	510 m

Table 5-9 Summary of the impact ranges for TTS criteria from Southall et al (2007) for installation of pin piles with a maximum blow energy of 2700 kJ

Table 5-10 to Table 5-13 include only the behavioural response ranges for LF and MF cetaceans. The behavioural response ranges for HF cetaceans are given in Table 5-14 to Table 5-17 using the Lucke *et al.* (2009) criteria.

Southall *et al.* (2007) - Behavioural				Monopile (500 kJ)		
				Maximum	**Mean**	**Minimum**
SW	**Likely Avoidance (SEL_{ss})**	LF Cetaceans	152 dB	4.5 km	4.5 km	4.5 km
		MF Cetaceans	170 dB	430 m	430 m	430 m
	Possible Avoidance (SEL_{ss})	LF Cetaceans	142 dB	12 km	12 km	12 km
		MF Cetaceans	160 dB	1.7 km	1.7 km	1.7 km
NE	**Likely Avoidance (SEL_{ss})**	LF Cetaceans	152 dB	2.4 km	2.4 km	2.4 km
		MF Cetaceans	170 dB	210 m	210 m	210 m
	Possible Avoidance (SEL_{ss})	LF Cetaceans	142 dB	7.3 km	7.0 km	6.8 km
		MF Cetaceans	160 dB	850 m	850 m	850 m

Table 5-10 Summary of the single strike impact ranges for behavioural response criteria from Southall et al (2007) for installation of a monopile using the soft start blow energy of 500 kJ

Southall *et al.* (2007) - Behavioural				Monopile (5000 kJ)		
				Maximum	**Mean**	**Minimum**
SW	**Likely Avoidance (SEL_{ss})**	LF Cetaceans	152 dB	14 km	14 km	13 km
		MF Cetaceans	170 dB	2.0 km	2.0 km	2.0 km
	Possible Avoidance (SEL_{ss})	LF Cetaceans	142 dB	28 km	27 km	25 km
		MF Cetaceans	160 dB	6.6 km	6.5 km	6.4 km
NE	**Likely Avoidance (SEL_{ss})**	LF Cetaceans	152 dB	8.8 km	8.4 km	8.2 km
		MF Cetaceans	170 dB	1.1 km	1.1 km	1.1 km
	Possible Avoidance (SEL_{ss})	LF Cetaceans	142 dB	19 km	18 km	17 km
		MF Cetaceans	160 dB	3.9 km	3.8 km	3.7 km

Table 5-11 Summary of the impact ranges for behavioural response criteria from Southall et al (2007) for installation of a monopile with a maximum blow energy of 5000 kJ

Southall *et al.* (2007) - Behavioural				Pin Pile (270 kJ)		
				Maximum	Mean	Minimum
SW	Likely Avoidance (SEL_{ss})	LF Cetaceans	152 dB	2.7 km	2.7 km	2.7 km
		MF Cetaceans	170 dB	230 m	230 m	230 m
	Possible Avoidance (SEL_{ss})	LF Cetaceans	142 dB	8.3 km	8.2 km	8.0 km
		MF Cetaceans	160 dB	940 m	940 m	930 m
NE	Likely Avoidance (SEL_{ss})	LF Cetaceans	152 dB	1.4 km	1.4 km	1.4 km
		MF Cetaceans	170 dB	120 m	120 m	110 m
	Possible Avoidance (SEL_{ss})	LF Cetaceans	142 dB	4.7 km	4.6 km	4.4 km
		MF Cetaceans	160 dB	470 m	470 m	470 m

Table 5-12 Summary of the single strike impact ranges for behavioural response criteria from Southall et al (2007) for installation of pin piles using the soft start blow energy of 270 kJ

Southall *et al.* (2007) - Behavioural				Pin Pile (2700 kJ)		
				Maximum	Mean	Minimum
SW	Likely Avoidance (SEL_{ss})	LF Cetaceans	152 dB	11 km	11 km	11 km
		MF Cetaceans	170 dB	1.5 km	1.5 km	1.5 km
	Possible Avoidance (SEL_{ss})	LF Cetaceans	142 dB	25 km	23 km	22 km
		MF Cetaceans	160 dB	5.1 km	5.0 km	5.0 km
NE	Likely Avoidance (SEL_{ss})	LF Cetaceans	152 dB	7.0 km	6.7 km	6.5 km
		MF Cetaceans	170 dB	800 m	800 m	790 m
	Possible Avoidance (SEL_{ss})	LF Cetaceans	142 dB	16 km	15 km	14 km
		MF Cetaceans	160 dB	2.9 km	2.8 km	2.8 km

Table 5-13 Summary of the impact ranges for behavioural response criteria from Southall et al (2007) for installation of pin piles with a maximum blow energy of 2700 kJ

5.2.1.2 Lucke et al. (2009) results

Table 5-14 to Table 5-17 present the predicted impact ranges in terms of the criteria from Lucke *et al.* (2009), covering auditory injury, TTS and behavioural reaction in harbour porpoise. These criteria are defined in section 2.2.2.1. The criteria from Lucke *et al.* (2009) are all unweighted single strike SELs. As before, impact ranges less than 50 m have not been given in detail.

Lucke *et al*. (2009)			Monopile (500 kJ)		
			Maximum	Mean	Minimum
SW	Auditory injury (SEL_{ss})	179 dB	120 m	120 m	120 m
	TTS (SEL_{ss})	164 dB	980 m	980 m	980 m
	Behavioural (SEL_{ss})	145 dB	9.4 km	9.3 km	9.0 km
NE	Auditory injury (SEL_{ss})	179 dB	60 m	60 m	60 m
	TTS (SEL_{ss})	164 dB	490 m	490 m	490 m
	Behavioural (SEL_{ss})	145 dB	5.4 km	5.2 km	5.1 km

Table 5-14 Summary of the single strike impact ranges for criteria from Lucke et al. (2009) for installation of a monopile using the soft start blow energy of 500 kJ

Lucke *et al*. (2009)			Monopile (5000 kJ)		
			Maximum	Mean	Minimum
SW	Auditory injury (SEL_{ss})	179 dB	610 m	610 m	600 m
	TTS (SEL_{ss})	164 dB	4.2 km	4.2 km	4.1 km
	Behavioural (SEL_{ss})	145 dB	24 km	22 km	21 km
NE	Auditory injury (SEL_{ss})	179 dB	340 m	340 m	330 m
	TTS (SEL_{ss})	164 dB	2.4 km	2.4 km	2.4 km
	Behavioural (SEL_{ss})	145 dB	15 km	15 km	14 km

Table 5-15 Summary of the impact ranges for criteria from Lucke et al. (2009) for installation of a monopile with a maximum blow energy of 5000 kJ

Lucke *et al*. (2009)			Pin Pile (270 kJ)		
			Maximum	**Mean**	**Minimum**
SW	**Auditory injury (SEL_{ss})**	179 dB	70 m	70 m	60 m
	TTS (SEL_{ss})	164 dB	540 m	540 m	540 m
	Behavioural (SEL_{ss})	145 dB	6.1 km	6.0 km	5.9 km
NE	**Auditory injury (SEL_{ss})**	179 dB	30 m	30 m	30 m
	TTS (SEL_{ss})	164 dB	270 m	270 m	270 m
	Behavioural (SEL_{ss})	145 dB	3.4 km	3.3 km	3.2 km

Table 5-16 Summary of the single strike impact ranges for criteria from Lucke et al. (2009) for installation of pin piles using the soft start blow energy of 270 kJ

Lucke *et al*. (2009)			Pin Pile (2700 kJ)		
			Maximum	**Mean**	**Minimum**
SW	**Auditory injury (SEL_{ss})**	179 dB	440 m	440 m	430 m
	TTS (SEL_{ss})	164 dB	3.2 km	3.2 km	3.2 km
	Behavioural (SEL_{ss})	145 dB	20 km	19 km	18 km
NE	**Auditory injury (SEL_{ss})**	179 dB	240 m	240 m	230 m
	TTS (SEL_{ss})	164 dB	1.8 km	1.7 km	1.7 km
	Behavioural (SEL_{ss})	145 dB	13 km	12 km	12 km

Table 5-17 Summary of the impact ranges for criteria from Lucke et al. (2009) for installation of pin piles with a maximum blow energy of 2700 kJ

5.2.1.3 NMFS (2016) results

Predicted auditory injury and TTS impact ranges are given in Table 5-18 to Table 5-25 using the NMFS unweighted SPL_{peak} and weighted SEL_{cum} criteria from NMFS (2016). Again, ranges less than 50 m (SPL_{peak}) and 100 m (SEL_{cum}) have not been given in detail.

NMFS (2016) - Auditory Injury				Monopile (500 kJ)		
				Maximum	**Mean**	**Minimum**
SW	**Unweighted SPL_{peak}**	LF Cetaceans	219 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	230 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	202 dB	70 m	70 m	70 m
		PW Pinnipeds	218 dB	< 50 m	< 50 m	< 50 m
NE	**Unweighted SPL_{peak}**	LF Cetaceans	219 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	230 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	202 dB	< 50 m	< 50 m	< 50 m
		PW Pinnipeds	218 dB	< 50 m	< 50 m	< 50 m

Table 5-18 Summary of the single strike impact ranges for auditory injury from NMFS (2016) for installation of a monopile using the soft start blow energy of 500 kJ

NMFS (2016) - Auditory Injury				Monopile (5000 kJ)		
				Maximum	**Mean**	**Minimum**
SW location	**Unweighted SPL_{peak}**	LF Cetaceans	219 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	230 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	202 dB	340 m	340 m	340 m
		PW Pinnipeds	218 dB	< 50 m	< 50 m	< 50 m
	Weighted SEL_{cum}	LF Cetaceans	183 dB	200 m	200 m	200 m
		MF Cetaceans	185 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	155 dB	< 100 m	< 100 m	< 100 m
		PW Pinnipeds	185 dB	< 100 m	< 100 m	< 100 m
NE location	**Unweighted SPL_{peak}**	LF Cetaceans	219 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	230 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	202 dB	190 m	190 m	180 m
		PW Pinnipeds	218 dB	< 50 m	< 50 m	< 50 m
	Weighted SEL_{cum}	LF Cetaceans	183 dB	< 100 m	< 100 m	< 100 m
		MF Cetaceans	185 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	155 dB	< 100 m	< 100 m	< 100 m
		PW Pinnipeds	185 dB	< 100 m	< 100 m	< 100 m

Table 5-19 Summary of the impact ranges for auditory injury from NMFS (2016) for installation of a monopile with a maximum blow energy of 5000 kJ

NMFS (2016) - Auditory Injury				Pin Pile (270 kJ)		
				Maximum	**Mean**	**Minimum**
SW	**Unweighted SPL_{peak}**	LF Cetaceans	219 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	230 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	202 dB	< 50 m	< 50 m	< 50 m
		PW Pinnipeds	218 dB	< 50 m	< 50 m	< 50 m
NE	**Unweighted SPL_{peak}**	LF Cetaceans	219 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	230 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	202 dB	< 50 m	< 50 m	< 50 m
		PW Pinnipeds	218 dB	< 50 m	< 50 m	< 50 m

Table 5-20 Summary of the single strike impact ranges for auditory injury from NMFS (2016) for installation of pin piles using the soft start blow energy of 270 kJ

NMFS (2016) - Auditory Injury				Pin Pile (2700 kJ)		
				Maximum	**Mean**	**Minimum**
SW location	**Unweighted SPL_{peak}**	LF Cetaceans	219 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	230 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	202 dB	250 m	250 m	240 m
		PW Pinnipeds	218 dB	< 50 m	< 50 m	< 50 m
	Weighted SEL_{cum} (6 hours)	LF Cetaceans	183 dB	< 100 m	< 100 m	< 100 m
		MF Cetaceans	185 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	155 dB	300 m	250 m	200 m
		PW Pinnipeds	185 dB	< 100 m	< 100 m	< 100 m
	Weighted SEL_{cum} (12 hours)	LF Cetaceans	183 dB	< 100 m	< 100 m	< 100 m
		MF Cetaceans	185 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	155 dB	400 m	350 m	300 m
		PW Pinnipeds	185 dB	< 100 m	< 100 m	< 100 m
NE location	**Unweighted SPL_{peak}**	LF Cetaceans	219 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	230 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	202 dB	130 m	130 m	130 m
		PW Pinnipeds	218 dB	< 50 m	< 50 m	< 50 m
	Weighted SEL_{cum} (6 hours)	LF Cetaceans	183 dB	< 100 m	< 100 m	< 100 m
		MF Cetaceans	185 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	155 dB	< 100 m	< 100 m	< 100 m
		PW Pinnipeds	185 dB	< 100 m	< 100 m	< 100 m
	Weighted SEL_{cum} (12 hours)	LF Cetaceans	183 dB	< 100 m	< 100 m	< 100 m
		MF Cetaceans	185 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	155 dB	< 100 m	< 100 m	< 100 m
		PW Pinnipeds	185 dB	< 100 m	< 100 m	< 100 m

Table 5-21 Summary of the impact ranges for auditory injury from NMFS (2016) for installation of pin piles with a maximum blow energy of 2700 kJ

NMFS (2016) - TTS				Monopile (500 kJ)		
				Maximum	**Mean**	**Minimum**
SW	**Unweighted SPL_{peak}**	LF Cetaceans	213 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	224 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	196 dB	160 m	160 m	160 m
		PW Pinnipeds	212 dB	< 50 m	< 50 m	< 50 m
NE	**Unweighted SPL_{peak}**	LF Cetaceans	213 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	224 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	196 dB	80 m	80 m	80 m
		PW Pinnipeds	212 dB	< 50 m	< 50 m	< 50 m

Table 5-22 Summary of the single strike impact ranges for TTS from NMFS (2016) for installation of a monopile using the soft start blow energy of 500 kJ

NMFS (2016) - TTS				Monopile (5000 kJ)		
				Maximum	**Mean**	**Minimum**
SW location	**Unweighted SPL_{peak}**	LF Cetaceans	213 dB	70 m	70 m	70 m
		MF Cetaceans	224 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	196 dB	790 m	780 m	780 m
		PW Pinnipeds	212 dB	80 m	80 m	80 m
	Weighted SEL_{cum}	LF Cetaceans	168 dB	18 km	16 km	14 km
		MF Cetaceans	170 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	140 dB	7.4 km	7.0 km	6.6 km
		PW Pinnipeds	170 dB	5.0 km	4.7 km	4.5 km
NE location	**Unweighted SPL_{peak}**	LF Cetaceans	213 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	224 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	196 dB	430 m	430 m	430 m
		PW Pinnipeds	212 dB	< 50 m	< 50 m	< 50 m
	Weighted SEL_{cum}	LF Cetaceans	168 dB	7.8 km	7.1 km	6.5 km
		MF Cetaceans	170 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	140 dB	2.5 km	2.2 km	2.0 km
		PW Pinnipeds	170 dB	1.1 km	1.0 km	800 m

Table 5-23 Summary of the impact ranges for TTS from NMFS (2016) for installation of a monopile with a maximum blow energy of 5000 kJ

NMFS (2016) - TTS				Pin Pile (270 kJ)		
				Maximum	**Mean**	**Minimum**
SW	**Unweighted SPL_{peak}**	LF Cetaceans	213 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	224 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	196 dB	90 m	90 m	90 m
		PW Pinnipeds	212 dB	< 50 m	< 50 m	< 50 m
NE	**Unweighted SPL_{peak}**	LF Cetaceans	213 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	224 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	196 dB	< 50 m	< 50 m	< 50 m
		PW Pinnipeds	212 dB	< 50 m	< 50 m	< 50 m

Table 5-24 Summary of the single strike impact ranges for TTS from NMFS (2016) for installation of pin piles using the soft start blow energy of 270 kJ

NMFS (2016) - TTS				Pin Pile (2700 kJ)		
				Maximum	**Mean**	**Minimum**
SW location	**Unweighted SPL_{peak}**	LF Cetaceans	213 dB	50 m	50 m	50 m
		MF Cetaceans	224 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	196 dB	570 m	570 m	570 m
		PW Pinnipeds	212 dB	60 m	60 m	60 m
	Weighted SEL_{cum} (6 hours)	LF Cetaceans	168 dB	13 km	12 km	11 km
		MF Cetaceans	170 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	140 dB	15 km	14 km	13 km
		PW Pinnipeds	170 dB	2.7 km	2.6 km	2.4 km
	Weighted SEL_{cum} (12 hours)	LF Cetaceans	168 dB	14 km	12 km	11 km
		MF Cetaceans	170 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	140 dB	16 km	15 km	13 km
		PW Pinnipeds	170 dB	3.1 km	2.9 km	2.7 km
NE location	**Unweighted SPL_{peak}**	LF Cetaceans	213 dB	< 50 m	< 50 m	< 50 m
		MF Cetaceans	224 dB	< 50 m	< 50 m	< 50 m
		HF Cetaceans	196 dB	300 m	300 m	300 m
		PW Pinnipeds	212 dB	< 50 m	< 50 m	< 50 m
	Weighted SEL_{cum} (6 hours)	LF Cetaceans	168 dB	5.0 km	4.4 km	3.9 km
		MF Cetaceans	170 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	140 dB	7.0 km	6.4 km	6.0 km
		PW Pinnipeds	170 dB	< 100 m	< 100 m	< 100 m
	Weighted SEL_{cum} (12 hours)	LF Cetaceans	168 dB	5.2 km	4.6 km	4.1 km
		MF Cetaceans	170 dB	< 100 m	< 100 m	< 100 m
		HF Cetaceans	140 dB	7.5 km	6.9 km	6.5 km
		PW Pinnipeds	170 dB	300 m	190 m	< 100 m

Table 5-25 Summary of the impact ranges for TTS from NMFS (2016) for installation of pin piles with a maximum blow energy of 2700 kJ

The ranges of impact vary depending on the functional hearing (species) group and severity of impact. This variation is expressed clearly between the results using the NMFS (2016) criteria, shown above. Looking at results from the SW monopile as an example, the LF weighting leads to the greatest ranges as the MF and HF cetacean and pinniped weightings filter out much of the piling energy. It is also worth noting that greater ranges are created at the SW location due to its position in deeper water.

The SEL_{cum} results for HF cetaceans using the NMFS (2016) criteria appear to give paradoxical results, as a larger hammer hitting a monopile results in lower impact ranges than a smaller hammer hitting a pin pile. This is due to the difference in sensitivity between the marine mammal hearing groups and the sound frequencies produced by the different piles. This can also be the case for MF cetaceans, but due to the low impact ranges this is not apparent in the tables.

The frequency spectra used as inputs to the model (Figure 4-2) show that the noise from pin piles contains more high frequency components than the noise from monopiles. The overall unweighted noise level is higher for the monopile due to the low frequency components of piling noise (i.e. most of the pile strike energy is in the lower frequencies). The MF and HF cetacean filters (Figure 2-1) both remove the low frequency components of the noise, as these marine mammals are much less sensitive to noise at these frequencies. This leaves the higher frequency noise, which, in the case of the pin piles, is higher than that for the monopiles.

To illustrate this, Figure 5-7 shows the sound frequency spectra for monopiles and pin piles, adjusted (weighted) to account for the sensitivities of MF and HF cetaceans. These can be compared to the original unweighted frequency spectra in Figure 4-2 (shown faintly in Figure 5-7). Overall, higher levels are present in the weighted pin pile spectrum.

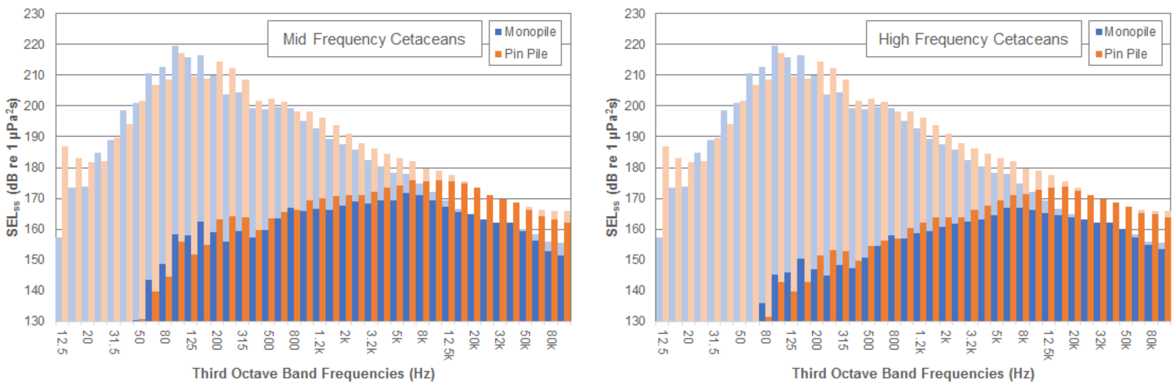

Figure 5-7 Filtered noise inputs for monopiles and pin piles using the MF and HF cetacean filters from NMFS (2016). The lighter coloured bars show the unweighted third octave levels

5.2.2 Impacts on fish

Table 5-26 to Table 5-37 give the maximum, minimum, and mean impact ranges for species of fish based on the injury criteria found in the Popper *et al.* (2014) guidance. For the SEL_{cum} criteria, a fleeing animal speed of 1.5 ms^{-1} has been used (Hirata, 1999). All the impact thresholds from the Popper *et al.* (2014) guidance are unweighted. It should be noted that some of the same noise levels are used as criteria for multiple effects. This is as per the Popper *et al.* (2014) guidelines (shown in Table 2-9), which is based on a comprehensive literature review. The data available to create the criteria are very limited and most criteria are “greater than”, with a precise threshold not identified. All ranges associated with criteria defined as “>” are therefore somewhat conservative and in practice the actual range at which an effect could occur will be somewhat lower. As with the marine mammal criteria, impact ranges less than 50 m (SPL_{peak}) and 100 m (SEL_{cum}) have not been included.

The results show that fish with swim bladders involved in hearing are the most sensitive to the impact piling noise with ranges of up to few hundreds of metres for the SPL_{peak} injury criteria and ranges up to 6.5 km for TTS (SEL_{cum}).

Popper *et al.* (2014) - Fish (no swim bladder)				Monopile (500 kJ)		
				Maximum	**Mean**	**Minimum**
SW	**SPL_{peak}**	Mortality and potential mortal injury	> 213 dB	< 50 m	< 50 m	< 50 m
		Recoverable injury	> 213 dB	< 50 m	< 50 m	< 50 m
NE	**SPL_{peak}**	Mortality and potential mortal injury	> 213 dB	< 50 m	< 50 m	< 50 m
		Recoverable injury	> 213 dB	< 50 m	< 50 m	< 50 m

Table 5-26 Summary of the single strike impact ranges for fish (no swim bladder) using the criteria from Popper et al. (2014) for installation of a monopile using the soft start blow energy of 500 kJ

Popper *et al.* (2014) - Fish (no swim bladder)				Monopile (5000 kJ)		
				Maximum	**Mean**	**Minimum**
SW location	**SPL$_{peak}$**	Mortality and potential mortal injury	> 213 dB	70 m	70 m	70 m
		Recoverable injury	> 213 dB	70 m	70 m	70 m
	SEL$_{cum}$	Mortality and potential mortal injury	> 219 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	> 216 dB	< 100 m	< 100 m	< 100 m
		TTS	>> 186 dB	6.5 km	6.2 km	5.8 km
NE location	**SPL$_{peak}$**	Mortality and potential mortal injury	> 213 dB	< 50 m	< 50 m	< 50 m
		Recoverable injury	> 213 dB	< 50 m	< 50 m	< 50 m
	SEL$_{cum}$	Mortality and potential mortal injury	> 219 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	> 216 dB	< 100 m	< 100 m	< 100 m
		TTS	>> 186 dB	2.0 km	1.7 km	1.6 km

Table 5-27 Summary of the impact ranges for fish (no swim bladder) using the criteria from Popper et al. (2014) for installation of a monopile with a maximum blow energy of 5000 kJ

Popper *et al.* (2014) - Fish (no swim bladder)				Pin Pile (270 kJ)		
				Maximum	**Mean**	**Minimum**
SW	**SPL$_{peak}$**	Mortality and potential mortal injury	> 213 dB	< 50 m	< 50 m	< 50 m
		Recoverable injury	> 213 dB	< 50 m	< 50 m	< 50 m
NE	**SPL$_{peak}$**	Mortality and potential mortal injury	> 213 dB	< 50 m	< 50 m	< 50 m
		Recoverable injury	> 213 dB	< 50 m	< 50 m	< 50 m

Table 5-28 Summary of the single strike impact ranges for fish (no swim bladder) using the criteria from Popper et al. (2014) for installation of pin piles using the soft start blow energy of 270 kJ

Popper *et al.* (2014) - Fish (no swim bladder)				Pin Pile (2700 kJ)		
				Maximum	**Mean**	**Minimum**
SW location	**SPL$_{peak}$**	Mortality and potential mortal injury	> 213 dB	50 m	50 m	50 m
		Recoverable injury	> 213 dB	50 m	50 m	50 m
	SEL$_{cum}$ (6 hours)	Mortality and potential mortal injury	> 219 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	> 216 dB	< 100 m	< 100 m	< 100 m
		TTS	>> 186 dB	3.6 km	3.5 km	3.3 km
	SEL$_{cum}$ (12 hours)	Mortality and potential mortal injury	> 219 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	> 216 dB	< 100 m	< 100 m	< 100 m
		TTS	>> 186 dB	4.1 km	3.9 km	3.7 km
NE location	**SPL$_{peak}$**	Mortality and potential mortal injury	> 213 dB	< 50 m	< 50 m	< 50 m
		Recoverable injury	> 213 dB	< 50 m	< 50 m	< 50 m
	SEL$_{cum}$ (6 hours)	Mortality and potential mortal injury	> 219 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	> 216 dB	< 100 m	< 100 m	< 100 m
		TTS	>> 186 dB	500 m	390 m	300 m
	SEL$_{cum}$ (12 hours)	Mortality and potential mortal injury	> 219 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	> 216 dB	< 100 m	< 100 m	< 100 m
		TTS	>> 186 dB	600 m	460 m	300 m

Table 5-29 Summary of the impact ranges for fish (no swim bladder) using the criteria from Popper et al. (2014) for installation of pin piles with a maximum blow energy of 2700 kJ

Popper *et al.* (2014) - Fish (swim bladder not involved in hearing)				Monopile (500 kJ)		
				Maximum	**Mean**	**Minimum**
SW	**SPL$_{peak}$**	Mortality and potential mortal injury	> 207 dB	< 50 m	< 50 m	< 50 m
		Recoverable injury	> 207 dB	< 50 m	< 50 m	< 50 m
NE	**SPL$_{peak}$**	Mortality and potential mortal injury	> 207 dB	< 50 m	< 50 m	< 50 m
		Recoverable injury	> 207 dB	< 50 m	< 50 m	< 50 m

Table 5-30 Summary of the single strike impact ranges for fish (swim bladder not involved in hearing) using the criteria from Popper et al. (2014) for installation of a monopile using the soft start blow energy of 500 kJ

Popper *et al.* (2014) - Fish (swim bladder not involved in hearing)				Monopile (5000 kJ)		
				Maximum	**Mean**	**Minimum**
SW location	**SPL$_{peak}$**	Mortality and potential mortal injury	> 207 dB	170 m	170 m	170 m
		Recoverable injury	> 207 dB	170 m	170 m	170 m
	SEL$_{cum}$	Mortality and potential mortal injury	210 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	203 dB	< 100 m	< 100 m	< 100 m
		TTS	> 186 dB	6.5 km	6.2 km	5.8 km
NE location	**SPL$_{peak}$**	Mortality and potential mortal injury	> 207 dB	90 m	90 m	90 m
		Recoverable injury	> 207 dB	90 m	90 m	90 m
	SEL$_{cum}$	Mortality and potential mortal injury	210 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	203 dB	< 100 m	< 100 m	< 100 m
		TTS	> 186 dB	2.0 km	1.7 km	1.6 km

Table 5-31 Summary of the impact ranges for fish (swim bladder not involved in hearing) using the criteria from Popper et al. (2014) for installation of a monopile with a maximum blow energy of 5000 kJ

Popper *et al.* (2014) - Fish (swim bladder not involved in hearing)				Pin Pile (270 kJ)		
				Maximum	**Mean**	**Minimum**
SW	**SPL$_{peak}$**	Mortality and potential mortal injury	> 207 dB	< 50 m	< 50 m	< 50 m
		Recoverable injury	> 207 dB	< 50 m	< 50 m	< 50 m
NE	**SPL$_{peak}$**	Mortality and potential mortal injury	> 207 dB	< 50 m	< 50 m	< 50 m
		Recoverable injury	> 207 dB	< 50 m	< 50 m	< 50 m

Table 5-32 Summary of the single strike impact ranges for fish (swim bladder not involved in hearing) using the criteria from Popper et al. (2014) for installation of pin piles using the soft start blow energy of 270 kJ

Popper *et al.* (2014) - Fish (swim bladder not involved in hearing)				Pin Pile (2700 kJ)		
				Maximum	**Mean**	**Minimum**
SW location	**SPL_{peak}**	Mortality and potential mortal injury	> 207 dB	120 m	120 m	120 m
		Recoverable injury	> 207 dB	120 m	120 m	120 m
	SEL_{cum} (6 hours)	Mortality and potential mortal injury	210 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	203 dB	< 100 m	< 100 m	< 100 m
		TTS	> 186 dB	3.6 km	3.5 km	3.3 km
	SEL_{cum} (12 hours)	Mortality and potential mortal injury	210 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	203 dB	< 100 m	< 100 m	< 100 m
		TTS	> 186 dB	4.1 km	3.9 km	3.7 km
NE location	**SPL_{peak}**	Mortality and potential mortal injury	> 207 dB	60 m	60 m	60 m
		Recoverable injury	> 207 dB	60 m	60 m	60 m
	SEL_{cum} (6 hours)	Mortality and potential mortal injury	210 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	203 dB	< 100 m	< 100 m	< 100 m
		TTS	> 186 dB	500 m	390 m	300 m
	SEL_{cum} (12 hours)	Mortality and potential mortal injury	210 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	203 dB	< 100 m	< 100 m	< 100 m
		TTS	> 186 dB	600 m	460 m	300 m

Table 5-33 Summary of the impact ranges for fish (swim bladder not involved in hearing) using the criteria from Popper et al. (2014) for installation of pin piles with a maximum blow energy of 2700 kJ

Popper *et al.* (2014) - Fish (swim bladder involved in hearing)				Monopile (500 kJ)		
				Maximum	**Mean**	**Minimum**
SW	**SPL_{peak}**	Mortality and potential mortal injury	> 207 dB	< 50 m	< 50 m	< 50 m
		Recoverable injury	> 207 dB	< 50 m	< 50 m	< 50 m
NE	**SPL_{peak}**	Mortality and potential mortal injury	> 207 dB	< 50 m	< 50 m	< 50 m
		Recoverable injury	> 207 dB	< 50 m	< 50 m	< 50 m

Table 5-34 Summary of the single strike impact ranges for fish (swim bladder involved in hearing) using the criteria from Popper et al. (2014) for installation of a monopile using the soft start blow energy of 500 kJ

Popper *et al.* (2014) - Fish (swim bladder involved in hearing)				Monopile (5000 kJ)		
				Maximum	**Mean**	**Minimum**
SW location	**SPL_{peak}**	Mortality and potential mortal injury	> 207 dB	170 m	170 m	170 m
		Recoverable injury	> 207 dB	170 m	170 m	170 m
	SEL_{cum}	Mortality and potential mortal injury	207 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	203 dB	< 100 m	< 100 m	< 100 m
		TTS	186 dB	6.5 km	6.2 km	5.8 km
NE location	**SPL_{peak}**	Mortality and potential mortal injury	> 207 dB	90 m	90 m	90 m
		Recoverable injury	> 207 dB	90 m	90 m	90 m
	SEL_{cum}	Mortality and potential mortal injury	207 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	203 dB	< 100 m	< 100 m	< 100 m
		TTS	186 dB	2.0 km	1.7 km	1.6 km

Table 5-35 Summary of the impact ranges for fish (swim bladder involved in hearing) using the criteria from Popper et al. (2014) for installation of a monopile with a maximum blow energy of 5000 kJ

Popper *et al.* (2014) - Fish (swim bladder involved in hearing)				**Pin Pile (270 kJ)**		
				Maximum	**Mean**	**Minimum**
SW	**SPL_{peak}**	Mortality and potential mortal injury	> 207 dB	< 50 m	< 50 m	< 50 m
		Recoverable injury	> 207 dB	< 50 m	< 50 m	< 50 m
NE	**SPL_{peak}**	Mortality and potential mortal injury	> 207 dB	< 50 m	< 50 m	< 50 m
		Recoverable injury	> 207 dB	< 50 m	< 50 m	< 50 m

Table 5-36 Summary of the single strike impact ranges for fish (swim bladder involved in hearing) using the criteria from Popper et al. (2014) for installation of pin piles using the soft start blow energy of 270 kJ

Popper *et al.* (2014) - Fish (swim bladder involved in hearing)				**Pin Pile (2700 kJ)**		
				Maximum	**Mean**	**Minimum**
SW location	**SPL_{peak}**	Mortality and potential mortal injury	> 207 dB	120 m	120 m	120 m
		Recoverable injury	> 207 dB	120 m	120 m	120 m
	SEL_{cum} (6 hours)	Mortality and potential mortal injury	207 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	203 dB	< 100 m	< 100 m	< 100 m
		TTS	186 dB	3.6 km	3.5 km	3.3 km
	SEL_{cum} (12 hours)	Mortality and potential mortal injury	207 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	203 dB	< 100 m	< 100 m	< 100 m
		TTS	186 dB	4.1 km	3.9 km	3.7 km
NE location	**SPL_{peak}**	Mortality and potential mortal injury	> 207 dB	60 m	60 m	60 m
		Recoverable injury	> 207 dB	60 m	60 m	60 m
	SEL_{cum} (6 hours)	Mortality and potential mortal injury	207 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	203 dB	< 100 m	< 100 m	< 100 m
		TTS	186 dB	500 m	390 m	300 m
	SEL_{cum} (12 hours)	Mortality and potential mortal injury	207 dB	< 100 m	< 100 m	< 100 m
		Recoverable injury	203 dB	< 100 m	< 100 m	< 100 m
		TTS	186 dB	600 m	460 m	300 m

Table 5-37 Summary of the impact ranges for fish (swim bladder involved in hearing) using the criteria from Popper et al. (2014) for installation of pin piles with a maximum blow energy of 2700 kJ

6 Other noise impacts

6.1 Introduction

Although impact piling is expected to be the primary noise source during the Norfolk Boreas development (Bailey *et al.* 2014), several other noise sources will also be present. Each of these has been considered and its impact assessed in this section.

Table 6-1 provides a summary of the various noise producing sources, aside from impact piling, that could be present during the construction and operation of Norfolk Boreas.

Activity	Description
Dredging	Trailer suction hopper dredger may be required on site for the export cable, array cable and interconnector cable installation.
Drilling	Necessary in case if impact piling refusal
Cable laying	Required during the offshore cable installation.
Rock placement	Potentially required on site for installation of offshore cables and scour protection.
Trenching	Plough trenching may be required during offshore cable installation.
Vessel noise	Jack-up barges for piling, substructure and turbine installation. Other large and medium sized vessels on site to carry out other construction tasks, dive support and anchor handling. Other small vessels for crew transport and maintenance on site.
Operational WTG	Noise transmitted through the water from operational wind turbine generators. The project design envelope gives turbine sizes of between 9 MW and 20 MW.

Table 6-1 Summary of the possible noise making activities at Norfolk Boreas

The NPL Good Practice Guide 133 for underwater noise (Robinson *et al*. 2014) indicates that under certain circumstances, a simple modelling approach may be considered acceptable. High-level modelling was undertaken using the SPEAR model and is considered sufficient and there would be little benefit in using a more detailed model for these sources. The limitations of this approach are noted, including the lack of frequency or bathymetry dependence.

6.2 SPEAR model description

The SPEAR (Simple Propagation Estimator And Ranking) model is based on Subacoustech Envrionmental's database of noise measurements. It uses a simple source level and transmission loss (SL-TL) spreading model for calculating impact ranges produced by the particular noise source. Results can easily be compared to determine the significance of the predicted impact as either the effect of the multiple noise sources on one species, or as the effect of one type of noise source against multiple species with varying hearing abilities. The SPEAR model is intended for the estimation of impact ranges from relatively low-level noises and also rank ordering of a number of activities that cause underwater noise in order of significance, so that the critical activities can be identified and selected or evaluated. Typically SPEAR can be used to identify the effect of a range of noise sources on a particular species or the effect of a particular noise source on a range of animals.

The simple model does not take bathymetry or other specific environmental parameters into account, but since it is built around noise data sampled in relatively shallow water around the UK, the relatively short ranges calculated are expected to be of the correct order at Norfolk Boreas. It is not intended for detailed modelling outputs, so where impact ranges demonstrate that there may be potentially significant adverse effects, a more in-depth underwater noise model would be recommended for further investigation.

6.3 Construction activities

For the purposes of identifying the greatest noise impacts, approximate subsea noise levels have been predicted using a simple modelling approach based on measured data scaled to relevant parameters for the site. Extrapolated source levels at 1 m range for the construction activities are presented in Table 6-2. Operational WTGs have been assessed separately in section 6.4.

At these levels, any marine mammal would have to remain in close proximity (i.e. less than 500 m, and in most cases less than 50 m) from the source for 24 hours to be exposed to levels sufficient to induce PTS as per NMFS (2016). In most hearing groups, the noise levels are low enough that there is negligible risk.

There is a low to negligible risk of any injury or TTS to fish, in line with guidance for continuous noise sources in Popper *et al.* (2014). These results are summarised in Table 6-3; it is worth noting that Popper gives different criteria for shipping and continuous noise than the criteria used for impact piling.

	Estimated unweighted source level	**Comments**
Dredging	186 dB re 1 µPa @ 1 m (RMS)	Based on five datasets from suction and cutter suction dredgers.
Drilling	179 dB re 1 µPa @ 1 m (RMS)	Based on seven datasets of offshore drilling using a variety of drill sizes and powers.
Cable laying	171 dB re 1 µPa @ 1 m (RMS)	Based on eleven datasets from a pipe laying vessel measuring 300 m in length; this is considered a worst-case noise source for cable laying operations.
Rock placement	172 dB re 1 µPa @ 1 m (RMS)	Based on four datasets from rock placement vessel 'Rollingstone.'
Trenching	172 dB re 1 µPa @ 1 m (RMS)	Based on three datasets of measurements from trenching vessels more than 100 m in length.
Vessel noise (large)	171 dB re 1 µPa @ 1 m (RMS)	Based on five datasets of large vessels including container ships, FPSOs and other vessels more than 100 m in length. Vessel speed assumed as 12 knots.
Vessel noise (medium)	164 dB re 1 µPa @ 1 m (RMS)	Based on three datasets of moderate sized vessels less than 100 m in length. Vessel speed assumed as 12 knots.

Table 6-2 Summary of the estimated unweighted source levels for the different construction noise sources considered

Due to uncertainty in the calculation of subsea noise propagation close to a relatively large source, single strike ranges less than 50 m and cumulative ranges less than 100 m are presented to these limits.

		Dredging	Drilling	Cable Laying	Rock Placement	Trenching	Vessels (Large)	Vessels (Medium)
Southall	198 dB LF SEL_{cum}	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	198 dB MF SEL_{cum}	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	198 dB HF SEL_{cum}	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	198 dB PW SEL_{cum}	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Lucke	179 dB Unwtd SEL_{ss}	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
	164 dB Unwtd SEL_{ss}	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
	145 dB Unwtd SEL_{ss}	150 m	130 m	110 m	180 m	120 m	150 m	< 50 m
NMFS	183 dB LF SEL_{cum}	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	185 dB MF SEL_{cum}	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	155 dB HF SEL_{cum}	150 m	< 100 m	< 100 m	460 m	< 100 m	< 100 m	< 100 m
	185 dB PW SEL_{cum}	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Popper	170 dB Unwtd RMS	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
	158 dB Unwtd RMS	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m

Table 6-3 Summary of the PTS impact ranges from the different construction noise sources

6.4 Operational WTG noise

It is believed that the main source of underwater noise from operational turbines will be mechanically generated vibration from the turbines, which is transmitted into the sea through the structure of the support pile and foundations (Nedwell *et al.*, 2003a). Noise levels generated above the water surface are low enough that no significant airborne sound will pass from the air to the water.

The project design envelope for Norfolk Boreas gives a range of WTG sizes, from 9 MW up to 20 MW. A summary of operational WTG where measurements have been collected is given in Table 6-4. As the turbines for Norfolk Boreas are going to be larger than these a scaling factor has been assumed in order to estimate source levels.

	Lynn	**Inner Dowsing**	**Gunfleet Sands 1 & 2**	**Gunfleet Sands 3**
Type of turbine used	Siemens SWT-3.6-107	Siemens SWT-3.6-107	Siemens SWT-3.6-107	Siemens SWT-6.0-120
Number of turbines	27	27	48	2
Rotor diameter	107 m	107 m	107 m	120 m
Water depths	6 to 18 m	6 to 14 m	0 to 15 m	5 to 12 m
Representative sediment type	Sandy gravel / Muddy sandy gravel	Sandy gravel / Muddy sandy gravel	Sand / Muddy sand / Muddy sandy gravel	Sand / Muddy sand / Muddy sandy gravel
Turbine separation (representative)	500 m	500 m	890 m	435 m

Table 6-4 Characteristics of measured operational wind farms used as a basis for modelling

The maximum and minimum turbine sizes for Norfolk Boreas have been modelled (9 MW and 20 MW) to give the expected spread of source levels for operational WTGs.

The estimation of the effects of operational noise in these situations has two features that make it harder to assess compared with noise sources such as impact piling. Primarily, the problem is one of level; noise measurements made at many wind farms have demonstrated that the operational noise produced was at such a low level that it was difficult to measure relative to the background noise (Cheesman, 2016). Also, an offshore wind farm should be considered as an extended, distributed noise source, as opposed to a 'point source' as would be appropriate for pile driving at a single location, for example. The measurement techniques used at the sites above have dealt with these issues by considering the operational noise spectra in terms of levels within and on the edge of the wind farm (but relatively close in, so that some measurements above background could be detected).

Both turbine sizes considered for this modelling are larger than those for which data is available, listed in Table 6-4. Norfolk Boreas is also in greater water depths and as such, estimations of a scaling factor must be highly conservative. However, it is recognised that the available data on which to base the scaling factor is limited and the extrapolation that must be made is significant.

The operational source levels (as SPL_{RMS}) for the measured sites are given in Table 6-5 (Cheesman, 2016), with an estimated source level for Norfolk Boreas in the bottom two rows. These were derived from measurement campaigns at each of the identified wind farm sites, based on data at multiple distances to predict a source level.

To predict to operational noise levels at Norfolk Boreas, the level sampled at each of the sites have been taken and then a linear correction factor has been included to scale up the source levels (Figure 6-1).

This fit was applied to the data available for operational wind turbine noise as this was the extrapolation that would lead to the highest, and thus worst case, estimation of source noise level from the larger 15 MW turbine. This resulted in an estimated source level of 158.5 dB SPL_{rms}, 12 dB higher than the 6 MW turbine, the largest for which noise data existed. Alternatively, using a logarithmic fit (3 dB per doubling of power output) to data would lead to a source level of 149.8 dB SPL_{rms}. A more extreme and unlikely 6 dB increase per doubling of power output would lead to 154.5 dB SPL_{rms}. Thus, the linear estimate used is considerably higher than alternatives and is considered precautionary.

	Unweighted source level (RMS)
Lynn	141 dB re 1 µPa (RMS) @ 1 m
Inner Dowsing	142 dB re 1 µPa (RMS) @ 1 m
Gunfleet Sands 1 & 2	145 dB re 1 µPa (RMS) @ 1 m
Gunfleet Sands 3	146 dB re 1 µPa (RMS) @ 1 m
Norfolk Boreas (9 MW)	150.2 dB re 1 µPa (RMS) @ 1 m
Norfolk Boreas (20 MW)	165.4 dB re 1 µPa (RMS) @ 1 m

Table 6-5 Measured operational noise taken at operational wind farms and the predicted source levels for the sizes of turbine considered at Norfolk Boreas

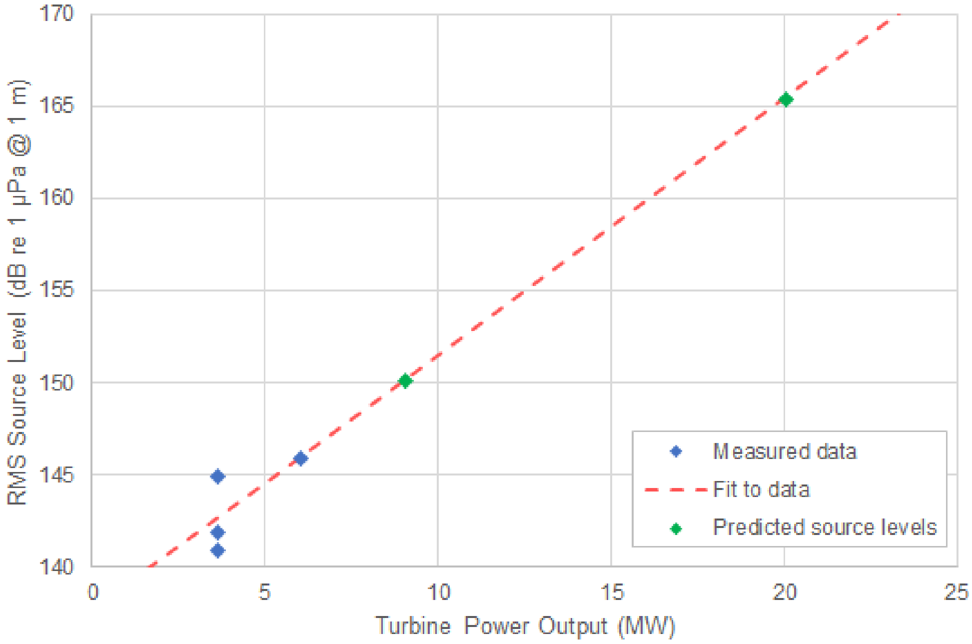

Figure 6-1 Extrapolated source levels from operational WTGs plotted with a linear fit to estimate source levels for larger turbines

A summary of the predicted impact ranges is given in Table 6-6.

		Operational WTG (9 MW)	**Operational WTG (20 MW)**
Southall	198 dB LF SEL_{cum}	< 100 m	< 100 m
	198 dB MF SEL_{cum}	< 100 m	< 100 m
	198 dB HF SEL_{cum}	< 100 m	< 100 m
	198 dB PW SEL_{cum}	< 100 m	< 100 m
Lucke	179 dB Unwtd SEL_{ss}	< 50 m	< 50 m
	164 dB Unwtd SEL_{ss}	< 50 m	< 50 m
	145 dB Unwtd SEL_{ss}	< 50 m	110 m
NMFS	183 dB LF SEL_{cum}	< 100 m	< 100 m
	185 dB MF SEL_{cum}	< 100 m	< 100 m
	155 dB HF SEL_{cum}	< 100 m	< 100 m
	185 dB PW SEL_{cum}	< 100 m	< 100 m
Popper	170 dB Unwtd RMS	< 50 m	< 50 m
	158 dB Unwtd RMS	< 50 m	< 50 m

Table 6-6 Summary of the impact ranges from the considered operational WTGs at Norfolk Boreas

Taking both sets of results into account (operational WTG noise and noise sources related to construction) and comparing them to the impact piling source levels in the following section (specifically Table 4-5), it is clear that impact piling is the much greater noise source and hence the proposed activity which has the potential to have the greatest effect during the development. Any injury risk is minimal, even assuming the receptor stays close to the turbine for 24 hours.

7 Summary and conclusions

Subacoustech Environmental has undertaken a study on behalf of Royal HaskoningDHV and Norfolk Boreas Limited to assess the effect of underwater noise during the development of the Norfolk Boreas Offshore Wind Farm. The study primarily focussed on impact piling noise as this is the foundation installation method known to have the greatest potential underwater noise impacts.

The level of underwater noise from the installation of monopiles and pin piles during construction has been estimated by using the INSPIRE subsea noise modelling software, which considers a wide variety of input parameters including bathymetry, hammer blow energy and frequency content of the noise.

Two representative locations were chosen at the site to give spatial variation as well as changes in depth. At each location, monopiles installed with a maximum hammer blow energy of 5000 kJ and pin piles installed with a maximum hammer blow energy of 2700 kJ were modelled. Greater levels of noise have been predicted overall at the deeper location when installing monopiles, compared with the shallower location.

The modelling results were analysed in terms of relevant noise metrics to assess the impacts of the predicted impact piling noise on marine mammals and fish.

Southall *et al*. (2007), Lucke *et al*. (2009) and NMFS (2016) all give impact criteria for various species of marine mammals using single pulse and cumulative metrics, both weighted and unweighted. The largest impact ranges for these criteria are summarised in Table 7-1 below. For all cases in the table below, the SW location provided the largest impact ranges.

Criteria	Effect	Species	Monopile (5000 kJ)	Pin Pile (2700 kJ)	
				6 hours	12 hours
Southall *et al*. (2007)	Auditory Injury (SEL_{cum})	LF Cetaceans	< 100 m	< 100 m	< 100 m
		MF Cetaceans	< 100 m	< 100 m	< 100 m
		HF Cetaceans	< 100 m	< 100 m	< 100 m
		PW Pinnipeds	3.1 km	2.0 km	2.3 km
	TTS (SEL_{ss})	LF Cetaceans	350 m	260 m	
		MF Cetaceans	140 m	130 m	
		HF Cetaceans	120 m	100 m	
		PW Pinnipeds	1.1 km	970 m	
	Behavioural (SEL_{ss})	LF Cetaceans	14 - 28 km	11 - 25 km	
		MF Cetaceans	2.0 - 6.6 km	1.5 - 5.1 km	
Lucke *et al*. (2009)	Auditory injury (SEL_{ss})	Harbour porpoise	610 m	440 m	
	TTS (SEL_{ss})		4.2 km	3.2 km	
	Behavioural (SEL_{ss})		24 km	20 km	
NMFS (2016)	Auditory injury (SEL_{cum})	LF Cetaceans	200 m	< 100 m	< 100 m
		MF Cetaceans	< 100 m	< 100 m	< 100 m
		HF Cetaceans	< 100 m	300 m	400 m
		PW Pinnipeds	< 100 m	< 100 m	< 100 m
	TTS (SEL_{cum})	LF Cetaceans	18 km	13 km	14 km
		MF Cetaceans	< 100 m	< 100 m	< 100 m
		HF Cetaceans	7.4 km	15 km	16 km
		PW Pinnipeds	5.0 km	2.7 km	3.1 km

Table 7-1 Summary of the maximum predicted impact range for marine mammal criteria

Popper *et al*. (2014) gives impact range criteria for various groups of fish, with ranges of up to 170 m for injury and out to 6.5 km for TTS at the maximum blow energies, when considering monopiles at the SW modelling location.

Various other noise sources have been considered using a high-level, simple noise modelling approach, including dredging, drilling, cable laying, rock placement, trenching, vessel noise and noise from operational wind turbines. The predicted levels for these fell below those predicted for impact piling noise. The risk of any potential injurious effects to fish or marine mammals from these sources are expected to be negligible as the noise emissions from these are very close to, or below, the appropriate injury criteria at the source of the noise.

8 References

1. Bailey H, Brookes K L, Thompson P M (2014). *Assessing environmental impacts of offshore wind farms: lessons learned and recommendations for the future*. Aquatic Biosystems 2014 10:8.
2. Bebb A H, Wright H C (1953). *Injury to animals from underwater explosions.* Medical Research Council, Royal Navy Physiological Report 53/732, Underwater Blast Report 31, January 1953.
3. Bebb A H, Wright H C (1954a). *Lethal conditions from underwater explosion blast.* RNP Report 51/654, RNPL 3/51, National archives reference ADM 298/109, March 1954.
4. Bebb A H, Wright H C (1954b). *Protection from underwater explosion blast. III. Animal experiments and physical measurements.* RNP report 57/792, RNPL 2/54, March. 1954
5. Bebb A H, Wright H C (1955). *Underwater explosion blast data from the Royal Navy Physiological Labs 1950/1955.* Medical Research Council, April 1955.
6. Bergström L, Kautsky L, Malm T, Rosenberg R, Wahlberg M, Capetillo N A and Wilhelmsson D. (2014) *Effects of offshore wind farms on marine wildlife—a generalized impact assessment*. Environ. Res. Lett. 9 (2014) 034012
7. Blix A S, Folkow L P (1995). *Daily energy expenditure in free living minke whales.* Acta Physio. Scand., 153: 61-66.
8. Brekhovskikh L M (1960). *Propagation of surface Rayleigh waves along the uneven boundary of an elastic body.* Sov. Phys. Acoust.
9. Caltrans (2001). *Pile installation demonstration project, San Francisco – Oakland Bridge, East Span Safety Project.* PIPD EA 01281, Caltrans contract 04A0148, August 2001.
10. Cheesman S (2016). *Measurement of operational wind turbine noise in UK waters.* In Popper A N, Hawkins A (eds) *The effects of Noise of Aquatic Life II. Advances in Experimental Medicine and Biology.* Vol 875, pp 153-160. DOI 10.1007/975-1-4939-2981-8_18.
11. Coull K A, Johnstone R, Rogers S I (1998). *Fisheries sensitivity maps in British Waters.* Published and distributed by UKOOA Ltd.
12. Dekeling R P A, Tasker M L, Van der Graaf A J, Ainslie M A, Andersson M H, André M, Borsani J F, Brensing K, Castellote M, Cronin D, Dalen J, Folegot T, Leaper R, Pajala J, Redman P, Robinson S P, Sigray P, Sutton G, Thomsen F, Werner S, Wittekind D, Young J V (2014). *Monitoring Guidance for Underwater Noise in European Seas, Part II: Monitoring Guidance Specifications*, JRC Scientific and Policy Report EUR 26555 EN, Publications Office of the European Union, Luxembourg, 2014, doi: 10.2788/27158.
13. Ellis J R, Milligan S, Readdy L, South A, Taylor N, Brown M (2010). *MB5301 Mapping spawning and nursery areas of species to be considered for Marine Protected Areas (Marine Conservation Zones). Report No 1: Final Report on development of derived data layers for 40 mobile species considered to be of conservation importance.* Cefas report for Defra, August 2010.
14. Etter P C (2013). *Underwater Acoustic Modeling and Simulation*. CRC Press FL (2013), 10.1201/b13906
15. Hastings M C, Popper A N (2005). *Effects of sound on fish.* Report to the California Department of Transport, under Contract No. 43A01392005, January 2005.

16. Hirata K (1999). *Swimming speeds of some common fish. National Maritime Research Institute (Japan).* Data Sourced from Iwai T, Hisada M (1998). *Fishes – Illustrated Book of Gakken (in Japanese), Gakken.* Accessed 8th March 2017 at http://www.nmri.go.jp/eng/khirata/general/ speed/speede/htm

17. Jensen F B, Kuperman W A, Porter M B, Schmidt H (2011). *Computational Ocean Acoustics.* Modern Acoustics and Signal Processing. Springer-Verlag, New York. ISBN: 978-1-4419-8678-8.

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

19. McCauley R D, Fewtrell J, Duncan A J, Jenner C, Jenner M-N, Penrose J D, Prince R I T, Adhitya A, Murdoch J, McCabe K (2000). *Marine seismic surveys – A study of environmental implications.* Appea Journal, pp 692-708.

20. National Marine Fisheries Service (NMFS) (2016). *Technical guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts.* U.S. Dept of Commer., NOAA. NOAA Technical Memorandum NMFS-OPR-55, 178 p.

21. Nedwell J R, Langworthy J, Howell D (2003a). *Assessment of subsea noise and vibration from offshore wind turbines and its impact on marine wildlife. Initial measurements of underwater noise during construction of offshore wind farms, and comparison with background noise.* Subacoustech report ref: 544R0423, published by COWRIE, May 2003.

22. Nedwell J R, Turnpenny A W H, Lovell J, Langworthy J W, Howell D M, Edwards B (2003b). *The effects of underwater noise from coastal piling on salmon (Salmo salar) and brown trout (Salmo trutta).* Subacoustech report to the Environment Agency, report ref: 576R0113, December 2003.

23. Nedwell J R, Parvin S J, Edwards B, Workman R, Brooker A G, Kynoch J E (2007). *Measurement and interpretation of underwater noise during construction and operation of offshore windfarms in UK waters.* Subacoustech report ref: 544R0738 to COWRIE. ISBN: 978-09554276-5-4.

24. Nedwell J R, Cheesman S T (2011). *Measurement and assessment of underwater noise during impact piling operations of the foundations of the met mast at hornsea windfarm.* Subacoustech Environmental report reference E322R0110.

25. Otani S, Naito T, Kato A, Kawamura A (2000). *Diving behaviour and swimming speed of a free-ranging harbour porpoise (Phocoena phocoena)*. Marine Mammal Science, Volume 16, Issue 4, pp 811-814, October 2000.

26. 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.* Report to CORE Ltd by Subacoustech, report ref: 710R0517.

27. Popper A N, Hawkins A D, Fay R R, Mann D A, Bartol S, Carlson T J, Coombs S, Ellison W T, Gentry R L, Halvorsen M B, Løkkeborg S, Rogers P H, Southall B L, Zeddies D G, Tavolga W N (2014). *Sound exposure guidelines for Fishes and Sea Turtles*. Springer Briefs in Oceanography. DOI 10. 1007/978-3-319-06659-2.

28. Rawlins J S P (1987). *Problems in predicting safe ranges from underwater explosions.* Journal of Naval Science, Volume 13, No. 4 pp. 235-246.

29. Robinson S P, Lepper P A, Hazelwood R A (2014). *Good practice guide for underwater noise measurement.* National Measurement Office, Marine Scotland, The Crown Estate. NPL Good Practice Guide No. 133, ISSN: 1368-6550.

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

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

32. Würsig B, Greene C R, Jefferson T A (2000). *Development of an air bubble curtain to reduce underwater noise of percussive piling.* Mar. Environ. Res. 49 pp. 79-93.

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Annex 1: Comparison of stationary and fleeing impact ranges for fish at Norfolk Boreas Offshore Wind Farm

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Introduction

Following from the underwater noise propagation modelling results presented in the main underwater noise report (reference: P227R0104), additional modelling has been carried out to explore the effects of using a stationary animal model for fish compared to the fleeing animal model assumed in the main report. The stationary animal model assumes that, when exposed to any noise from piling, the fish do not react in any way to reduce their exposure to noise, which will remain at the highest level modelled in the water column. It is considered unlikely that, whether the fish reacts specifically to the noise or not, it would remain at the position of highest noise level for the hours of piling. This stationary animal assumption therefore represents an unrealistic worst case.

Modelling has been undertaken for impact piling at the south west location of the Norfolk Boreas site for the fish criteria given in Popper *et al*. (2014)[1]. All parameters used for modelling are the same as those presented in the main report, with the exception of assumptions of movement of fish during piling activities. The following section presents the stationary animal modelling results alongside the fleeing animal results from the main report.

Popper *et al*. (2014) criteria

A summary of the Popper *et al*. (2014) noise criteria for species of fish and eggs and larvae from impact piling noise is given in Table 1. The SEL_{cum} criteria have been used for the modelling comparisons in the next section. Calculated SPL_{peak} impact ranges will stay the same as in the main report as these do not take noise exposure over time (or receptor movement) into consideration.

Type of animal	Mortality and potential mortal injury	Impairment	
		Recoverable injury	TTS (Temporary Threshold Shift)
Fish: no swim bladder	>219 dB SEL_{cum} or >213 dB SPL_{peak}	>216 dB SEL_{cum} or >213 dB SPL_{peak}	>>186 dB SEL_{cum}
Fish: swim bladder is not involved in hearing	210 dB SEL_{cum} or >207 dB SPL_{peak}	203 dB SEL_{cum} or >207 dB SPL_{peak}	>186 dB SEL_{cum}
Fish: swim bladder involved in hearing	207 dB SEL_{cum} or >207 dB SPL_{peak}	203 dB SEL_{cum} or >207 dB SPL_{peak}	186 dB SEL_{cum}
Eggs and larvae	210 dB SEL_{cum} or >207 dB SPL_{peak}	-	-

Table 1 Criteria for assessment of mortality and potential mortal injury, recoverable injury and TTS in species of fish and eggs and larvae as a consequence of impact piling noise (Popper et al., 2014)

Modelling results

Table 2 to Table 4 present the modelled impact ranges based on the Popper *et al*. (2014) criteria, showing the increase in predicted ranges when using a stationary animal model compared to the fleeing animal model used in the main report. Maximum ranges are predicted of 18 km for stationary animals when considering the 186 dB SEL_{cum} criteria for fish during installation of monopiles, and pin piles over a 12-hour period.

[1] Popper A N, Hawkins A D, Fay R R, Mann D A, Bartol S, Carlson T J, Coombs S, Ellison W T, Gentry R L, Halvorsen M B, Løkkeborg S, Rogers P H, Southall B L, Zeddies D G, Tavolga W N (2014). *Sound exposure guidelines for Fishes and Sea Turtles*. Springer Briefs in Oceanography. DOI 10. 1007/978-3-319-06659-2.

As with the main report, detail for ranges calculated to be less than 100 m have not been included as confidence cannot be given to the accuracy of the results at such close range.

Monopile (5000 kJ)	Stationary animal (0 ms^{-1})			Fleeing animal (1.5 ms^{-1})		
	Maximum	Mean	Minimum	Maximum	Mean	Minimum
219 dB SEL_{cum}	500 m	450 m	400 m	< 100 m	< 100 m	< 100 m
216 dB SEL_{cum}	700 m	650 m	600 m	< 100 m	< 100 m	< 100 m
210 dB SEL_{cum}	1.5 km	1.5 km	1.4 km	< 100 m	< 100 m	< 100 m
207 dB SEL_{cum}	2.2 km	2.1 km	2.0 km	< 100 m	< 100 m	< 100 m
203 dB SEL_{cum}	3.5 km	3.4 km	3.3 km	< 100 m	< 100 m	< 100 m
186 dB SEL_{cum}	18 km	17 km	16 km	6.5 km	6.2 km	5.8 km

Table 2 Summary of the SEL_{cum} impact ranges for fish using criteria from Popper et al. (2014) for installation of a monopile with a maximum blow energy of 5000 kJ

Pin Pile (2700 kJ) (6 hours)	Stationary animal (0 ms^{-1})			Fleeing animal (1.5 ms^{-1})		
	Maximum	Mean	Minimum	Maximum	Mean	Minimum
219 dB SEL_{cum}	400 m	350 m	300 m	< 100 m	< 100 m	< 100 m
216 dB SEL_{cum}	500 m	450 m	400 m	< 100 m	< 100 m	< 100 m
210 dB SEL_{cum}	1.0 km	950 m	900 m	< 100 m	< 100 m	< 100 m
207 dB SEL_{cum}	1.4 km	1.4 km	1.3 km	< 100 m	< 100 m	< 100 m
203 dB SEL_{cum}	2.3 km	2.2 km	2.1 km	< 100 m	< 100 m	< 100 m
186 dB SEL_{cum}	13 km	13 km	13 km	3.6 km	3.5 km	3.3 km

Table 3 Summary of the SEL_{cum} impact ranges for fish using criteria from Popper et al. (2014) for installation of pin piles with a maximum blow energy of 2700 kJ over a period of 6 hours

Pin Pile (2700 kJ) (12 hours)	Stationary animal (0 ms^{-1})			Fleeing animal (1.5 ms^{-1})		
	Maximum	Mean	Minimum	Maximum	Mean	Minimum
219 dB SEL_{cum}	600 m	550 m	500 m	< 100 m	< 100 m	< 100 m
216 dB SEL_{cum}	800 m	750 m	700 m	< 100 m	< 100 m	< 100 m
210 dB SEL_{cum}	1.6 km	1.5 km	1.4 km	< 100 m	< 100 m	< 100 m
207 dB SEL_{cum}	2.2 km	2.2 km	2.1 km	< 100 m	< 100 m	< 100 m
203 dB SEL_{cum}	3.6 km	3.5 km	3.4 km	< 100 m	< 100 m	< 100 m
186 dB SEL_{cum}	18 km	17 km	17 km	4.1 km	3.9 km	3.7 km

Table 4 Summary of the SEL_{cum} impact ranges for fish using criteria from Popper et al. (2014) for installation of pin piles with a maximum blow energy of 2700 kJ over a period of 12 hours

The impact ranges, assuming that the receptor remains static during noise exposure, are considerably greater than when based on a fleeing assumption. It is worth noting that the nearest low intensity fish spawning ground, for sole at 17 km to the west (Ellis *et al.*, 2010[2]), is on the edge of the calculated range in this direction. All other spawning grounds for sole and herring therefore are beyond the calculated range of impact, based on the worst-case assumption for fish behavioural reaction during noise exposure.

[2] Ellis J R, Milligan S, Readdy L, South A, Taylor N, Brown M (2010). *MB5301 Mapping spawning and nursery areas of species to be considered for Marine Protected Areas (Marine Conservation Zones). Report No 1: Final Report on development of derived data layers for 40 mobile species considered to be of conservation importance*. Cefas report for Defra, August 2010.