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Norfolk Vanguard Offshore Wind Farm: Underwater noise assessment

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1 Introduction

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

1.1 Norfolk Vanguard Offshore Wind Farm

Norfolk Vanguard is a proposed wind farm in development in the North Sea, located approximately 50 km off the coast of Norfolk. The location is shown in Figure 1-1. Norfolk Vanguard comprises two distinct areas, Norfolk Vanguard East (NV East) and Norfolk Vanguard West (NV West) ('the OWF sites'), and will be connected to the shore by offshore export cables installed within the offshore cable corridor. The proposed project would comprise a potential capacity of up to 1800 MW.

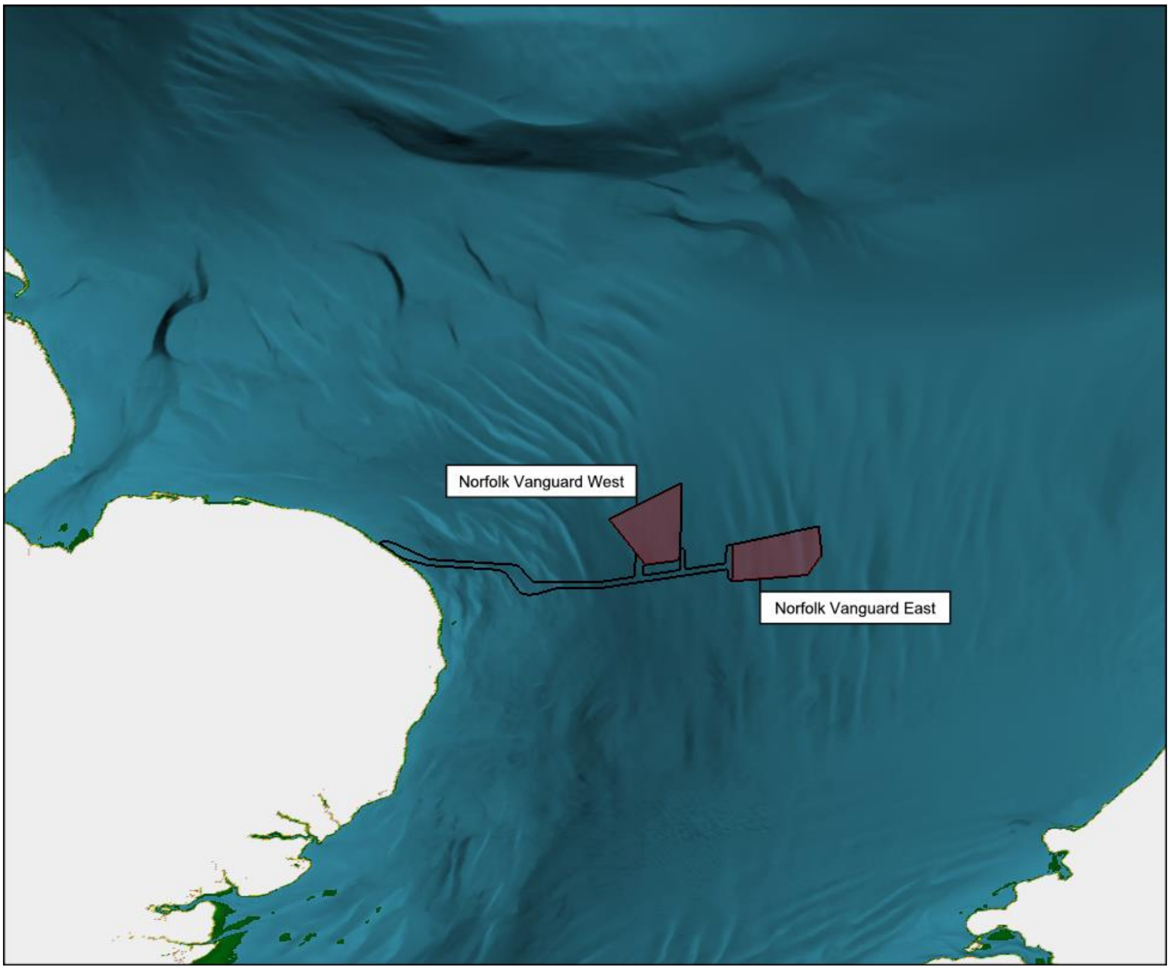

Figure 1-1 Map showing the boundaries of the Norfolk Vanguard Offshore Wind Farm Project

1.2 Noise assessment

This report focusses on pile driving activities during construction at the Norfolk Vanguard OWF sites. Underwater noise modelling has been carried out using a combined parabolic equation (PE) and ray tracing method considering bathymetry, seabed type and frequency content at all depths in the water column.

1.2.1 Impact piling

As part of a series of construction options, impact piling has been proposed to drive the foundation piles of the wind turbines into the seabed. Impact piling may be used to install the following foundation options:

- Monopiles;
- Pin-piles for;
    - Tripod;
    - Quadropod; or
    - Floating platforms with anchored tension mooring lines.

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; 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 its head. 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.

At the end of the pile, force is exerted on the substrate not only by the force transmitted from the hammer by the pile, but also by the structural waves travelling down the pile which then induce lateral waves in the seabed. These may travel as both compressional waves, in a similar manner to the sound in the water, or as a seismic wave, where the displacement travels as Rayleigh waves (Brekhovskikh, 1960). The waves can travel outwards through the seabed or by reflection from deeper sediments. As they propagate, sound will tend to "leak" upwards into the water, contributing to the waterborne wave. Since the speed of sound is generally greater in consolidated sediments than in water, these waves usually arrive at a distant receptor first as a pre-cursor to the waterborne wave. The level of the seismic wave is typically 10 to 20 dB below the waterborne arrival, and hence it is the latter that dominates the noise.

1.3 Scope of work

This report presents a detailed assessment of the potential underwater noise from impact piling at Norfolk Vanguard 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 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 and conclusions (Section 6).
- Remodelling has been carried out using the INSPIRE model, an amended report is included in Appendix A.

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.

Where not 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 und. 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 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 taken 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.

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 the acoustic energy and, therefore, 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 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 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 Vanguard.

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:

- Lethal effect and physical injury from Parvin *et al* (2007);
- 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; and
- Sound exposure guidelines for fishes and sea turtles by Popper *et al.* (2014).

At the time of writing, these present the most up to date and authoritative criteria for assessing environmental effects for use in impact assessments.

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

- Lethal effect may occur when peak noise levels exceed 240 dB re 1 µPa; and
- Physical injury may occur when peak noise levels exceed 220 dB re 1 µPa.

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. The criteria from Southall *et al.* (2007) are based on M-Weighted SELs, which are generalised frequency weighting functions to filter underwater noise data to better represent the levels of underwater noise 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)	Habour 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 strike 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 functional hearing groups 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)

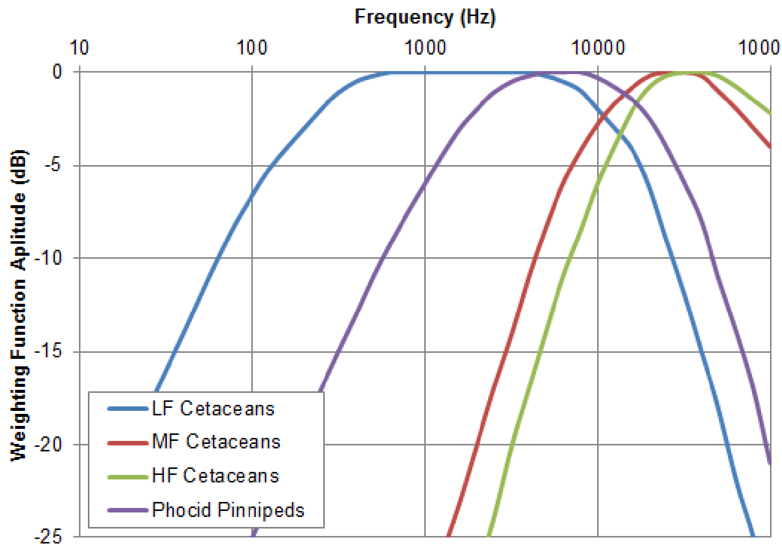

Figure 2-1 Auditory weighting functions for low frequency (LF) cetaceans, mid frequency (MF) cetaceans, high frequency (HF) cetaceans, and phocid pinnipeds (PW) (underwater) (from NMFS, 2016)

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 by this point it will have received the majority of the noise from piling.

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.

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 conservative. The modelled criteria are summarised in Table 2-9. Similarly to marine mammals for SEL_{cum} results, a fleeing animal model has been used assuming a receptor 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)

3 Baseline ambient noise

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

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, although present, have a lower overall contribution. There are no dredging areas or Active Dredge Zones and Dredging Application Option and Prospecting Areas within the Norfolk Vanguard boundary.

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 Vanguard study area, although this is unlikely to contribute to the overall ambient noise. Clearance of UXO contributes high but infrequent and localised 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 Vanguard 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 the same region as Norfolk Vanguard, 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 on two days. This survey sampled noise levels of 112 to 122 dB re 1 µPa RMS over two days, which were stated 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.

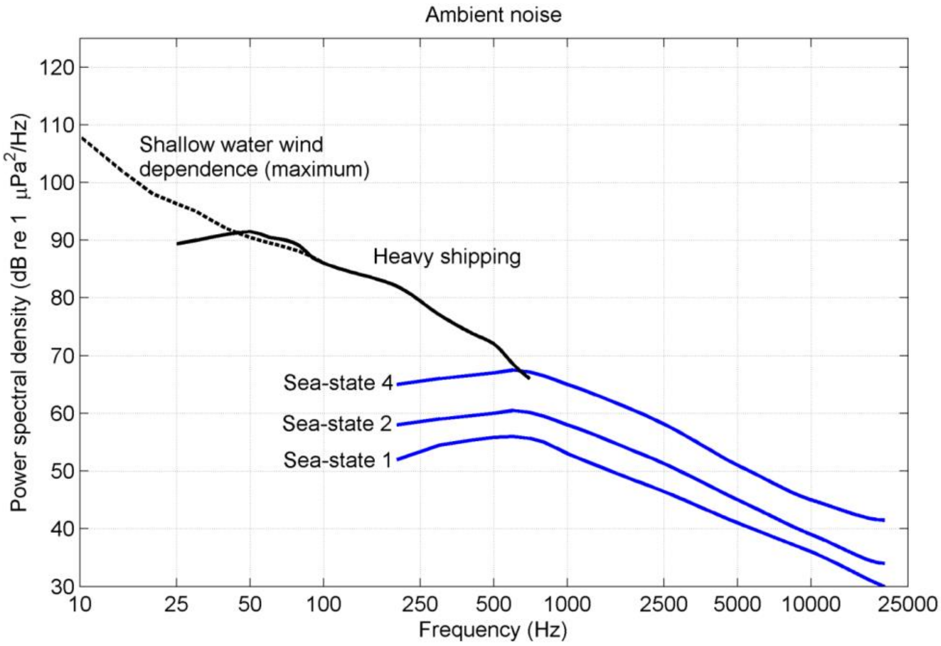

Figure 3-1 Ambient underwater noise as shown in Wenz (1962) showing frequency dependency from different noise sources.

There is little documented, additional 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, 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*., 2005) 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 Modelling methodology

4.1 Introduction

To estimate the noise levels likely to arise during construction of Norfolk Vanguard, predictive underwater 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).

Modelling of underwater noise is complex and can be approached in many ways. The modelling approach chosen uses a numerical approach based on two different solvers. This approach was agreed with stakeholders at the Evidence Plan Process meeting on 15th Feb 2017 and is as detailed in the method statement.

- A parabolic equation (PE) method for lower frequencies (12.5 Hz to 250 Hz); and
- A ray tracing method for higher frequencies (315 Hz to 100 kHz).

The PE method is widely used within the underwater acoustics community but has computational limitations at high frequencies. Ray tracing is more computationally efficient at higher frequencies and not suited to low frequencies (Etter, 2013; Dekeling *et al* 2014).

These solvers consider a wide array of input parameters, including bathymetry, sediment data, sound speed and source frequency content to ensure as detailed results as possible. 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;
- Ramp-up profiles;
- Receptor swim speeds; and
- Position of the receptor in the water column.

The input parameters for the modelling are detailed in section 4.2.

4.2 Locations

Modelling has been undertaken at four representative locations to assess simultaneous piling operations (section 5.3). Two of these are in NV West, covering the position closest to land (SW) and the furthest position from this location (NE) within NV West. In addition, two locations at the extents NV East have been assessed. The chosen locations are shown in Figure 4-1 and summarised in Table 4-1, below.

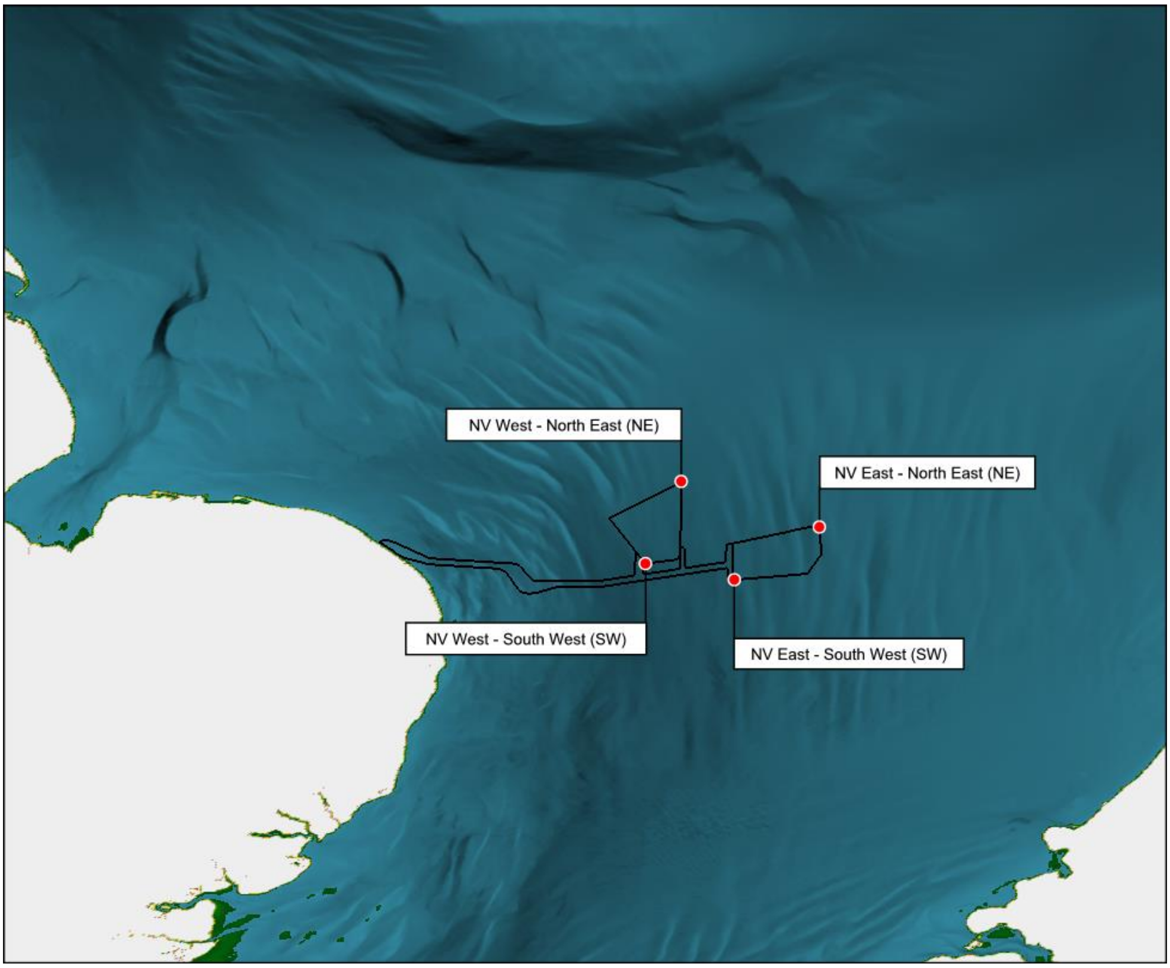

Figure 4-1 Map showing the modelled locations covering the Norfolk Vanguard site

	Norfolk Vanguard West		Norfolk Vanguard East	
	South West (SW)	North East (NE)	South West (SW)	North East (NE)
Latitude	52.80098°N	53.04354°N	52.75323°N	52.91596°N
Longitude	002.44379°E	002.57117°E	002.76044°E	003.07780°E
Water depth	40 m	35 m	39 m	28 m

Table 4-1 Summary of the modelling locations and the water depths at each location

The two locations at the NV West site have been used for the majority of the modelling. These are representative of the worst case for the NV West and NV East sites as the deeper water in NV West is conducive of higher noise source levels and greater overall noise propagation. In respect of location sensitivity, the locations in NV West are closest to nature conservation designations.

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 WTG foundations across the Norfolk Vanguard OWF farm sites. These are:

- Monopiles installed using a maximum blow energy of 5000 kJ; and

- Pin piles installed using a maximum 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 and Table 4-3, below. The ramp up takes place over the first half-hour of piling, starting at ten percent of maximum, gradually increasing in blow energy and strike rate until reaching the maximum energy, where it stays for the remaining time.

The monopile scenario contains 7200 pile strikes over 255 minutes (4 hours 15 minutes). The pin pile scenario includes four individual piles installed consecutively, leading to a total of 8400 strikes over 6 hours (1 hour 30 minutes for each pin pile). For the purposes of noise modelling, it is assumed that there is no pause between each individual pin pile, and thus assumes that the marine mammal or fish receptor continues swimming away from the source.

	10%	Ramp up	100%
Monopile blow energy	500 kJ	Gradual increase	5000 kJ
Number of strikes	150 strikes	300 strikes	6750 strikes
Duration	10 minutes	20 minutes	225 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	150 strikes	300 strikes	1650 strikes
Duration	10 minutes	20 minutes	60 minutes

Table 4-3 Summary of the ramp up scenario used for calculating cumulative SELs for a single pin pile (modelling assumes four piles installed consecutively 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. Subacoustech has undertaken numerous measurements of impact piling offshore and have developed a sound level model based primarily on the blow energy and water depth of a piling operation, which have been shown to be the primary factors when comparing piling operations and the subsequent subsea noise levels produced.

As the model assumes that the noise source acts as a single point, the water depth at the noise source has been used to adjust the source level to allow for the length of pile in contact with the water.

The unweighted SPL_{peak} and SEL_{ss} source levels estimated for this project are provided in Table 4-4 to Table 4-7 for both the maximum and minimum (soft start) blow energies.

	Monopile source level (5000 kJ)	Pin pile source level (2700 kJ)
NV West (SW)	243.6 dB re 1 µPa @ 1 m	241.3 dB re 1 µPa @ 1 m
NV West (NE)	241.5 dB re 1 µPa @ 1 m	239.1 dB re 1 µPa @ 1 m
NV East (SW)	243.2 dB re 1 µPa @ 1 m	240.9 dB re 1 µPa @ 1 m
NV East (NE)	238.4 dB re 1 µPa @ 1 m	235.8 dB re 1 µPa @ 1 m

Table 4-4 Summary of the unweighted source levels (SPL_{peak}) used for full energy modelling in this study

	Monopile source level (500 kJ)	Pin pile source level (270 kJ)
NV West (SW)	232.4 dB re 1 µPa @ 1 m	228.1 dB re 1 µPa @ 1 m
NV West (NE)	229.9 dB re 1 µPa @ 1 m	225.6 dB re 1 µPa @ 1 m
NV East (SW)	231.9 dB re 1 µPa @ 1 m	227.6 dB re 1 µPa @ 1 m
NV East (NE)	226.3 dB re 1 µPa @ 1 m	222.0 dB re 1 µPa @ 1 m

Table 4-5 Summary of the unweighted source levels (SPL_{peak}) used for modelling soft start in this study

	Monopile source level (5000 kJ)	Pin pile source level (2700 kJ)
NV West (SW)	223.6 dB re 1 µPa²s @ 1 m	221.3 dB re 1 µPa²s @ 1 m
NV West (NE)	221.5 dB re 1 µPa²s @ 1 m	219.1 dB re 1 µPa²s @ 1 m
NV East (SW)	223.2 dB re 1 µPa²s @ 1 m	220.9 dB re 1 µPa²s @ 1 m
NV East (NE)	218.4 dB re 1 µPa²s @ 1 m	215.8 dB re 1 µPa²s @ 1 m

Table 4-6 Summary of the unweighted source levels (SEL_{ss}) used for full energy modelling in this study

	Monopile source level (500 kJ)	Pin pile source level (270 kJ)
NV West (SW)	212.4 dB re 1 µPa²s @ 1 m	208.1 dB re 1 µPa²s @ 1 m
NV West (NE)	209.9 dB re 1 µPa²s @ 1 m	205.6 dB re 1 µPa²s @ 1 m
NV East (SW)	211.9 dB re 1 µPa²s @ 1 m	207.6 dB re 1 µPa²s @ 1 m
NV East (NE)	206.3 dB re 1 µPa²s @ 1 m	202.0 dB re 1 µPa²s @ 1 m

Table 4-7 Summary of the unweighted source levels (SEL_{ss}) used for modelling soft start in this study

4.3.3 Frequency content

The size of the pile being installed is used for estimating the frequency content of the noise. For this modelling, frequency data has been sourced from Subacoustech's noise measurement database and an average taken to obtain representative third-octave (i.e. frequency) levels for installing monopiles and pin piles. The third-octave 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.

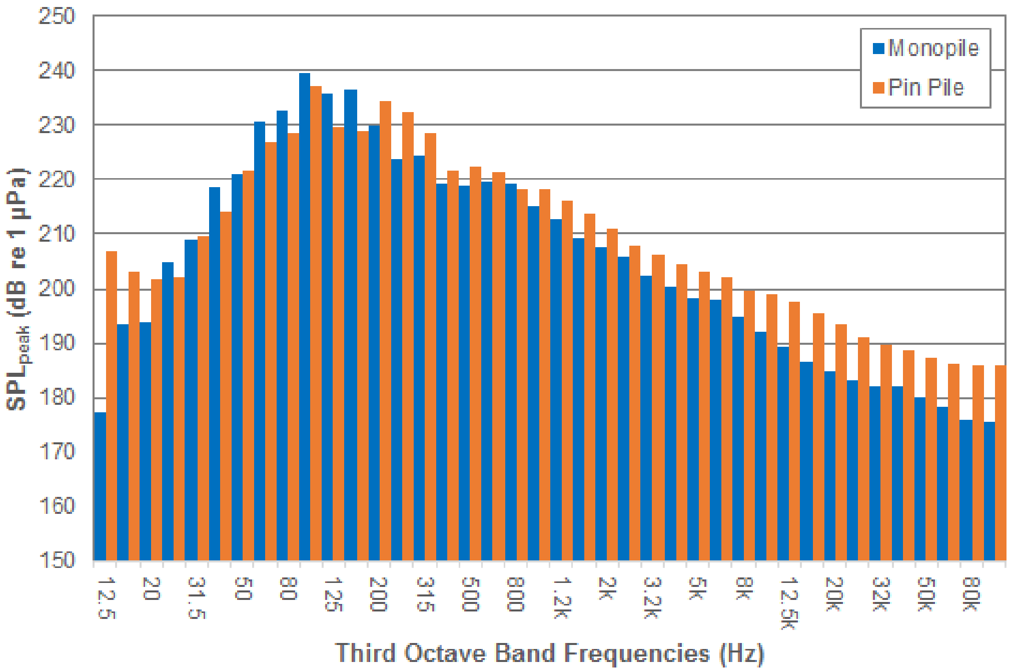

Figure 4-2 Third-octave source level frequency spectra for the south west location, maximum blow energy

Piles more than 7.0 m in diameter, the largest where measured data is available, have been used for the monopile modelling and piles of approximately 4.0 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 dimensions and acoustics of the pile. This trend would be expected to continue to larger piles under consideration for the monopiles at Norfolk Vanguard. As noted in section 4.3.2, this would have a negligible effect on the overall source level and could move the dominant frequency further below the frequencies of greatest hearing sensitivity of marine mammals, and thus would appear slightly quieter. Marine mammal hearing sensitivity is described in section 2.2.

4.3.4 Environmental conditions

Accurate modelling of underwater noise propagation requires knowledge of the sea and seabed conditions. Data from the Marine Environment Mapping Programme (MAREMAP) and the British Geological Survey (BGS), the seabed type using for the modelling is assumed to be made up predominantly of sand. The geoacoustic properties for the sediment types are taken from Jensen *et al.* (2011).

The speed of sound in water at the Norfolk Vanguard OWF sites has been calculated using mean temperature and salinity data for the North Sea over the whole year. The levels used in the model vary from 1489.1 ms^{-1} at the surface to 1490.7 ms^{-1} in the deepest waters.

Mean tidal depth has been used throughout for the bathymetry as the tidal state will fluctuate throughout installation of foundations. The tidal range at the site varies between 3.2 m above chart datum at MHWS and 0.6 m above chart datum at MLWS, using the mean depth is a reasonable assumption to cover the differences that the tide variation will bring.

5 Subsea noise modelling outputs

This section presents the unweighted noise level results from the modelling undertaken for impact piling operations using the modelling parameters detailed in section 4.

5.1 Unweighted subsea noise modelling

The figures below present unweighted SPL_{peak} noise levels from impact piling operations at Norfolk Vanguard West. The colours shown on the map represent the highest modelled noise level in the water column at that location, and give a worst-case overview of the unweighted noise levels from impact piling. 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 SW location) when driving a monopile. The effect of the deep water on noise transmission is also shown when considering the Outer Silver Pit, a seabed feature of deeper water directly to the north of the site (at the top-centre of the figures), where noise propagates noticeably further.

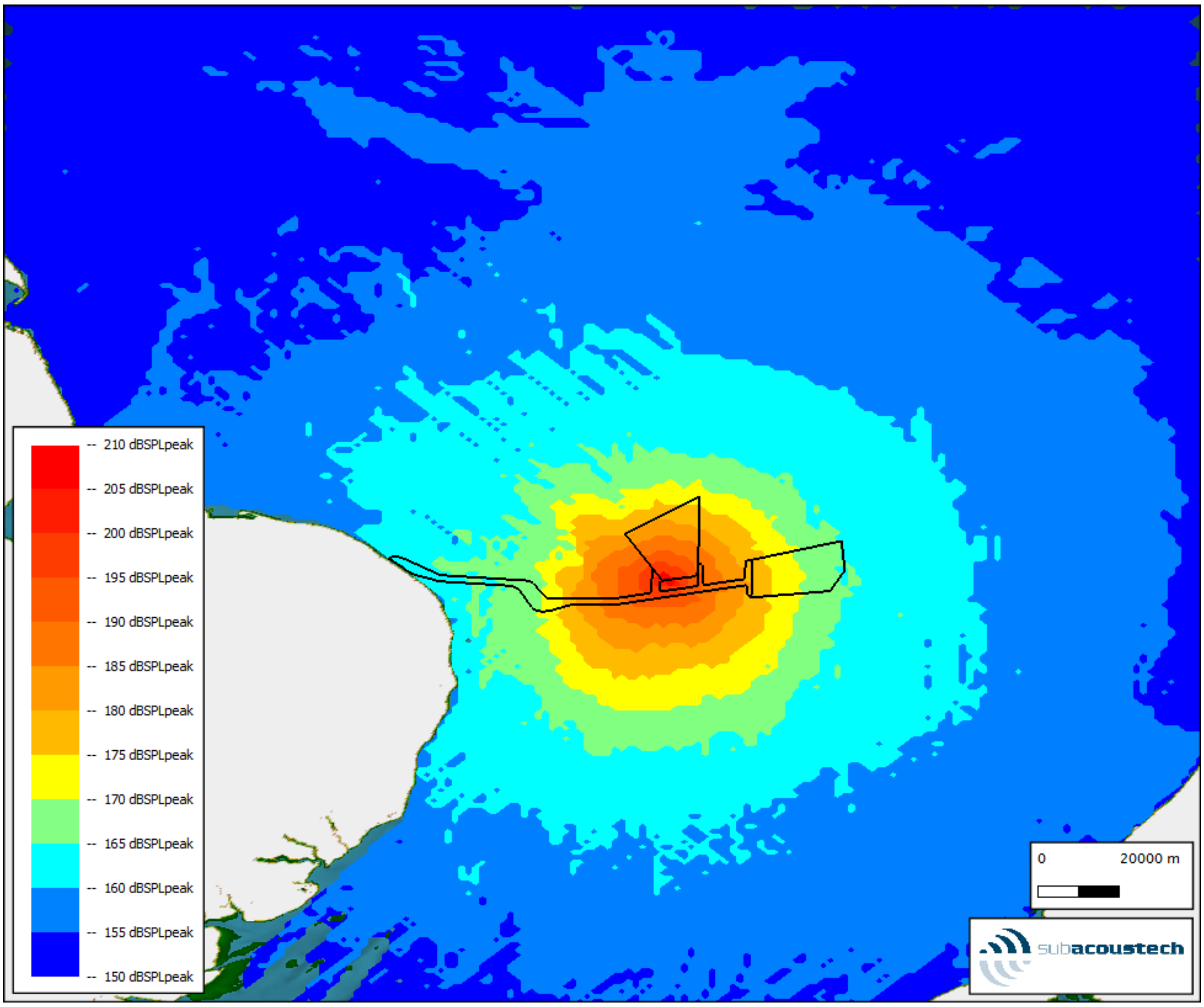

Figure 5-1 Noise level plot showing the predicted SPL_{peak} noise levels predicted for installing a monopile at the SW location

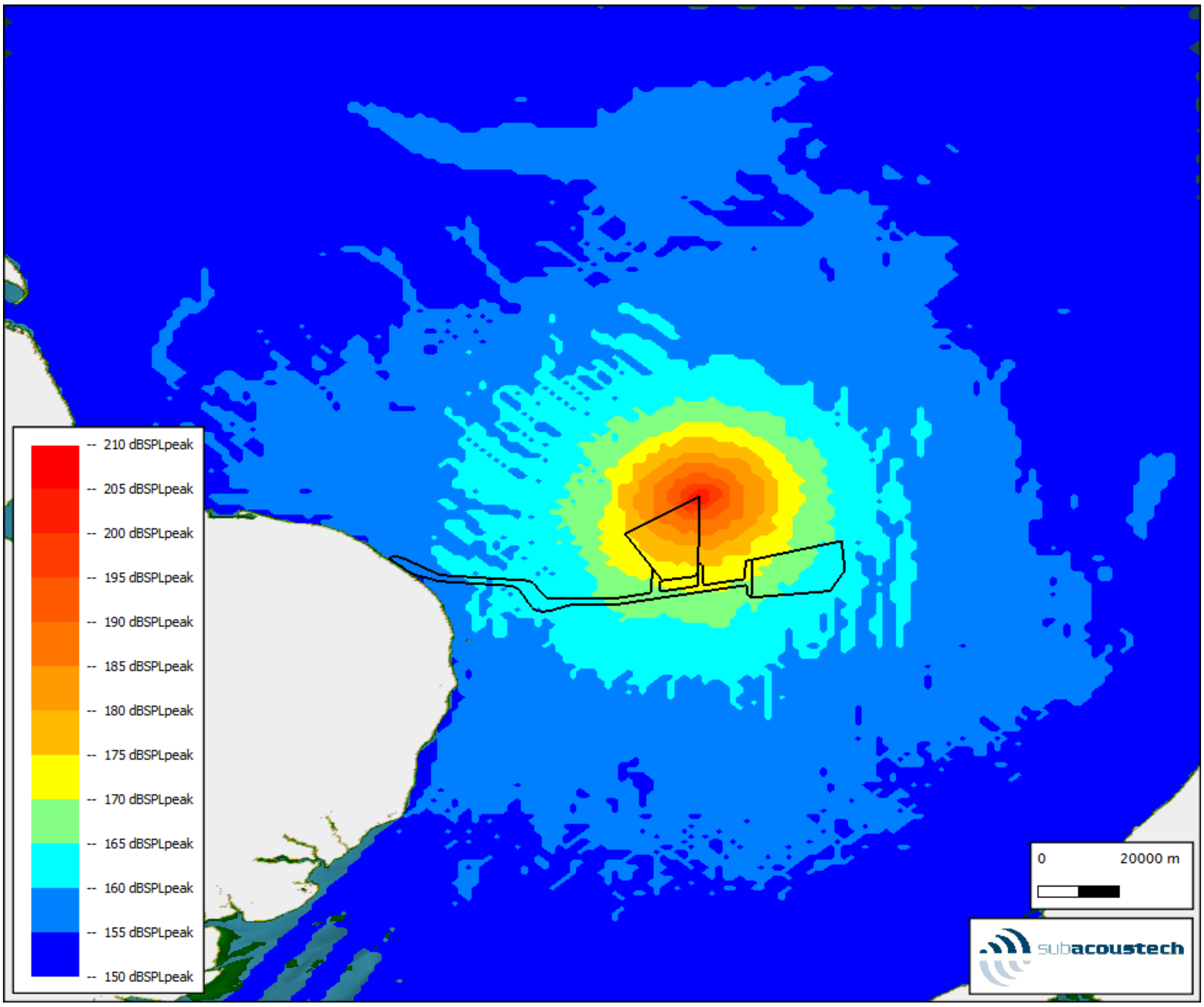

Figure 5-2 Noise level plot showing the predicted SPL_{peak} noise levels predicted for installing a monopile at the NE location

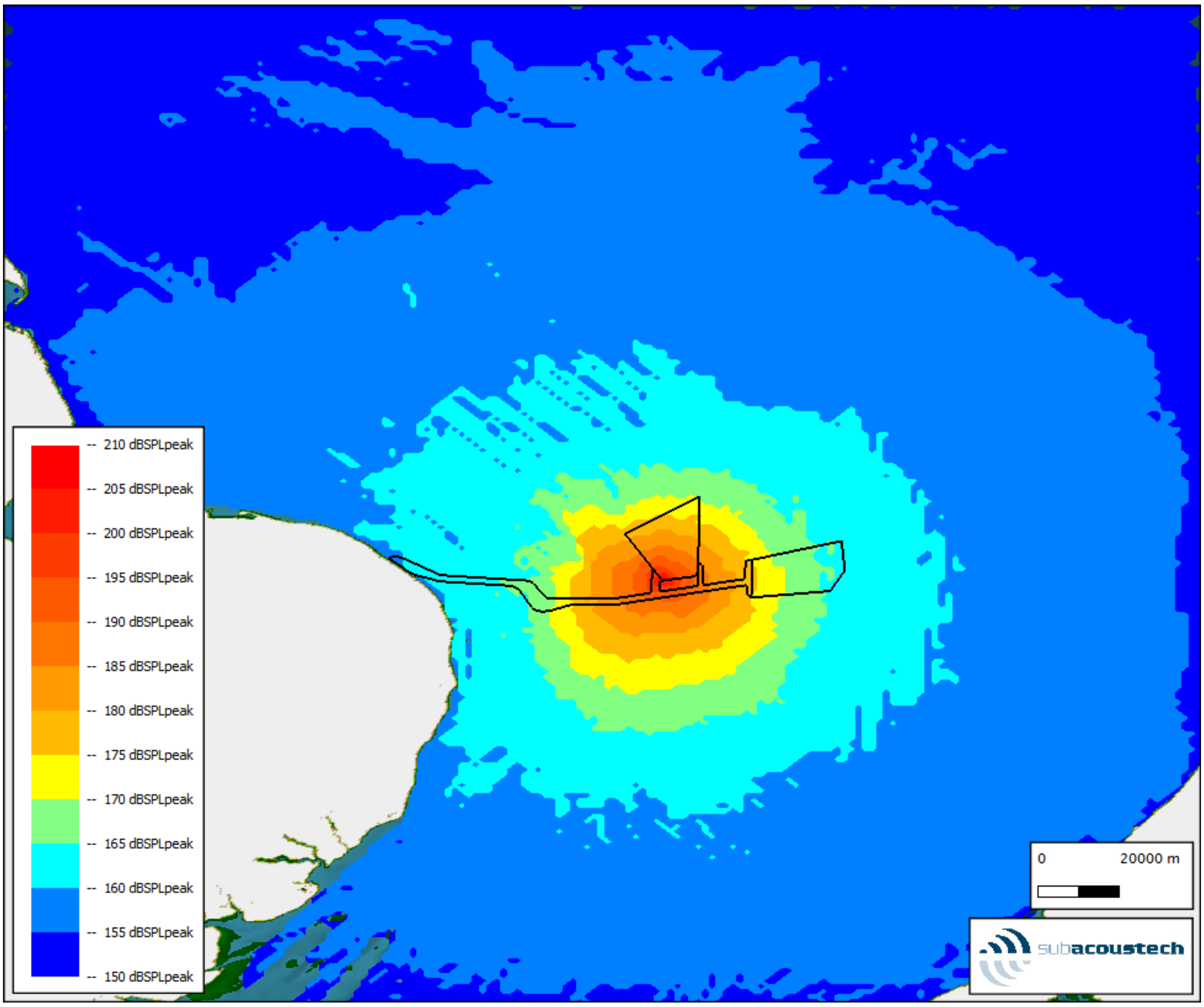

Figure 5-3 Noise level plot showing the predicted SPL_{peak} noise levels predicted for installing a pin pile at the SW location

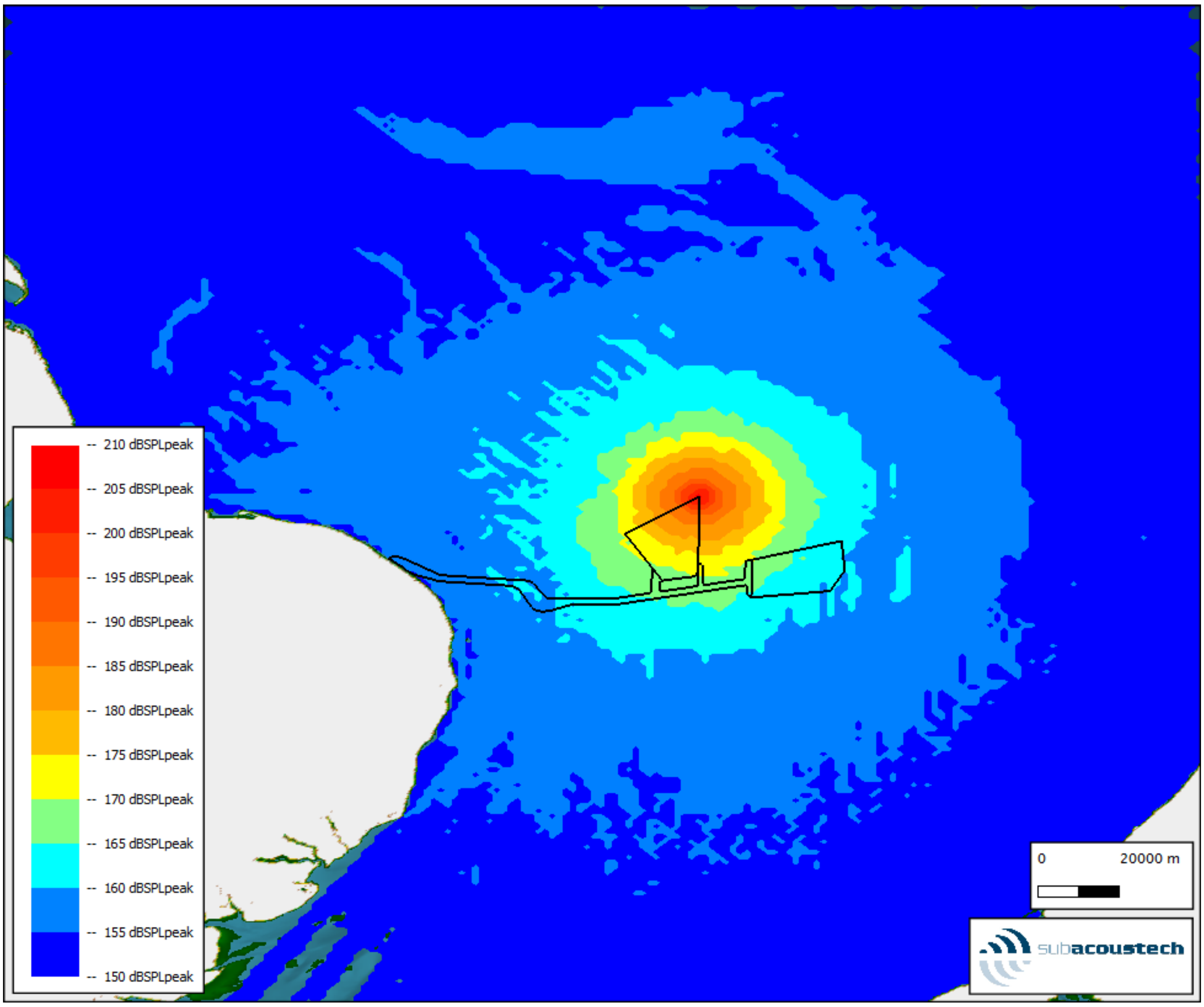

Figure 5-4 Noise level plot showing the predicted SPL_{peak} noise levels predicted for installing a pin pile at the NE location

The lower extent of the noise levels on these plots, denoted in dB SPL_{peak} suitable for impulsive noise, 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.

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. For single strike criteria, the impact ranges during soft start have also been included.

5.2.1 Lethal effect and physical injury

Table 5-1 and Table 5-2 present the lethal effect and physical injury effects using the SPL_{peak} criteria from Parvin *et al* (2007); these criteria cover both marine mammals and fish. The results show that these effects are likely to only be at close range out to a maximum of 100 m.

Unweighted SPL_{peak}			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
SW Location	Lethal Effect	240 dB	2 m	2 m	1 m	1 m	1 m	1 m
	Physical Injury	220 dB	100 m	95 m	85 m	66 m	59 m	52 m
NE Location	Lethal Effect	240 dB	1 m	1 m	1 m	< 1 m	< 1 m	< 1 m
	Physical Injury	220 dB	85 m	77 m	69 m	50 m	45 m	40 m

Table 5-1 Summary of the SPL_{peak} lethal effect and physical injury impact ranges from Parvin et al (2007) for maximum hammer blow energy

Unweighted SPL_{peak}			Monopile (500 kJ)			Pin Pile (270 kJ)		
			Max	Mean	Min	Max	Mean	Min
SW Location	Lethal Effect	240 dB	< 1 m	< 1 m	< 1 m	< 1 m	< 1 m	< 1 m
	Physical Injury	220 dB	11 m	11 m	10 m	4 m	4 m	4 m
NE Location	Lethal Effect	240 dB	< 1 m	< 1 m	< 1 m	< 1 m	< 1 m	< 1 m
	Physical Injury	220 dB	7 m	7 m	7 m	3 m	3 m	2 m

Table 5-2 Summary of the SPL_{peak} lethal effect and physical injury impact ranges from Parvin et al (2007) for soft start hammer blow energy

5.2.2 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).

5.2.2.1 Southall et al. (2007) results

Table 5-3 to Table 5-10 present the predicted auditory injury and TTS impact ranges for various cetaceans and pinniped hearing groups from Southall *et al.* (2007). Behavioural avoidance for low and mid frequency cetaceans are given in Table 5-11 and Table 5-14. 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 includes the noise exposure to an animal receptor over an entire six-hour piling event. In line with the unweighted results from the section 5.1, maximum ranges were predicted for monopiles installed at the deeper SW location. The effect of the water depth at the source should also be noted, with the differences shown between the SW and NE locations. The shallower water in the NE location gives a reduction in impact ranges.

Auditory Injury – SW location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
Unweighted SPL_{peak}	Cetaceans	230 dB	15 m	13 m	12 m	9 m	8 m	8 m
	Pinnipeds	218 dB	160 m	140 m	120 m	98 m	86 m	75 m
M-Weighted single strike (SEL_{ss})	LF Cetaceans	198 dB	160 m	140 m	120 m	98 m	86 m	75 m
	MF Cetaceans	198 dB	33 m	30 m	28 m	28 m	26 m	23 m
	HF Cetaceans	198 dB	19 m	18 m	16 m	19 m	18 m	16 m
	PW Pinnipeds	186 dB	890 m	760 m	640 m	590 m	500 m	420 m
M-Weighted multiple pulse (SEL_{cum})	LF Cetaceans	198 dB	8.7 km	7.0 km	5.1 km	4.1 km	3.3 km	2.2 km
	MF Cetaceans	198 dB	3.5 km	3.1 km	2.4 km	2.1 km	1.7 km	1.3 km
	HF Cetaceans	198 dB	1.6 km	1.2 km	810 m	950 m	610 m	270 m
	PW Pinnipeds	186 dB	29 km	22 km	17 km	22 km	17 km	13 km

Table 5-3 Summary of the impact ranges at the SW location for auditory injury criteria from Southall et al (2007) for maximum hammer blow energy

Auditory Injury – SW location			Monopile (500 kJ)			Pin Pile (270 kJ)		
			Max	Mean	Min	Max	Mean	Min
Unweighted SPL_{peak}	Cetaceans	230 dB	1 m	1 m	1 m	< 1 m	< 1 m	< 1 m
	Pinnipeds	218 dB	17 m	16 m	15 m	7 m	6 m	6 m
M-Weighted single strike (SEL_{ss})	LF Cetaceans	198 dB	17 m	16 m	15 m	7 m	6 m	6 m
	MF Cetaceans	198 dB	3 m	3 m	3 m	2 m	2 m	2 m
	HF Cetaceans	198 dB	2 m	2 m	2 m	1 m	1 m	1 m
	PW Pinnipeds	186 dB	98 m	87 m	78 m	45 m	41 m	37 m

Table 5-4 Summary of the impact ranges at the SW location for auditory injury criteria from Southall et al (2007) for soft start hammer blow energy

Auditory Injury – NE location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
Unweighted SPL_{peak}	Cetaceans	230 dB	10 m	10 m	9 m	6 m	6 m	5 m
	Pinnipeds	218 dB	120 m	110 m	100 m	75 m	68 m	59 m
M-Weighted single strike (SEL_{ss})	LF Cetaceans	198 dB	120 m	110 m	100 m	75 m	68 m	59 m
	MF Cetaceans	198 dB	24 m	23 m	21 m	20 m	19 m	18 m
	HF Cetaceans	198 dB	14 m	13 m	12 m	14 m	13 m	12 m
	PW Pinnipeds	186 dB	770 m	660 m	550m	490 m	430 m	350 m
M-Weighted multiple pulse (SEL_{cum})	LF Cetaceans	198 dB	4.2 km	3.2 km	3.0 km	1.6 km	1.3 km	950 m
	MF Cetaceans	198 dB	2.0 km	1.8 km	1.5 km	1.1 km	830 m	620 m
	HF Cetaceans	198 dB	660 m	490 m	310 m	280 m	130 m	40 m
	PW Pinnipeds	186 dB	18 km	15 km	13 km	14 km	11 km	9.8 km

Table 5-5 Summary of the impact ranges at the NE location for auditory injury criteria from Southall et al (2007) for maximum hammer blow energy

Auditory Injury – NE location			Monopile (500 kJ)			Pin Pile (270 kJ)		
			Max	Mean	Min	Max	Mean	Min
Unweighted SPL_{peak}	Cetaceans	230 dB	< 1 m	< 1 m	< 1 m	< 1 m	< 1 m	< 1 m
	Pinnipeds	218 dB	11 m	11 m	10 m	4 m	4 m	4 m
M-Weighted single strike (SEL_{ss})	LF Cetaceans	198 dB	11 m	11 m	10 m	1 m	1 m	1 m
	MF Cetaceans	198 dB	2 m	2 m	2 m	1 m	1 m	1 m
	HF Cetaceans	198 dB	1 m	1 m	1 m	4 m	4 m	4 m
	PW Pinnipeds	186 dB	71 m	64 m	57 m	32 m	29 m	26 m

Table 5-6 Summary of the impact ranges at the NE location for auditory injury criteria from Southall et al (2007) for soft start hammer blow energy

TTS – SW location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
Unweighted SPL_{peak}	Cetaceans	224 dB	49 m	44 m	40 m	30 m	27 m	24 m
	Pinnipeds	212 dB	540 m	460 m	380 m	320 m	270 m	230 m
M-Weighted single strike (SEL_{ss})	LF Cetaceans	183 dB	2.4 km	2.2 km	1.9 km	1.7 km	1.5 km	1.2 km
	MF Cetaceans	183 dB	610 m	520 m	450 m	490 m	420 m	350 m
	HF Cetaceans	183 dB	340 m	300 m	260 m	330 m	280 m	230 m
	PW Pinnipeds	171 dB	2.4 km	2.2 km	1.9 km	5.3 km	4.8 km	4.2 km

Table 5-7 Summary of the impact ranges at the SW location for TTS criteria from Southall et al (2007) for maximum hammer blow energy

TTS – SW location			Monopile (500 kJ)			Pin Pile (270 kJ)		
			Max	Mean	Min	Max	Mean	Min
Unweighted SPL_{peak}	Cetaceans	224 dB	5 m	5 m	4 m	2 m	2 m	2 m
	Pinnipeds	212 dB	58 m	52 m	46 m	23 m	21 m	19 m
M-Weighted single strike (SEL_{ss})	LF Cetaceans	183 dB	340 m	290 m	250 m	130 m	120 m	100 m
	MF Cetaceans	183 dB	69 m	62 m	57 m	39 m	36 m	32 m
	HF Cetaceans	183 dB	39 m	36 m	34 m	27 m	25 m	22 m
	PW Pinnipeds	171 dB	1.7 km	1.5 km	1.2 km	820 m	690 m	580 m

Table 5-8 Summary of the impact ranges at the SW location for TTS criteria from Southall et al (2007) for soft start hammer blow energy

TTS – NE location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
Unweighted SPL_{peak}	Cetaceans	224 dB	37 m	34 m	31 m	22 m	20 m	18 m
	Pinnipeds	212 dB	440 m	390 m	330 m	260 m	220 m	190 m
M-Weighted single strike (SEL_{ss})	LF Cetaceans	183 dB	2.2 km	2.0 km	1.8 km	1.6 km	1.3 km	1.0 km
	MF Cetaceans	183 dB	520 m	450 m	380 m	400 m	350 m	300 m
	HF Cetaceans	183 dB	280 m	245 m	210 m	260 m	230 m	200 m
	PW Pinnipeds	171 dB	5.4 km	5.2 km	4.8 km	4.3 km	4.1 km	3.8 km

Table 5-9 Summary of the impact ranges at the NE location for TTS criteria from Southall et al (2007) for maximum hammer blow energy

TTS – NE location			Monopile (500 kJ)			Pin Pile (270 kJ)		
			Max	Mean	Min	Max	Mean	Min
Unweighted SPL_{peak}	Cetaceans	224 dB	3 m	3 m	3 m	1 m	1 m	1 m
	Pinnipeds	212 dB	40 m	37 m	34 m	16 m	14 m	13 m
M-Weighted single strike (SEL_{ss})	LF Cetaceans	183 dB	260 m	230 m	200 m	100 m	91 m	78 m
	MF Cetaceans	183 dB	49 m	45 m	41 m	28 m	26 m	23 m
	HF Cetaceans	183 dB	28 m	26 m	24 m	19 m	17 m	16 m
	PW Pinnipeds	171 dB	1.5 km	1.3 km	1.0 km	670 m	570 m	470 m

Table 5-10 Summary of the impact ranges at the NE location for TTS criteria from Southall et al (2007) for soft start hammer blow energy

Behavioural – SW location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
Likely Avoidance (SEL_{ss})	LF Cetaceans	152 dB	42 km	35 km	29 km	36 km	29 km	24 km
	MF Cetaceans	170 dB	11 km	10 km	9.0 km	8.2 km	7.6 km	6.8 km
Possible Avoidance (SEL_{ss})	LF Cetaceans	142 dB	120 km	101 km	54 km	103 km	92 km	54 km
	MF Cetaceans	160 dB	25 km	22 km	18 km	21 km	18 km	15 km

Table 5-11 Summary of the impact ranges at the SW location for behavioural response criteria from Southall et al (2007) for maximum hammer blow energy

Behavioural – SW location			Monopile (500 kJ)			Pin Pile (270 kJ)		
			Max	Mean	Min	Max	Mean	Min
Likely Avoidance (SEL_{ss})	LF Cetaceans	152 dB	20 km	18 km	15 km	13 km	12 km	10 km
	MF Cetaceans	170 dB	3.1 km	2.7 km	2.4 km	1.7 km	1.4 km	1.1 km
Possible Avoidance (SEL_{ss})	LF Cetaceans	142 dB	39 km	32 km	26 km	29 km	24 km	20 km
	MF Cetaceans	160 dB	9.9 km	9.0 km	8.1 km	5.7 km	5.3 km	4.7 km

Table 5-12 Summary of the impact ranges at the SW location for behavioural response criteria from Southall et al (2007) for soft start hammer blow energy

Behavioural – NE location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
Likely Avoidance (SEL_{ss})	LF Cetaceans	152 dB	29 km	25 km	21 km	24 km	21 km	19 km
	MF Cetaceans	170 dB	8.4 km	7.9 km	7.5 km	6.5 km	6.2 km	5.8 km
Possible Avoidance (SEL_{ss})	LF Cetaceans	142 dB	92 km	82 km	71 km	69 km	66 km	62 km
	MF Cetaceans	160 dB	18 km	16 km	14 km	15 km	13 km	12 km

Table 5-13 Summary of the impact ranges at the NE location for behavioural response criteria from Southall et al (2007) for maximum hammer blow energy

Behavioural – NE location			Monopile (500 kJ)			Pin Pile (270 kJ)		
			Max	Mean	Min	Max	Mean	Min
Likely Avoidance (SEL_{ss})	LF Cetaceans	152 dB	14 km	13 km	12 km	9.5 km	8.9 km	8.3 km
	MF Cetaceans	170 dB	2.5 km	2.4 km	2.2 km	1.4 km	1.2 km	990 m
Possible Avoidance (SEL_{ss})	LF Cetaceans	142 dB	27 km	22 km	20 km	19 km	17 km	16 km
	MF Cetaceans	160 dB	7.3 km	6.9 km	6.6 km	4.7 km	4.4 km	4.1 km

Table 5-14 Summary of the impact ranges at the NE location for behavioural response criteria from Southall et al (2007) for soft start hammer blow energy

5.2.2.2 Lucke et al (2009) results

Table 5-15 and Table 5-18 present the predicted impact ranges in terms of the criteria from Lucke *et al.* (2009), covering auditory injury, TTS and behavioural reaction is harbour porpoise. The criteria from Lucke *et al.* (2009) are all unweighted single strike SELs.

Lucke *et al.* (2009) – SW location		Monopile (5000 kJ)			Pin Pile (2700 kJ)		
		Max	Mean	Min	Max	Mean	Min
Auditory injury (SEL_{ss})	179 dB	4.0 km	3.6 km	3.2 km	2.9 km	2.6 km	2.3 km
TTS (SEL_{ss})	164 dB	19 km	17 km	14 km	15 km	13 km	11 km
Behavioural (SEL_{ss})	145 dB	84 km	77 km	54 km	68 km	63 km	54 km

Table 5-15 Summary of the impact ranges at the SW location for criteria from Lucke et al (2009) for maximum hammer blow energy

Lucke *et al.* (2009) – SW location		Monopile (500 kJ)			Pin Pile (270 kJ)		
		Max	Mean	Min	Max	Mean	Min
Auditory injury (SEL_{ss})	179 dB	770 m	650 m	540 m	300 m	250 m	210 m
TTS (SEL_{ss})	164 dB	6.2 km	5.8 km	5.2 km	3.6 km	3.2 km	2.8 km
Behavioural (SEL_{ss})	145 dB	33 km	27 km	21 km	23 km	20 km	17 km

Table 5-16 Summary of the impact ranges at the SW location for criteria from Lucke et al (2009) for soft start hammer blow energy

Lucke *et al.* (2009) – NE location		Monopile (5000 kJ)			Pin Pile (2700 kJ)		
		Max	Mean	Min	Max	Mean	Min
Auditory injury (SEL_{ss})	179 dB	3.4 km	3.3 km	3.0 km	2.4 km	2.3 km	2.1 km
TTS (SEL_{ss})	164 dB	14 km	12 km	12 km	11 km	10 km	9.3 km
Behavioural (SEL_{ss})	145 dB	61 km	57 km	52 km	50 km	43 km	37 km

Table 5-17 Summary of the impact ranges at the NE location for criteria from Lucke et al (2009) for maximum hammer blow energy

Lucke *et al.* (2009) – NE location		Monopile (500 kJ)			Pin Pile (270 kJ)		
		Max	Mean	Min	Max	Mean	Min
Auditory injury (SEL_{ss})	179 dB	590 m	520 m	440 m	230 m	200 m	170 m
TTS (SEL_{ss})	164 dB	5.1 km	4.8 km	4.4 km	2.9 km	2.8 km	2.5 km
Behavioural (SEL_{ss})	145 dB	22 km	19 km	17 km	16 km	15 km	13 km

Table 5-18 Summary of the impact ranges at the NE location for criteria from Lucke et al (2009) for soft start hammer blow energy

5.2.2.3 NMFS (2016) results

Predicted auditory injury and TTS impact ranges are given in Table 5-19 and Table 5-22 using the NMFS unweighted SPL_{peak} and weighted SEL_{cum} criteria from NMFS (2016). Note that the weightings applied to the different species create a large variation in the ranges for nominally identical thresholds; for example, the 185 dB SEL_{cum} MF weighted range is much smaller than the 185 dB SEL_{cum} PW weighted range.

NMFS (2016) – SW location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
Auditory Injury (unweighted SPL_{peak})	LF Cetaceans	219 dB	130 m	110 m	100 m	80 m	71 m	62 m
	MF Cetaceans	230 dB	15 m	13 m	12 m	9 m	8 m	8 m
	HF Cetaceans	202 dB	2.8 km	2.5 km	2.2 km	1.9 km	1.7 km	1.4 km
	PW Pinnipeds	218 dB	160 m	140 m	120 m	98 m	86 m	75 m
Auditory Injury (Weighted SEL_{cum})	LF Cetaceans	183 dB	22 km	17 km	13 km	16 km	13 km	8.9 km
	MF Cetaceans	185 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	HF Cetaceans	155 dB	420 m	240 m	110 m	1.5 km	1.0 km	700 m
	PW Pinnipeds	185 dB	2.4 km	2.1 km	1.6 km	1.7 km	1.3 km	880 m
TTS (unweighted SPL_{peak})	LF Cetaceans	213 dB	440 m	375 m	320 m	260 m	220 m	190 m
	MF Cetaceans	224 dB	49 m	44 m	40 m	30 m	27 m	24 m
	HF Cetaceans	196 dB	5.7 km	5.3 km	4.7 km	4.2 km	3.7 km	3.3 km
	PW Pinnipeds	212 dB	540 m	460 m	380 m	320 m	270 m	230 m
TTS (Weighted SEL_{cum})	LF Cetaceans	168 dB	154 km	123 km	54 km	91 km	79 km	54 km
	MF Cetaceans	170 dB	10 m	10 m	10 m	10 m	10 m	10 m
	HF Cetaceans	140 dB	7.4 km	6.6 km	5.9 km	11 km	8.8 km	8.1 km
	PW Pinnipeds	170 dB	21 km	17 km	13 km	17 km	14 km	11 km

Table 5-19 Summary of the impact ranges at the SW location for auditory injury and TTS criteria from NMFS (2016) for maximum hammer blow energy

NMFS (2016) – SW location			Monopile (500 kJ)			Pin Pile (270 kJ)		
			Max	Mean	Min	Max	Mean	Min
Auditory Injury (unweighted SPL_{peak})	LF Cetaceans	219 dB	14 m	13 m	12 m	5 m	5 m	5 m
	MF Cetaceans	230 dB	1 m	1 m	1 m	< 1 m	< 1 m	< 1 m
	HF Cetaceans	202 dB	420 m	360 m	300 m	170 m	140 m	120 m
	PW Pinnipeds	218 dB	17 m	16 m	15 m	7 m	6m	6 m
TTS (unweighted SPL_{peak})	LF Cetaceans	213 dB	47 m	43 m	38 m	19 m	17 m	16 m
	MF Cetaceans	224 dB	5 m	5 m	4 m	2 m	2 m	2 m
	HF Cetaceans	196 dB	1.4 km	1.1 km	950 m	550 m	460 m	380 m
	PW Pinnipeds	212 dB	58 m	52 m	46 m	23 m	21 m	19 m

Table 5-20 Summary of the SPL_{peak} impact ranges at the SW location for auditory injury and TTS criteria from NMFS (2016) for soft start hammer blow energy

NMFS (2016) – NE location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
Auditory Injury (unweighted SPL_{peak})	LF Cetaceans	219 dB	100 m	94 m	84 m	61 m	56 m	49 m
	MF Cetaceans	230 dB	10 m	10 m	9 m	6 m	6 m	5 m
	HF Cetaceans	202 dB	2.4 km	2.3 km	2.1 km	1.8 km	1.6 km	1.3 km
	PW Pinnipeds	218 dB	120 m	110 m	100 m	75 m	68 m	59 m
Auditory Injury (Weighted SEL_{cum})	LF Cetaceans	183 dB	13 km	10 km	8.6 km	8.9 km	7.1 km	6.2 km
	MF Cetaceans	185 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	HF Cetaceans	155 dB	60 m	30 m	20 m	900 m	700 m	410 m
	PW Pinnipeds	185 dB	1.3 km	1.1 km	820 m	700 m	490 m	310 m
TTS (unweighted SPL_{peak})	LF Cetaceans	213 dB	360 m	320 m	270 m	210 m	180 m	150 m
	MF Cetaceans	224 dB	37 m	34 m	31 m	22 m	20 m	18 m
	HF Cetaceans	196 dB	4.9 km	4.6 km	4.3 km	3.4 km	3.3 km	3.0 km
	PW Pinnipeds	212 dB	440 m	390 m	330 m	260 m	220 m	190 m
TTS (Weighted SEL_{cum})	LF Cetaceans	168 dB	103 km	95 km	71 km	91 km	59 km	52 km
	MF Cetaceans	170 dB	< 10 m	< 10 m	< 10 m	10 m	10 m	10 m
	HF Cetaceans	140 dB	5.0 km	4.3 km	3.8 km	5.9 km	5.3 km	4.7 km
	PW Pinnipeds	170 dB	13 km	11 km	9.5 km	11 km	8.8 km	7.9 km

Table 5-21 Summary of the impact ranges at the NE location for auditory injury and TTS criteria from NMFS (2016) for maximum hammer blow energy

NMFS (2016) – NE location			Monopile (500 kJ)			Pin Pile (270 kJ)		
			Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
Auditory Injury (unweighted SPL_{peak})	LF Cetaceans	219 dB	9 m	9 m	8 m	3 m	3 m	3 m
	MF Cetaceans	230 dB	< 1 m	< 1 m	< 1 m	< 1 m	< 1 m	< 1 m
	HF Cetaceans	202 dB	320 m	280 m	240 m	120 m	110 m	96 m
	PW Pinnipeds	218 dB	11 m	10 m	10 m	4 m	4 m	4 m
TTS (unweighted SPL_{peak})	LF Cetaceans	213 dB	33 m	30 m	27 m	13 m	12 m	11 m
	MF Cetaceans	224 dB	3 m	3 m	3 m	1 m	1 m	1 m
	HF Cetaceans	196 dB	1.1 km	940 m	790 m	430 m	370 m	300 m
	PW Pinnipeds	212 dB	40 m	37 m	34 m	16 m	14 m	13 m

Table 5-22 Summary of the SPL_{peak} impact ranges at the NE location for auditory injury and TTS criteria from NMFS (2016) for soft start hammer blow energy

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 mean SEL_{cum} ranges are shown below (Table 5-23), the LF weighting leads to the greatest ranges as the MF and HF cetacean weightings filter out much of the piling energy, especially using the NMFS criteria. This is discussed further below.

Auditory injury ranges (SW location)		Weighted SEL_{cum} (Fleeing animal) (dB re 1 µPa²s)	
	Weighting	**Criterion**	**Mean range**
Monopile (5000kJ)	LF Cetaceans	183 dB	17 km
	MF Cetaceans	185 dB	< 10 m
	HF Cetaceans	155 dB	240 m
	Pinnipeds (in water)	185 dB	2.1 km

Table 5-23 Same ranges for auditory injury for marine mammals at the SW modelling location using the NMFS (2016) criteria for maximum hammer blow energy

The SEL_{cum} results for HF cetaceans using the NMFS (2016) criteria (Table 5-19 and Table 5-21) 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 explained by examining the difference in sensitivity between the marine mammal hearing groups and the sound frequencies produced by the different piles. This is also the case for MF cetaceans, however 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 5-5 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 5-5). Overall, higher levels are present in the weighted pin pile spectrum.

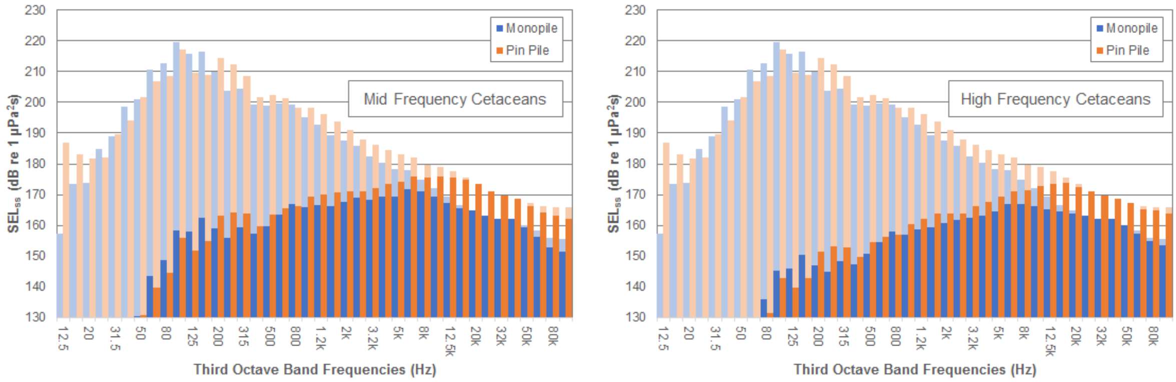

Figure 5-5 Filtered noise inputs for monopiles and pin piles using the MF and HF cetacean filters from NMFS (2016). The lighter coloured bars show the unweighted third octave levels

5.2.3 Impacts on fish

Table 5-24 to Table 5-35 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 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. In fact, the data available to create the criteria is limited and most criteria are “greater than”, with a precise threshold not identified. All ranges associated with criteria defined as “>” are therefore somewhat conservative.

The results show that fish with swim bladders that are involved in hearing are the most sensitive to the impact piling noise with ranges of up to 8.3 km recoverable injury and 58 km TTS.

Fish (no swim bladder) – SW location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
SPL_{peak}	Mortality and potential mortal injury	>213 dB	440 m	380 m	320 m	260 m	220 m	190 m
	Recoverable injury	>213 dB	440 m	380 m	320 m	260 m	220 m	190 m
SEL_{cum}	Mortality and potential mortal injury	>219 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	Recoverable injury	>216 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	TTS	>>186 dB	58 km	48 km	43 km	37 km	34 km	30 km

Table 5-24 Summary of the impact ranges at the SW location for fish with no swim bladder using the criteria from Popper et al (2014) for maximum hammer blow energy

Fish (no swim bladder) – SW location			Monopile (500 kJ)			Pin Pile (270 kJ)		
			Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
SPL_{peak}	Mortality and potential mortal injury	>213 dB	47 m	43 m	38 m	19 m	17 m	16 m
	Recoverable injury	>213 dB	47 m	43 m	38 m	19 m	17 m	16 m

Table 5-25 Summary of the impact ranges at the SW location for fish with no swim bladder using the criteria from Popper et al (2014) for soft start hammer blow energy

Fish (no swim bladder) – NE location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
SPL_{peak}	Mortality and potential mortal injury	>213 dB	360 m	320 m	270 m	210 m	180 m	150 m
	Recoverable injury	>213 dB	360 m	320 m	270 m	210 m	180 m	150 m
SEL_{cum}	Mortality and potential mortal injury	>219 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	Recoverable injury	>216 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	TTS	>>186 dB	32 km	28 km	25 km	23 km	19 km	17 km

Table 5-26 Summary of the impact ranges at the NE location for fish with no swim bladder using the criteria from Popper et al (2014) for maximum hammer blow energy

Fish (no swim bladder) – NE location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
SPL_{peak}	Mortality and potential mortal injury	>213 dB	33 m	30 m	27 m	13m	12 m	11 m
	Recoverable injury	>213 dB	33 m	30 m	27 m	13 m	12 m	11 m

Table 5-27 Summary of the impact ranges at the NE location for fish with no swim bladder using the criteria from Popper et al (2014) for soft start hammer blow energy

Fish (swim bladder not involved in hearing) – SW location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
SPL_{peak}	Mortality and potential mortal injury	>207 dB	1.4 km	1.2 km	990 m	860 m	710 m	580 m
	Recoverable injury	>207 dB	1.4 km	1.2 km	990 m	860 m	710 m	580 m
SEL_{cum}	Mortality and potential mortal injury	210 dB	1.5 km	1.2 km	790 m	40 m	20 m	10 m
	Recoverable injury	203 dB	8.3 km	7.0 km	5.5 km	4.0 km	3.6 km	2.8 km
	TTS	>186 dB	58 km	48 km	43 km	37 km	34 km	30 km

Table 5-28 Summary of the impact ranges at the SW location for fish with swim bladder not involved in hearing using the criteria from Popper et al (2014) for maximum hammer blow energy

Fish (swim bladder not involved in hearing) – SW location			Monopile (500 kJ)			Pin Pile (270 kJ)		
			Max	Mean	Min	Max	Mean	Min
SPL_{peak}	Mortality and potential mortal injury	>207 dB	150 m	132 m	120 m	63 m	55 m	49 m
	Recoverable injury	>207 dB	150 m	132 m	120 m	63 m	55 m	49 m

Table 5-29 Summary of the impact ranges at the SW location for fish with swim bladder not involved in hearing using the criteria from Popper et al (2014) for soft start hammer blow energy

Fish (swim bladder not involved in hearing) – NE location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
SPL_{peak}	Mortality and potential mortal injury	>207 dB	1.2 km	1.0 km	890 m	720 m	620 m	500 m
	Recoverable injury	>207 dB	1.2 km	1.0 km	890 m	720 m	620 m	500 m
SEL_{cum}	Mortality and potential mortal injury	210 dB	620 m	450 m	270 m	10 m	< 10 m	< 10 m
	Recoverable injury	203 dB	4.7 km	4.2 km	3.7 km	2.3 km	2.0 km	1.7 km
	TTS	>186 dB	32 km	28 km	25 km	23 km	19 km	17 km

Table 5-30 Summary of the impact ranges at the NE location for fish with swim bladder not involved in hearing using the criteria from Popper et al (2014) for maximum hammer blow energy

Fish (swim bladder not involved in hearing) – NE location			Monopile (500 kJ)			Pin Pile (270 kJ)		
			Max	Mean	Min	Max	Mean	Min
SPL_{peak}	Mortality and potential mortal injury	>207 dB	110 m	99 m	91 m	45 m	41 m	36m
	Recoverable injury	>207 dB	110 m	99 m	91 m	45 m	41 m	36m

Table 5-31 Summary of the impact ranges at the NE location for fish with swim bladder not involved in hearing using the criteria from Popper et al (2014) for soft start hammer blow energy

Fish (swim bladder involved in hearing) – SW location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
SPL_{peak}	Mortality and potential mortal injury	>207 dB	1.4 km	1.2 km	990 m	860 m	710 m	580 m
	Recoverable injury	>207 dB	1.4 km	1.2 km	990 m	860 m	710 m	580 m
SEL_{cum}	Mortality and potential mortal injury	207 dB	3.7 km	3.2 km	2.5 km	1.2 km	870 m	520 m
	Recoverable injury	203 dB	8.3 km	7.0 km	5.5 km	4.0 km	3.6 km	2.8 km
	TTS	186 dB	58 km	48 km	43 km	37 km	34 km	30 km

Table 5-32 Summary of the impact ranges at the SW location for fish with swim bladder involved in hearing using the criteria from Popper et al (2014) for maximum hammer blow energy

Fish (swim bladder involved in hearing) – SW location			Monopile (500 kJ)			Pin Pile (270 kJ)		
			Max	Mean	Min	Max	Mean	Min
SPL_{peak}	Mortality and potential mortal injury	>207 dB	150 m	132 m	120 m	63 m	55 m	49 m
	Recoverable injury	>207 dB	150 m	132 m	120 m	63 m	55 m	49 m

Table 5-33 Summary of the impact ranges at the SW location for fish with swim bladder involved in hearing using the criteria from Popper et al (2014) for soft start hammer blow energy

Fish (swim bladder involved in hearing) – NE location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
SPL$_{peak}$	Mortality and potential mortal injury	>207 dB	1.2 km	1.0 km	890 m	720 m	620 m	500 m
	Recoverable injury	>207 dB	1.2 km	1.0 km	890 m	720 m	620 m	500 m
SEL$_{cum}$	Mortality and potential mortal injury	207 dB	2.1 km	1.8 km	1.5 km	420 m	270 m	90 m
	Recoverable injury	203 dB	4.7 km	4.2 km	3.7 km	2.3 km	2.0 km	1.7 km
	TTS	186 dB	32 km	28 km	25 km	23 km	19 km	17 km

Table 5-34 Summary of the impact ranges at the SW location for fish with swim bladder involved in hearing using the criteria from Popper et al (2014) for maximum hammer blow energy

Fish (swim bladder involved in hearing) – NE location			Monopile (500 kJ)			Pin Pile (270 kJ)		
			Max	Mean	Min	Max	Mean	Min
SPL$_{peak}$	Mortality and potential mortal injury	>207 dB	110 m	99 m	91 m	45 m	41 m	36m
	Recoverable injury	>207 dB	110 m	99 m	91 m	45 m	41 m	36m

Table 5-35 Summary of the impact ranges at the SW location for fish with swim bladder involved in hearing using the criteria from Popper et al (2014) for soft start hammer blow energy

5.3 In-combination effects

It is possible that up to four piling vessels could be operational at the same time during construction work at Norfolk Vanguard. Modelling has been carried out to show the impact of all piling vessels operating simultaneously: two locations in NV West and two locations in NV East (as detailed in section 4.2), this gives a large spatial range of noise propagation for the two parts of the site. The modelling is presented in Figure 5-6 to Figure 5-9. All the results are given as unweighted single strike SELs.

Further modelling showing piling at all four locations simultaneously are presented in Figure 5-10 and Figure 5-11.

The results show that monopiles are louder at closer ranges, whereas at far-field ranges the noise from pin piles is slightly higher. This most likely due to the frequency content of the two pile sizes, with greater high frequency noise in the pin pile noise signature (see section 4.3.3) attenuating at different rates over large distances, especially in shallow water.

The results for the four pile scenarios show greater impact ranges than for piling at two locations but with similar characteristics of noise when comparing monopiles and pin piles at close range and at distance.

It should be noted that this simultaneous piling scenario is a worst case, as it is based on the previous worst case modelling presented in the previous sections and relies on the piling vessels reaching their maximum blow energies at the same time. It also makes the assumption of striking simultaneously, with the propagating strike pulses meeting at all points. The compound nature of these worst case scenarios would lead to a somewhat unrealistic modelled situation, and as such, the results should be considered very conservative.

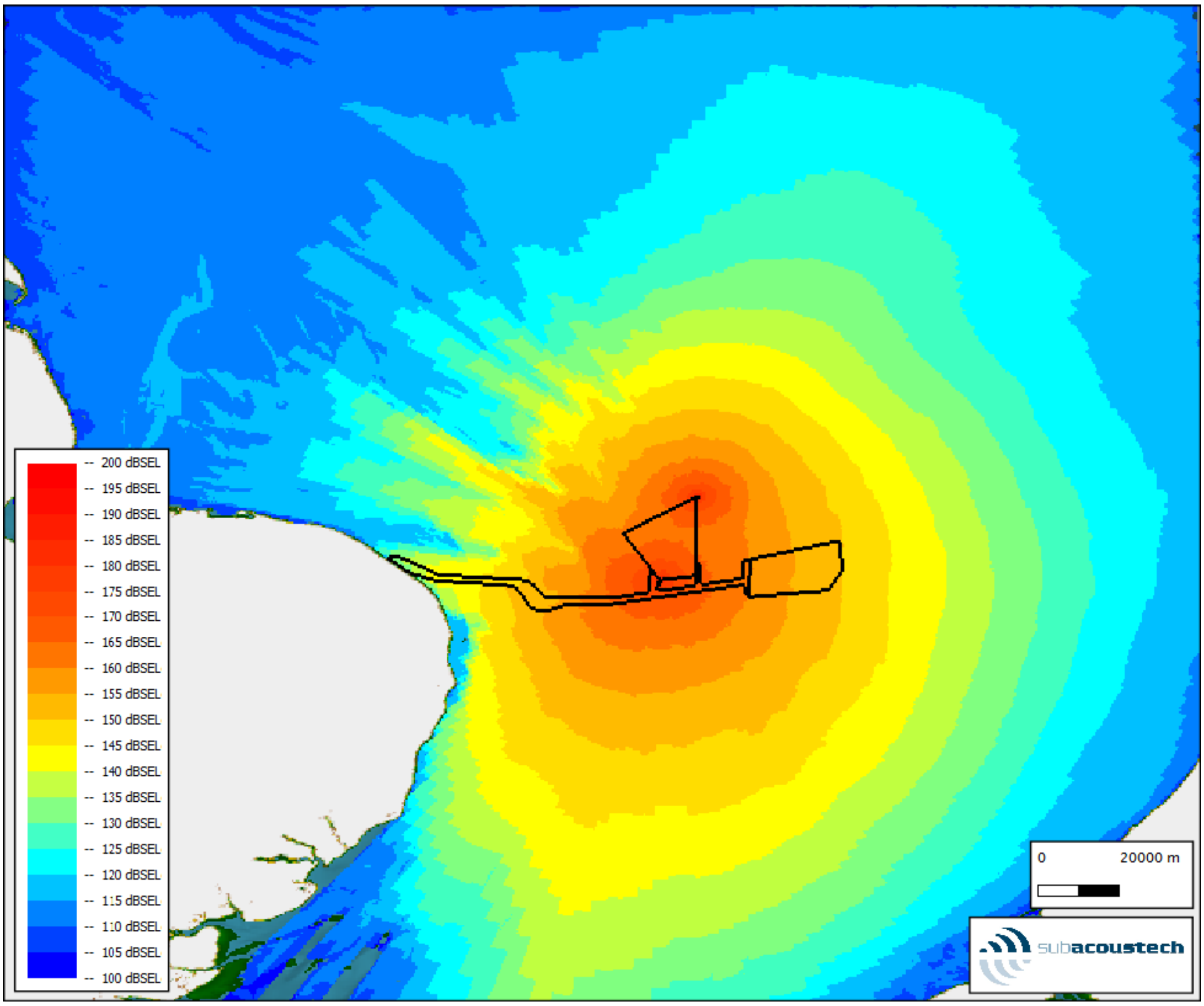

Figure 5-6 Noise level plot showing the predicted in-combination SEL_{ss} noise levels predicted for installing monopiles at two locations in the Norfolk Vanguard West site

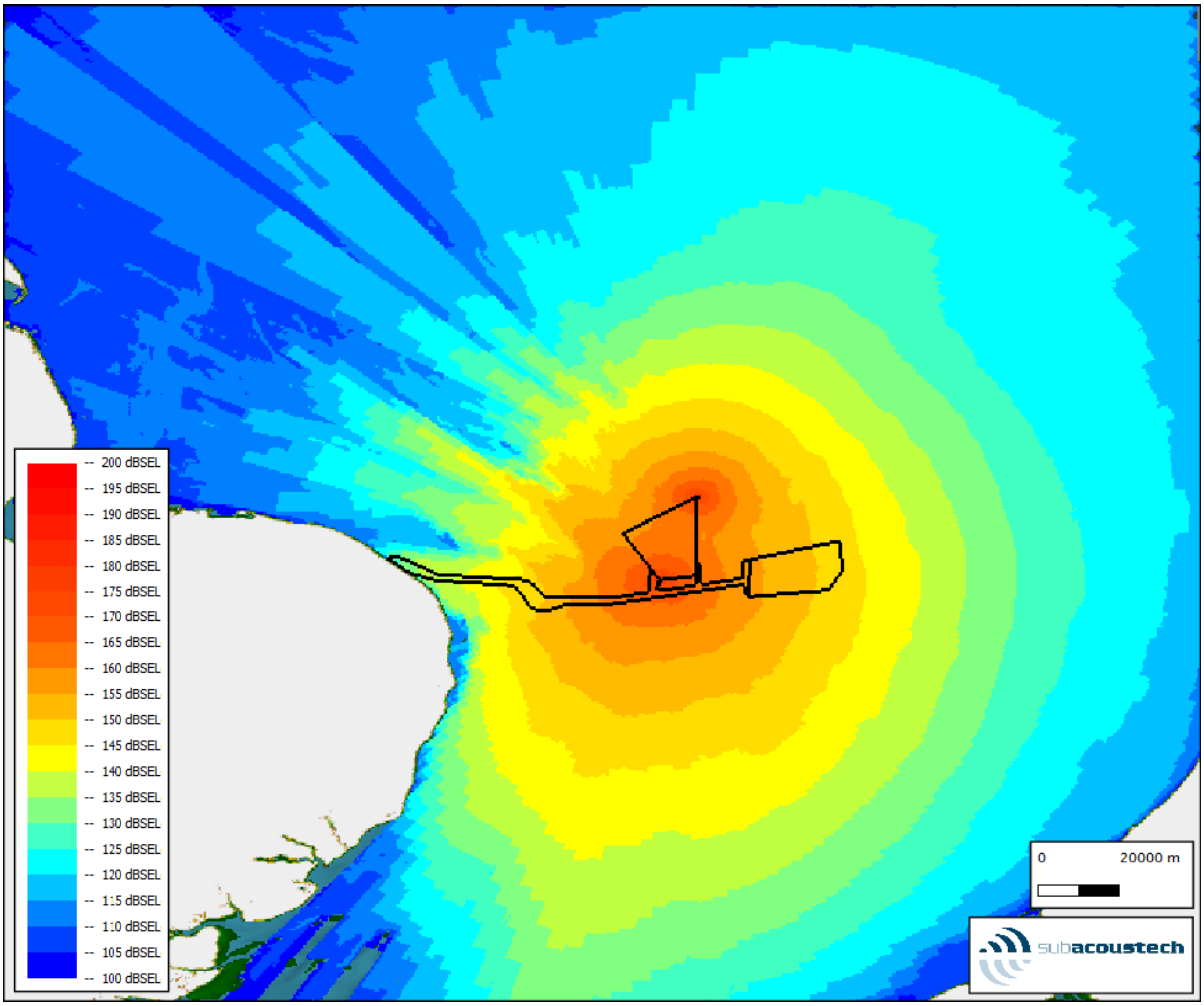

Figure 5-7 Noise level plot showing the predicted in-combination SEL_{ss} noise levels predicted for installing pin piles at two locations in the Norfolk Vanguard West site

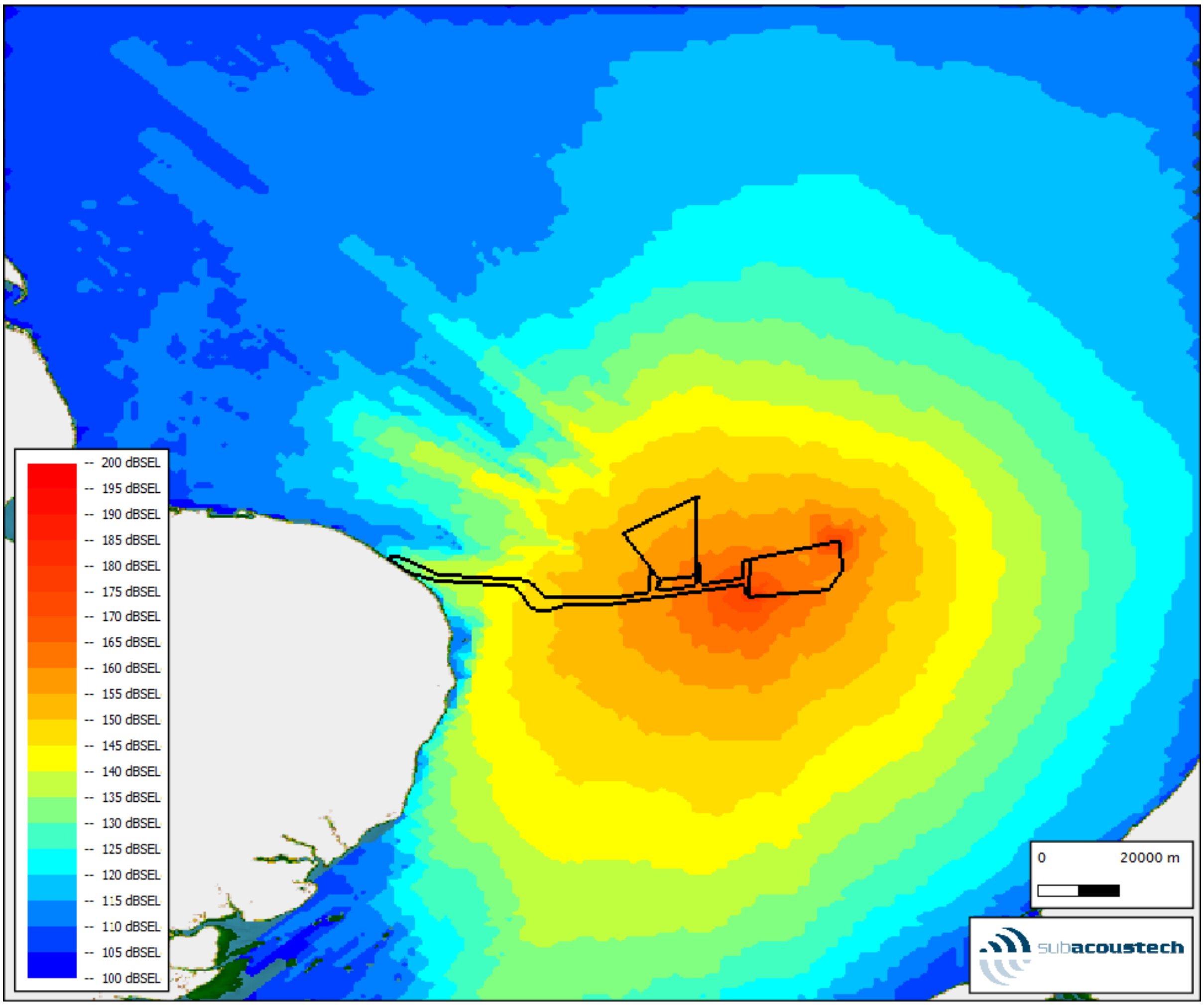

Figure 5-8 Noise level plot showing the predicted in-combination SEL_{ss} noise levels predicted for installing monopiles at two locations in the Norfolk Vanguard East site

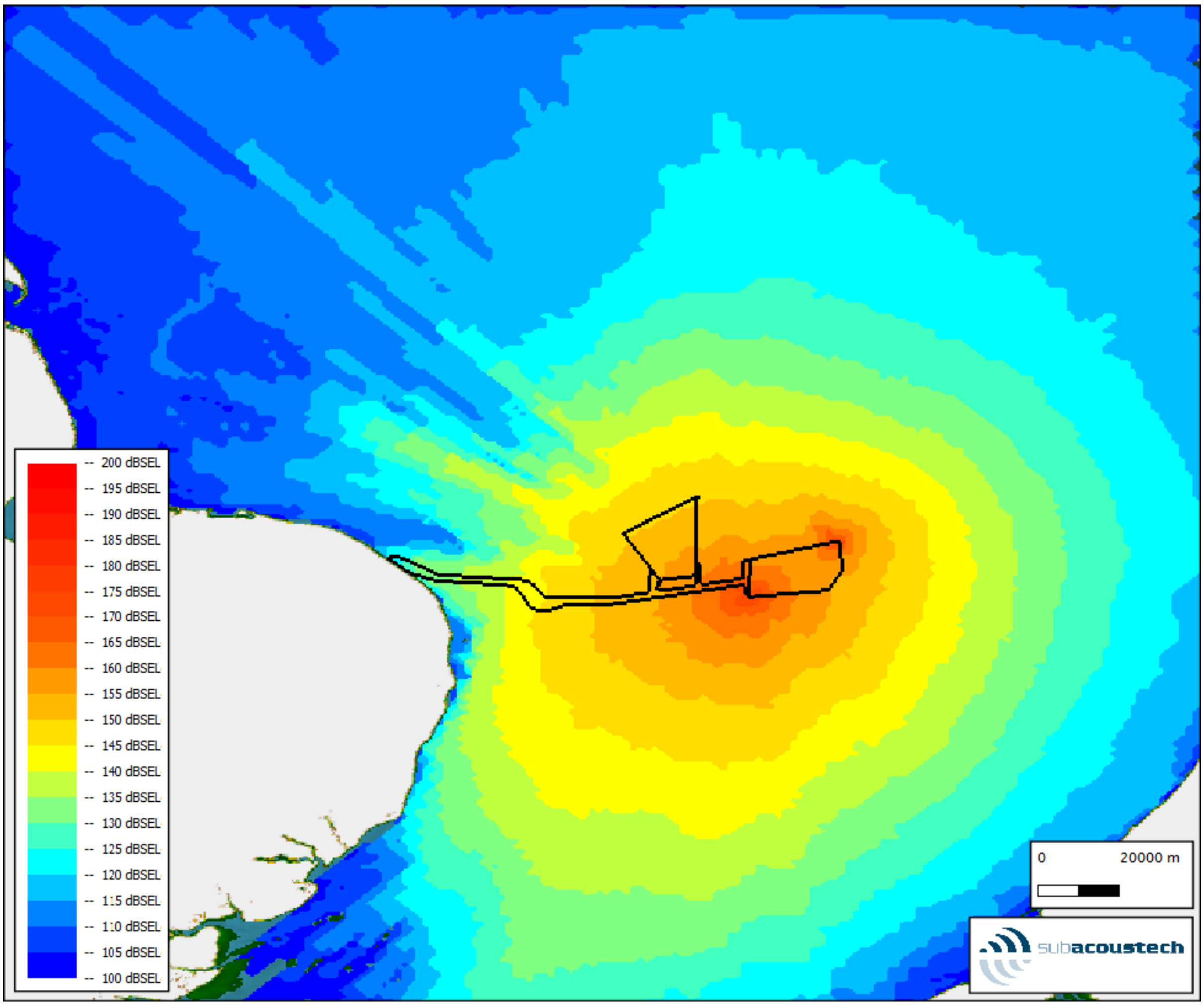

Figure 5-9 Noise level plot showing the predicted in-combination SEL_{ss} noise levels predicted for installing pin piles at two locations in the Norfolk Vanguard East site

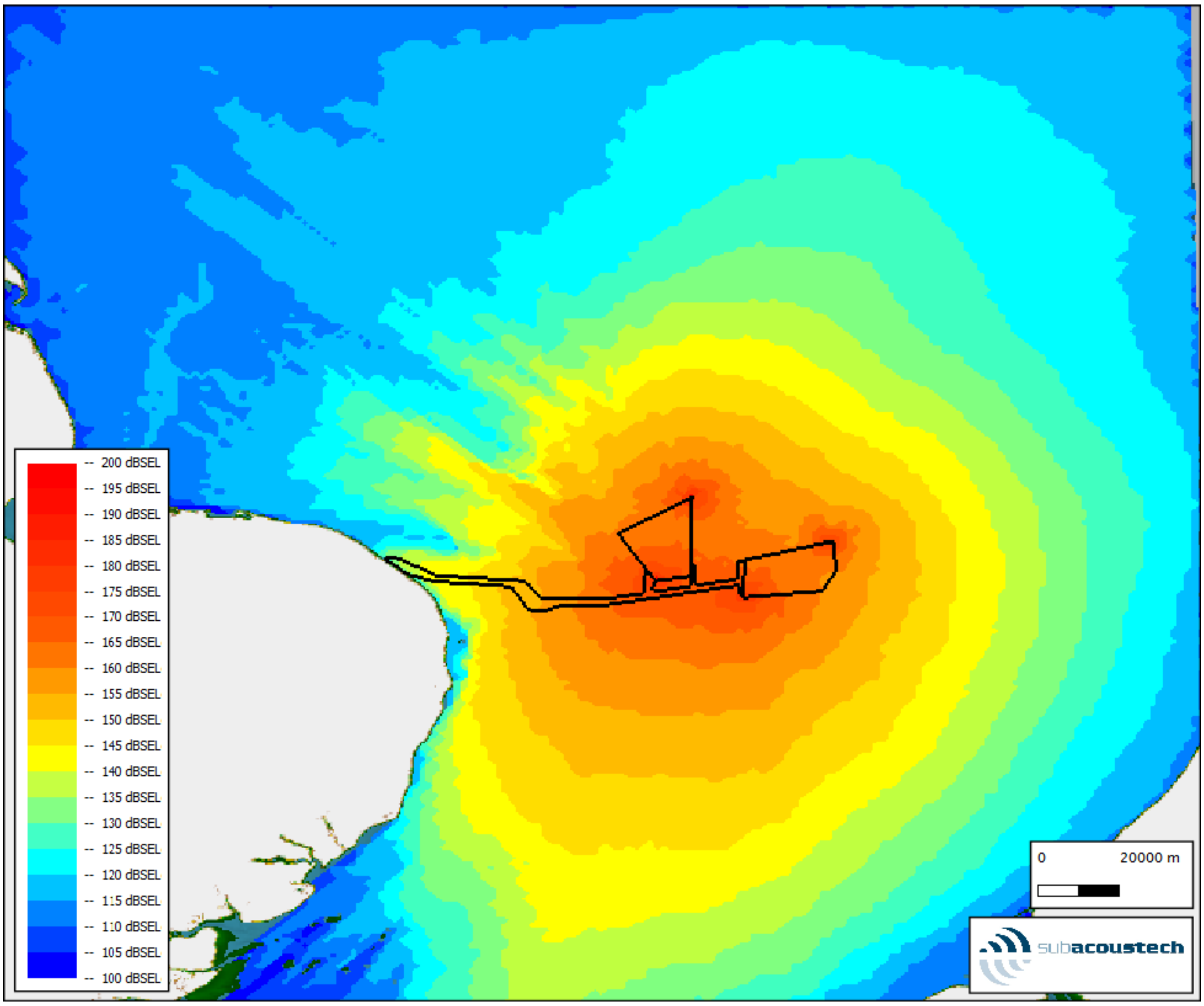

Figure 5-10 Noise level plot showing the predicted in-combination SEL_{ss} noise levels predicted for installing monopiles at four locations, two in the Norfolk Vanguard West site and two in the Norfolk Vanguard East site

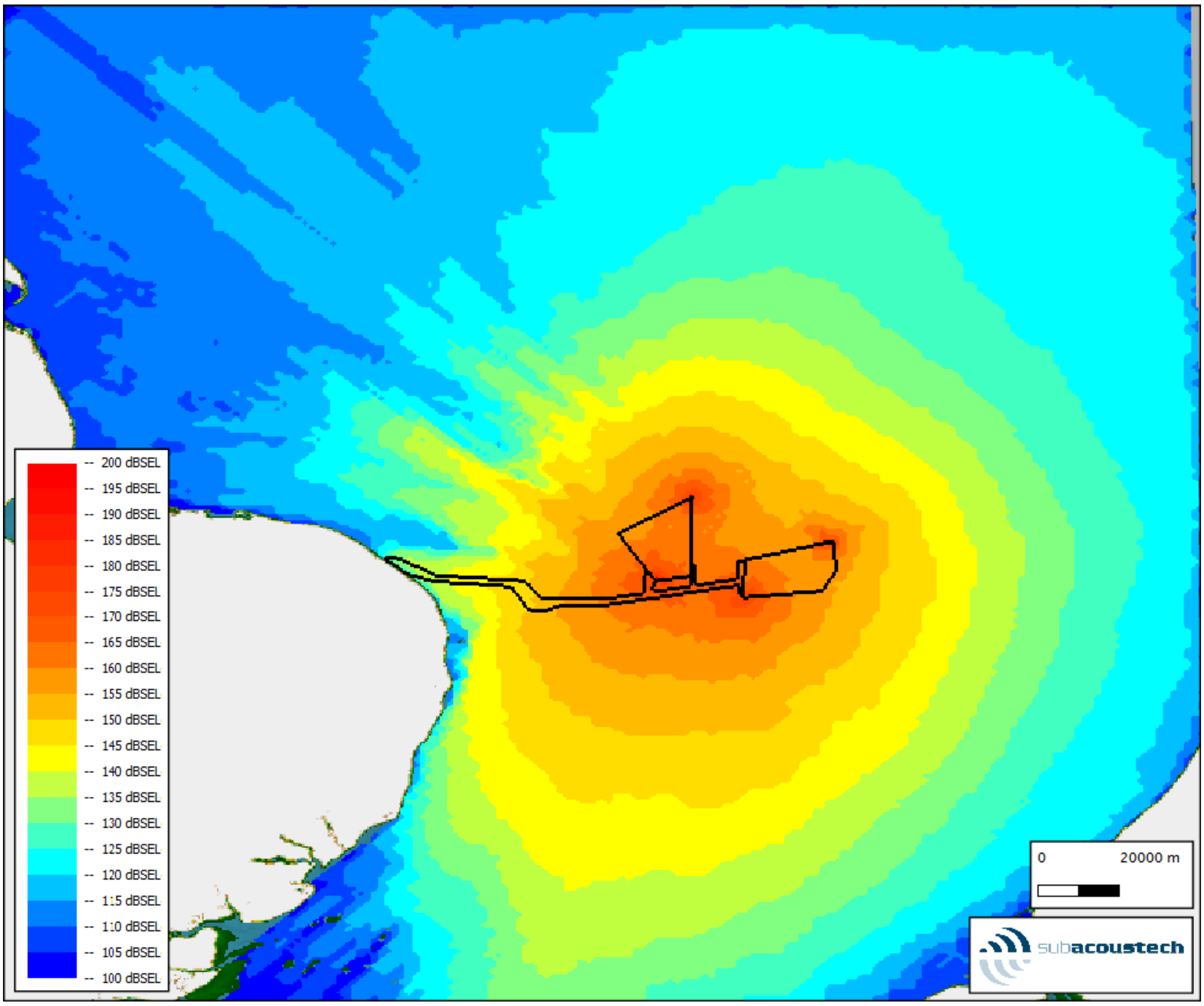

Figure 5-11 Noise level plot showing the predicted in-combination SEL_{ss} noise levels predicted for installing pin piles at four locations, two in the Norfolk Vanguard West site and two in the Norfolk Vanguard East site

6 Summary and conclusions

Subacoustech Environmental has undertaken a study on behalf of Royal HaskoningDHV to assess the effect of impact piling noise during construction of the Norfolk Vanguard Offshore Wind Farm.

The level of underwater noise from the installation of monopiles and pin piles during construction has been estimated by using a combined parabolic equation (PE) and ray tracing modelling method. The modelling considers a wide variety of input parameters including bathymetry, hammer blow energy, frequency content, seabed properties and the speed of sound in water.

Two representative locations were chosen at the Norfolk Vanguard East and the Norfolk Vanguard West 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. Louder 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 (Southall *et al.*, 2007, Lucke *et al.*, 2009, and NMFS, 2016) and fish (Popper *et al.*, 2014).

In addition, the possibility of up to four operational piling vessels piling at the same time has been assessed by modelling the in-combination effects of noise at two locations in NV West and two in NV East. This showed that simultaneous piling of monopiles resulted in higher noise levels at close range whereas, at greater ranges, the in-combination effects of the pin pile noise (and the high frequency components of the source) resulted in slightly higher levels.

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Appendix A Remodelling using INSPIRE

Following issue of the report, remodelling was carried out using the INSPIRE model. This appendix presents an updated version of the report using the new modelling methodology. The report was previously issued as Subacoustech Report Ref. E603R0303.

A.1 Introduction

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

A.1.1 Norfolk Vanguard Offshore Wind Farm

Norfolk Vanguard is a proposed wind farm in development in the North Sea, located approximately 50 km off the coast of Norfolk. The location is shown in Figure A 1. Norfolk Vanguard comprises two distinct areas, Norfolk Vanguard East (NV East) and Norfolk Vanguard West (NV West) ('the OWF sites') and will be connected to the shore by offshore export cables installed within the offshore cable corridor. The proposed project would have a potential capacity of up to 1800 MW.

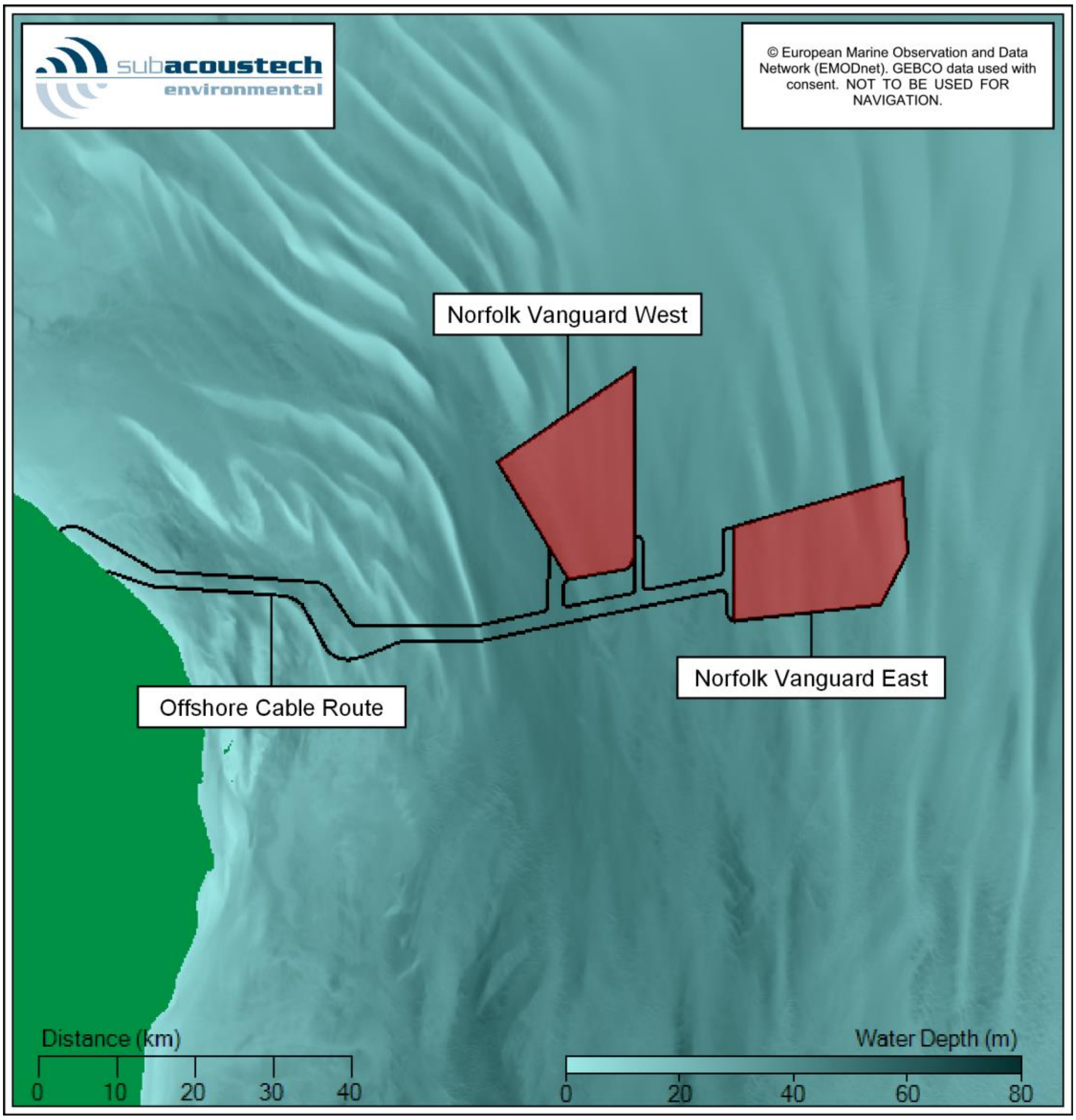

Figure A 1 Map showing the boundaries of the Norfolk Vanguard Offshore Wind Farm Project

A.1.2 Noise assessment

This report focusses on pile driving activities during construction at the Norfolk Vanguard OWF sites. Underwater noise modelling has been carried out using Subacoustech's INSPIRE subsea noise propagation and prediction software, which considers bathymetry and frequency content of noise when calculating noise levels.

Impact piling

As part of a series of construction options, impact piling has been proposed to drive the foundation piles of the wind turbines into the seabed. Impact piling may be used to install either monopile or pin pile 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; 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 its head. 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.

A.1.3 Scope of work

This report presents a detailed assessment of the potential underwater noise from impact piling at Norfolk Vanguard 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 A.2).
- A brief discussion of baseline ambient noise (Section A.3).
- Discussion of the approach, input parameters and assumptions for the noise modelling undertaken (Section A.4).
- Presentation of detailed subsea noise modelling using unweighted metrics (Section A.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 A.5.2).
- Summary and conclusions (Section A.6).

A.2 Measurement of noise

A.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.

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.

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.

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.

Sound exposure level

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.

A.2.2 Analysis of environmental effects

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 Vanguard.

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:

- Lethal effect and physical injury from Parvin *et al.* (2007);
- 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 present the most up to date and authoritative criteria for assessing environmental effects for use in impact assessments.

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

- Lethal effect may occur when peak noise levels exceed 240 dB re 1 µPa; and

Physical injury may occur when peak noise levels exceed 220 dB re 1 µPa.

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 A 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)	Habour 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 A 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 A 2 to Table A 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 A 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 µPa²s)**	**Auditory Injury (M-Weighted SEL_{cum} dB re 1 µPa²s)**	**TTS (M-Weighted SEL_{ss} dB re 1 µPa²s)**
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 A 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 A 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 A 5.

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

Table A 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 functional hearing groups 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 A 6 and Figure A 2. 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 A 6 Marine mammal hearing groups (from NMFS, 2016))

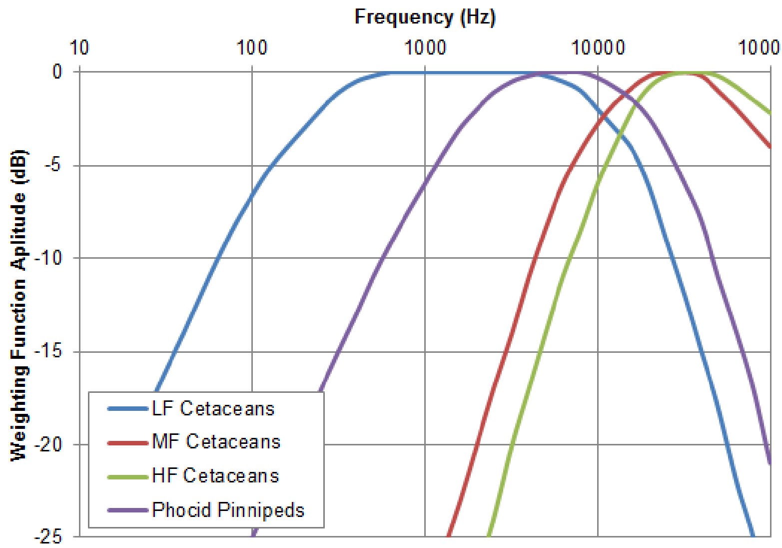

Figure A 2 Auditory weighting functions for low frequency (LF) cetaceans, mid frequency (MF) cetaceans, high frequency (HF) cetaceans, and phocid pinnipeds (PW) (underwater) (from NMFS, 2016)

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 A 7 and Table A 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 A 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 A 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 by this point it will have received the majority of the noise from piling.

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).

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.

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 conservative. The modelled criteria are summarised in Table A 9. In a similar fashion to marine mammals for SEL_{cum} results, a fleeing animal model has been used assuming a receptor 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 A 9 Criteria for assessment of mortality and potential mortal injury, recoverable injury and TTS in species of fish (Popper et al, 2014)

A.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 or Active Dredge Zones and Dredging Application Option and Prospecting Areas within the Norfolk Vanguard boundary.

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 Vanguard study area, although this is unlikely to contribute to the overall ambient noise. Clearance of UXO contributes high but infrequent and localised 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 Vanguard 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 A 3 below. Figure A 3 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 the same region as Norfolk Vanguard, 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.

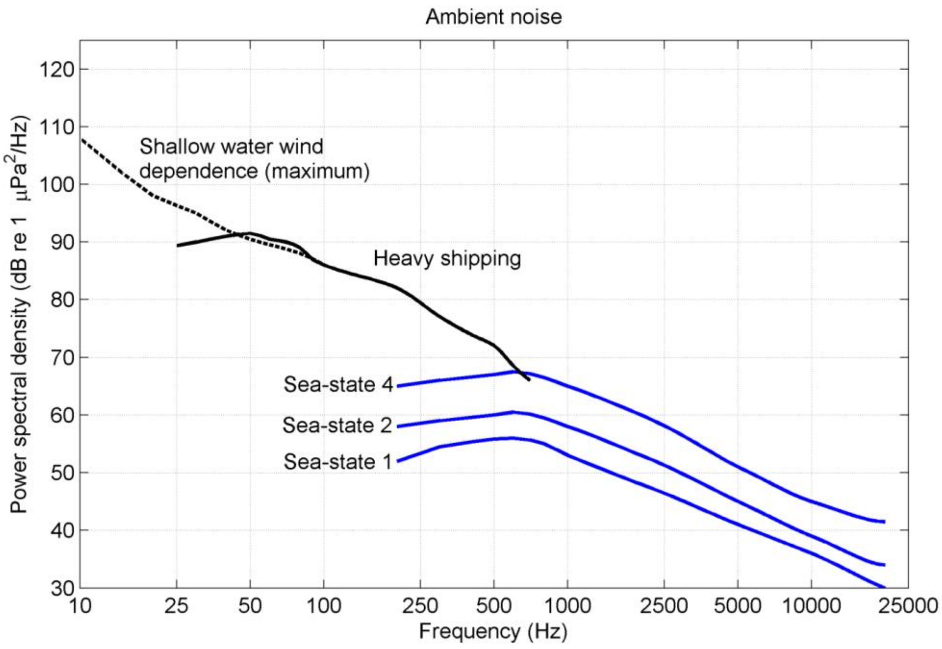

Figure A 3 Ambient underwater noise as shown in Wenz (1962) showing frequency dependency from different noise sources.

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 A.2.2 are all considerably above the level of background noise, any noise baseline would not feature in an assessment to these criteria.

A.4 Modelling methodology

A.4.1 Introduction

To estimate the underwater noise levels likely to arise during construction of Norfolk Vanguard, 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, coastal water, typical of the coastal conditions around the UK and very well suited to the Norfolk Vanguard site.

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 as detailed results as possible. 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.

A.4.2 Locations

Modelling has been undertaken at four representative locations: two in NV West, covering the position closest to land (SW) and the furthest position from this location (NE) in NV West, and two additional locations in NV East (following the pattern from NV West). The chosen locations are shown in Figure A 4 and summarised in Table A 10, below.

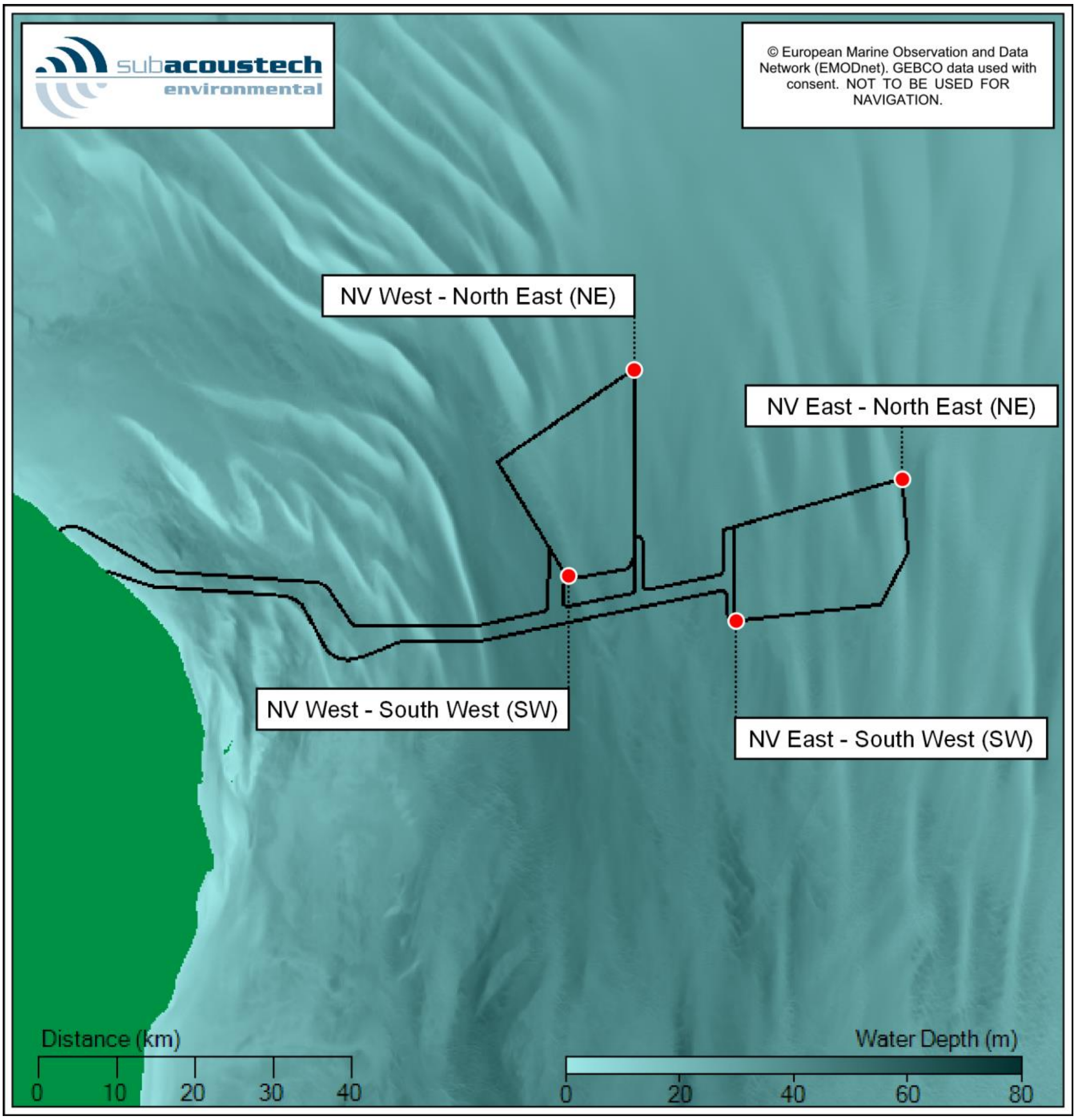

Figure A 4 Map showing the underwater noise modelling locations in the Norfolk Vanguard OWF site

	Norfolk Vanguard West		**Norfolk Vanguard East**	
	South West (SW)	North East (NE)	South West (SW)	North East (NE)
Latitude	52.80098°N	53.04354°N	52.75323°N	52.91596°N
Longitude	002.44379°E	002.57117°E	002.76044°E	003.07780°E
Water depth	40 m	35 m	39 m	28 m

Table A 10 Summary of the underwater noise modelling locations and associated water depths (mean tide)

The two locations at NV West are representative of the worst case for the NV West and NV East sites as the deeper water in NV West is conducive of higher noise source levels and greater overall noise propagation. In respect of location sensitivity, the locations in NV West are also closest to nature conservation designations.

A.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.

Impact piling

Two piling source scenarios have been modelled to include monopile and pin pile WTG foundations across the Norfolk Vanguard OWF farm sites. These are:

- Monopiles installed using a maximum blow energy of 5000 kJ; and
- Pin piles installed using a maximum 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 A 11 and Table A 12, below. The ramp up takes place over the first half-hour of piling, starting at ten percent of maximum, gradually increasing in blow energy and strike rate until reaching the maximum energy, where it stays for the remaining time. The monopile scenario contains 7200 pile strikes over 255 minutes (4 hours 15 minutes). The pin pile scenario includes 4 individual piles installed consecutively, which contains a total of 8400 strikes over 6 hours (1 hour 30 minutes for each pin pile). For the purposes of noise modelling, it is assumed that there is no pause between each individual pin pile, and thus assumes that the marine mammal or fish receptor continues swimming away from the source when no piling is occurring.

	10%	**Ramp up**	**100%**
Monopile blow energy	500 kJ	Gradual increase	5000 kJ
Number of strikes	150 strikes	300 strikes	6750 strikes
Duration	10 minutes	20 minutes	225 minutes

Table A 11 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	150 strikes	300 strikes	1650 strikes
Duration	10 minutes	20 minutes	60 minutes

Table A 12 Summary of the ramp up scenario used for calculating cumulative SELs for a single pin pile (modelling assumes four consecutive piles installed at the same location)

Source levels

Modelling requires knowledge of the source level, which is the theoretical noise level at 1 m from the noise source. Subacoustech has undertaken numerous measurements of impact piling offshore and has developed a sound level model based primarily on the blow energy and water depth of a piling operation, which have been shown to be the primary factors when comparing piling operations and the subsequent subsea noise levels produced.

As the model assumes that the noise source acts as a single point, the water depth at the noise source has been used to adjust the source level to allow for the length of pile in contact with the water.

The unweighted SPL_{peak} and SEL_{ss} source levels estimated for this project are provided in Table A 13 and Table A 16 for the starting and maximum hammer blow energies respectively.

	Monopile source level (500 kJ)	Pin pile source level (270 kJ)
NV West (SW)	243.6 dB re 1 µPa @ 1 m	241.3 dB re 1 µPa @ 1 m
NV West (NE)	241.5 dB re 1 µPa @ 1 m	239.1 dB re 1 µPa @ 1 m
NV East (SW)	243.2 dB re 1 µPa @ 1 m	240.9 dB re 1 µPa @ 1 m
NV East (NE)	238.4 dB re 1 µPa @ 1 m	235.8 dB re 1 µPa @ 1 m

Table A 13 Summary of the unweighted source levels (SPL_{peak}) used for full energy modelling in this study

	Monopile source level (500 kJ)	Pin pile source level (270 kJ)
NV West (SW)	232.4 dB re 1 µPa @ 1 m	228.1 dB re 1 µPa @ 1 m
NV West (NE)	229.9 dB re 1 µPa @ 1 m	225.6 dB re 1 µPa @ 1 m
NV East (SW)	231.9 dB re 1 µPa @ 1 m	227.6 dB re 1 µPa @ 1 m
NV East (NE)	226.3 dB re 1 µPa @ 1 m	222.0 dB re 1 µPa @ 1 m

Table A 14 Summary of the unweighted source levels (SPL_{peak}) used for modelling soft start in this study

	Monopile source level (5000 kJ)	Pin pile source level (2700 kJ)
NV West (SW)	223.6 dB re 1 µPa^{2}s @ 1 m	221.3 dB re 1 µPa^{2}s @ 1 m
NV West (NE)	221.5 dB re 1 µPa^{2}s @ 1 m	219.1 dB re 1 µPa^{2}s @ 1 m
NV East (SW)	223.2 dB re 1 µPa^{2}s @ 1 m	220.9 dB re 1 µPa^{2}s @ 1 m
NV East (NE)	218.4 dB re 1 µPa^{2}s @ 1 m	215.8 dB re 1 µPa^{2}s @ 1 m

Table A 15 Summary of the unweighted source levels (SEL_{ss}) used for full energy modelling in this study

	Monopile source level (500 kJ)	Pin pile source level (270 kJ)
NV West (SW)	212.4 dB re 1 µPa^{2}s @ 1 m	208.1 dB re 1 µPa^{2}s @ 1 m
NV West (NE)	209.9 dB re 1 µPa^{2}s @ 1 m	205.6 dB re 1 µPa^{2}s @ 1 m
NV East (SW)	211.9 dB re 1 µPa^{2}s @ 1 m	207.6 dB re 1 µPa^{2}s @ 1 m
NV East (NE)	206.3 dB re 1 µPa^{2}s @ 1 m	202.0 dB re 1 µPa^{2}s @ 1 m

Table A 16 Summary of the unweighted source levels (SEL_{ss}) used for modelling soft start in this study

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 (i.e. frequency) levels for installing monopiles and pin piles. The third-octave frequency spectrum levels used for modelling the SW location are illustrated in Figure A 5 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.

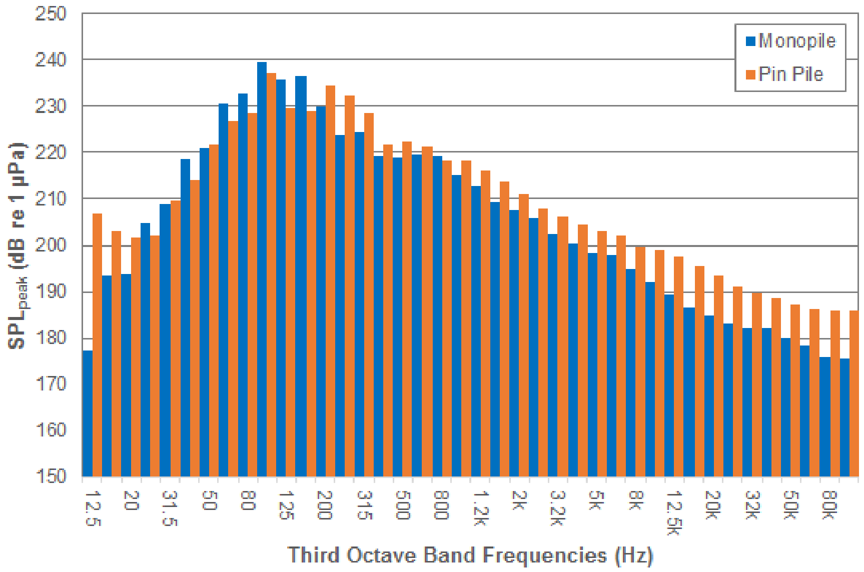

Figure A 5 Third-octave source level frequency spectra for the south west location, maximum blow energy

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 Vanguard. A larger diameter would be expected to move the dominant frequency of the sound produced lower, further below the frequencies of greatest hearing sensitivity of marine mammals, and thus the sound would appear slightly quieter to a receptor. Marine mammal hearing sensitivity is covered in section A.2.2.

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 Vanguard 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. The tidal range at the site varies between 3.2 m above chart datum at MHWS and 0.6 m above chart datum at MLWS, using the mean depth is a reasonable assumption to cover the differences that the tide variation will bring.

A.5 Subsea noise modelling outputs

A.5.1 Unweighted subsea noise modelling

This section presents the unweighted noise level (i.e. in the absence of any weighting for marine mammal hearing sensitivity) 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 NV West. Figure A 6 to Figure A 9 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). Plots for NV West only are shown, full details of both NV West and East sites are provided in tables in Section A.5.2.

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 north and west of the site, where the 'sawtooth' range pattern occurs between the ridges as a consequence of the differences in water depth.

The lower extent of the noise levels on these plots, denoted in dB SPL_{peak} suitable for impulsive noise, 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.

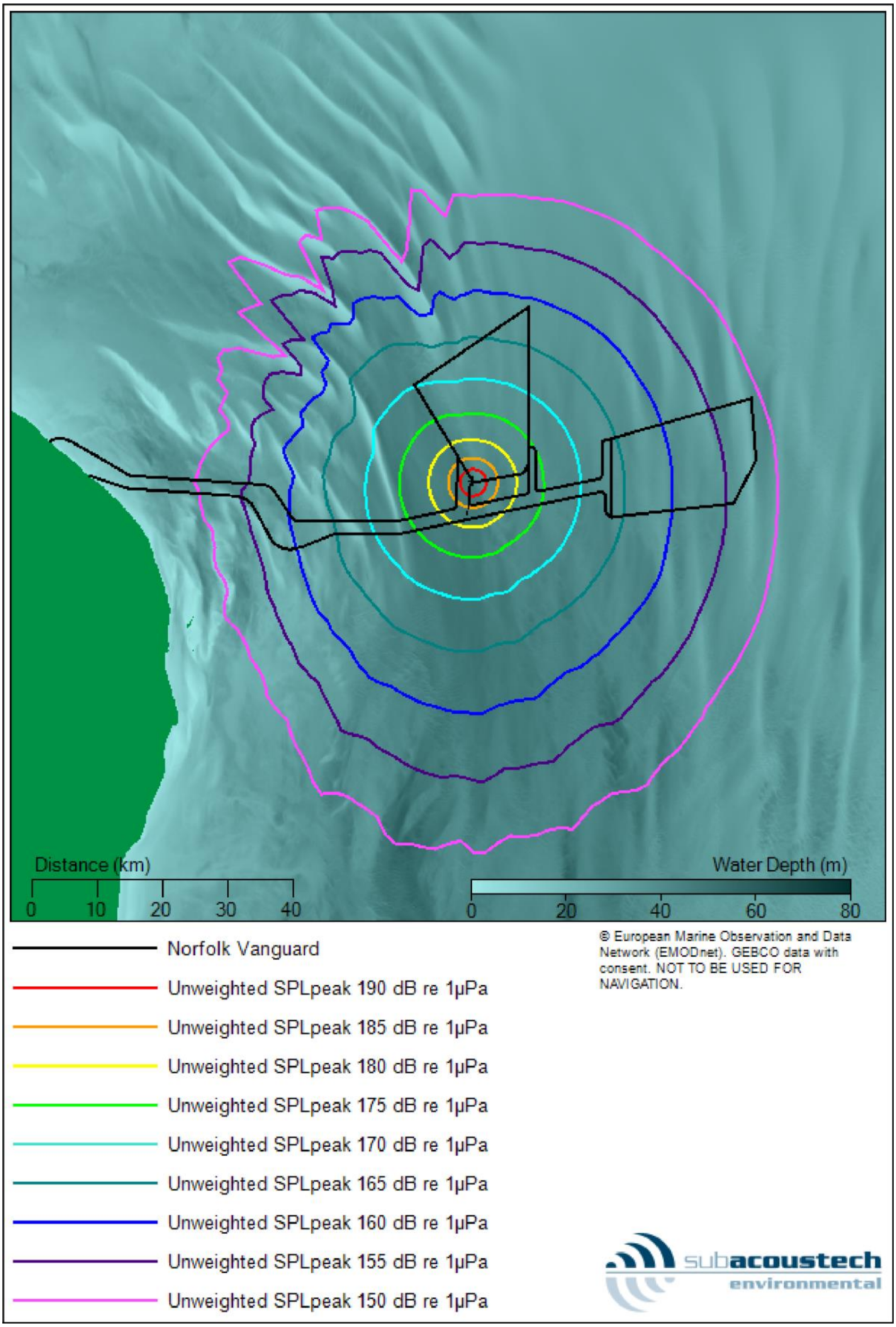

Figure A 6 Noise level plot showing the predicted SPL_{peak} noise levels predicted for installing a monopile at the SW location of NV West

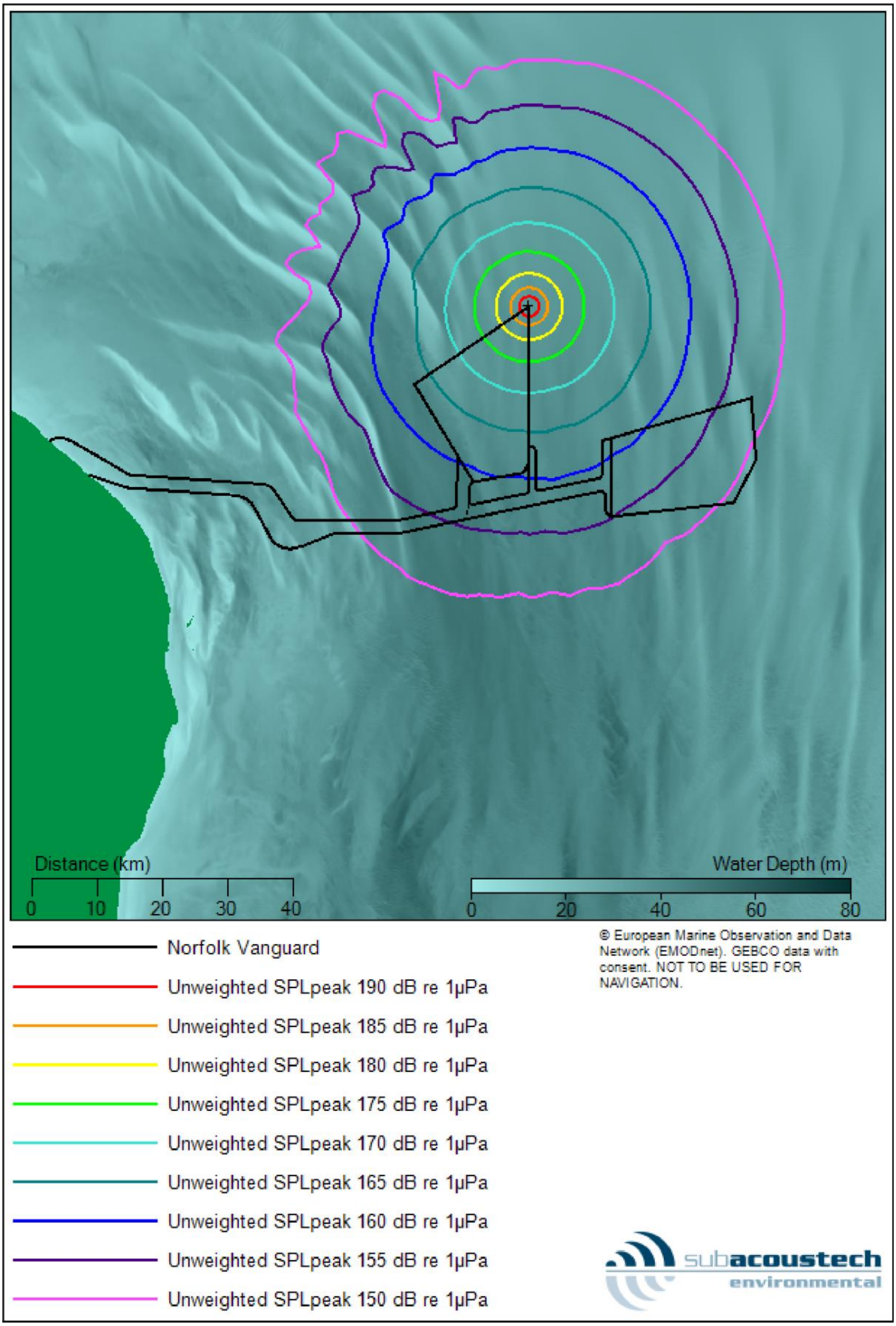

Figure A 7 Noise level plot showing the predicted SPL_{peak} noise levels predicted for installing a monopile at the NE location of NV West

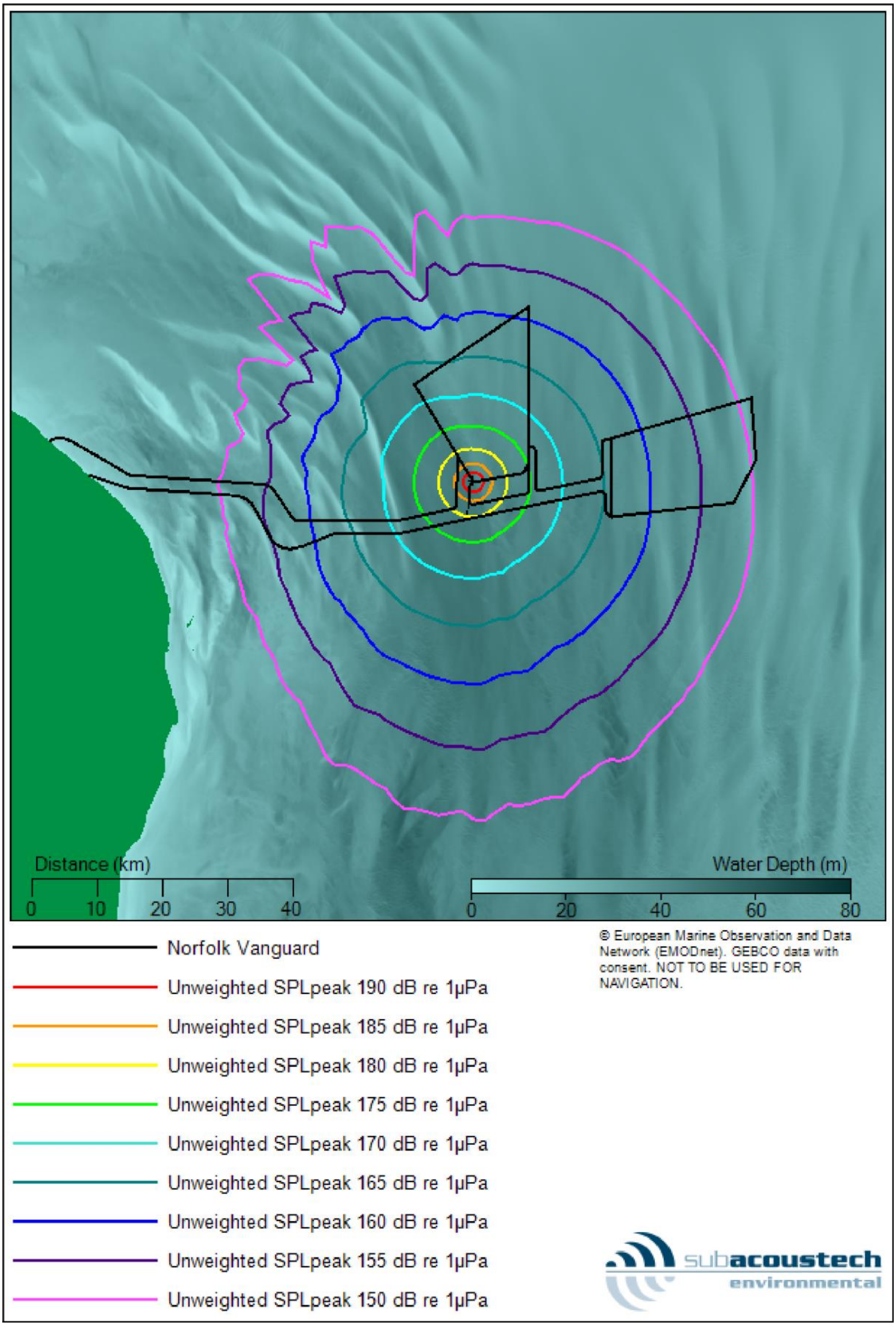

Figure A 8 Noise level plot showing the predicted SPL_{peak} noise levels predicted for installing a pin pile at the SW location of NV West

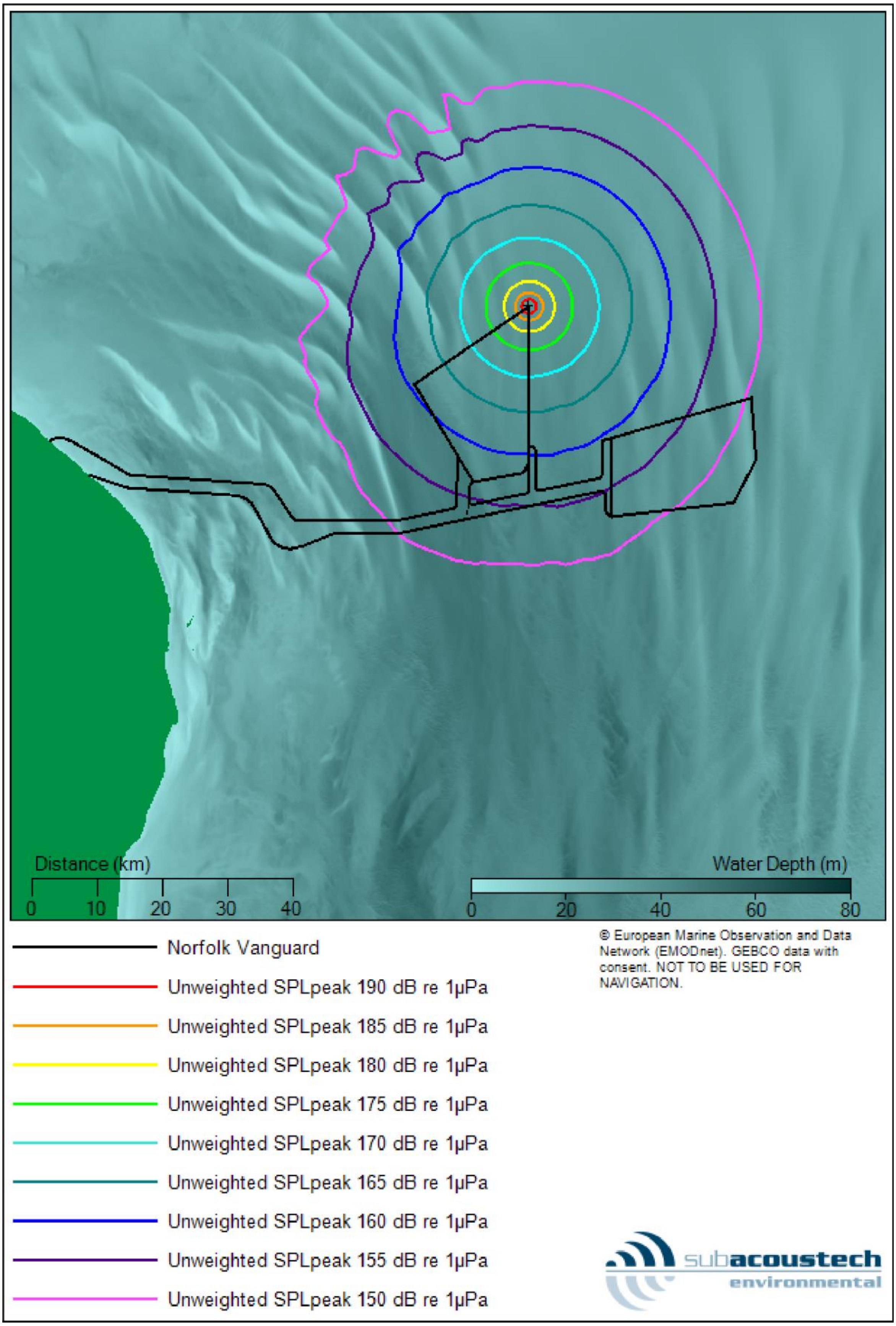

Figure A 9 Noise level plot showing the predicted SPL_{peak} noise levels predicted for installing a pin pile at the NE location of NV West

A.5.2 Interpretation of results

This section presents the modelling results in terms of the noise metrics and criteria covered in section A.2.2. This discussion will guide the assessment of environmental impact to marine species from the proposed impact piling noise. For single strike criteria, the impact ranges during soft start have also been included.

Lethal effect and physical injury

Table A 17 presents the lethal effect and physical injury effects using the SPL_{peak} criteria from Parvin *et al.* (2007); these criteria cover both marine mammals and fish. The results show that these effects are likely to only be at close range, out to a few tens of metres.

Unweighted SPL_{peak}			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
NV West: SW location	Lethal Effect	240 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	Physical Injury	220 dB	31 m	31 m	30 m	23 m	23 m	22 m
NV West: NE location	Lethal Effect	240 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	Physical Injury	220 dB	23 m	23 m	22 m	17 m	17 m	16 m
NV East: SW location	Lethal Effect	240 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	Physical Injury	220 dB	29 m	29 m	28 m	22 m	22 m	21 m
NV East: NE location	Lethal Effect	240 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	Physical Injury	220 dB	16 m	16 m	15 m	11 m	11 m	10 m

Table A 17 Summary of the SPL_{peak} lethal effect and physical injury impact ranges from Parvin et al (2007) for maximum hammer blow energy

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).

Southall *et al*. (2007) results

Table A 18 to Table A 21 present the predicted auditory injury and TTS impact ranges for various cetaceans and pinniped hearing groups from Southall *et al.* (2007). Behavioural avoidance results for low and mid frequency cetaceans are given in Table A 22 and Table A 23. 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 A 11 and Table A 12). In line with the unweighted results from section A.5.1, maximum ranges were predicted for monopiles installed at the deeper NV West SW location. The effect of the water depth at the source should also be noted, with the differences shown between the various locations – the shallower water in the two NE locations result in a reduction of impact ranges compared to NV West.

Auditory Injury – NV West				Monopile (5000 kJ)			Pin Pile (2700 kJ)		
				Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
SW location	**Unweighted SPL_{peak}**	Cetaceans	230 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Pinnipeds	218 dB	41 m	41 m	40 m	30 m	30 m	29 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	198 dB	47 m	47 m	46 m	34 m	34 m	33 m
		MF Cetaceans	198 dB	19 m	19 m	18 m	17 m	17 m	16 m
		HF Cetaceans	198 dB	15 m	15 m	14 m	13 m	13 m	12 m
		PW Pinnipeds	186 dB	150 m	150 m	150 m	140 m	140 m	140 m
	M-Weighted multiple pulse (SEL_{cum})	LF Cetaceans	198 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		MF Cetaceans	198 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	198 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		PW Pinnipeds	186 dB	4.5 km	4.1 km	3.6 km	2.6 km	2.4 km	2.1 km
NE location	**Unweighted SPL_{peak}**	Cetaceans	230 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Pinnipeds	218 dB	31 m	31 m	30 m	22 m	22 m	21 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	198 dB	35 m	35 m	34 m	25 m	25 m	24 m
		MF Cetaceans	198 dB	14 m	14 m	13 m	12 m	12 m	11 m
		HF Cetaceans	198 dB	12 m	12 m	11 m	10 m	10 m	< 10 m
		PW Pinnipeds	186 dB	110 m	110 m	110 m	99 m	99 m	98 m
	M-Weighted multiple pulse (SEL_{cum})	LF Cetaceans	198 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		MF Cetaceans	198 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	198 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		PW Pinnipeds	186 dB	2.0 km	1.9 km	1.7 km	730 m	680 m	610 m

Table A 18 Summary of the impact ranges for the NV West locations for auditory injury criteria from Southall et al (2007) for maximum hammer blow energy

Auditory Injury – NV East				Monopile (5000 kJ)			Pin Pile (2700 kJ)		
				Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
SW location	**Unweighted SPL_{peak}**	Cetaceans	230 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Pinnipeds	218 dB	39 m	39 m	38 m	28 m	28 m	27 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	198 dB	44 m	44 m	43 m	32 m	32 m	31 m
		MF Cetaceans	198 dB	18 m	18 m	17 m	16 m	16 m	15 m
		HF Cetaceans	198 dB	14 m	14 m	13 m	12 m	12 m	11 m
		PW Pinnipeds	186 dB	150 m	150 m	140 m	130 m	130 m	130 m
	M-Weighted multiple pulse (SEL_{cum})	LF Cetaceans	198 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		MF Cetaceans	198 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	198 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		PW Pinnipeds	186 dB	3.8 km	3.5 km	3.2 km	2.1 km	1.9 km	1.7 km
NE location	**Unweighted SPL_{peak}**	Cetaceans	230 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Pinnipeds	218 dB	20 m	20 m	19 m	14 m	14 m	13 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	198 dB	23 m	23 m	22 m	16 m	16 m	15 m
		MF Cetaceans	198 dB	10 m	10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	198 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		PW Pinnipeds	186 dB	74 m	74 m	73 m	62 m	62 m	61 m
	M-Weighted multiple pulse (SEL_{cum})	LF Cetaceans	198 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		MF Cetaceans	198 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	198 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		PW Pinnipeds	186 dB	360 m	250 m	170 m	30 m	30 m	30 m

Table A 19 Summary of the impact ranges for the NV East locations for auditory injury criteria from Southall et al (2007) for maximum hammer blow energy

TTS – NV West				Monopile (5000 kJ)			Pin Pile (2700 kJ)		
				Max	Mean	Min	Max	Mean	Min
SW location	Unweighted SPL_{peak}	Cetaceans	224 dB	18 m	18 m	17 m	14 m	14 m	13 m
		Pinnipeds	212 dB	95 m	95 m	94 m	69 m	69 m	68 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	183 dB	390 m	390 m	390 m	280 m	280 m	280 m
		MF Cetaceans	183 dB	150 m	150 m	150 m	130 m	130 m	130 m
		HF Cetaceans	183 dB	120 m	120 m	120 m	100 m	100 m	99 m
		PW Pinnipeds	171 dB	1.3 km	1.2 km	1.2 km	1.1 km	1.1 km	1.1 km
NE location	Unweighted SPL_{peak}	Cetaceans	224 dB	14 m	14 m	13 m	10 m	10 m	< 10 m
		Pinnipeds	212 dB	71 m	71 m	70 m	50 m	50 m	49 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	183 dB	290 m	290 m	290 m	210 m	210 m	210 m
		MF Cetaceans	183 dB	110 m	110 m	110 m	96 m	96 m	95 m
		HF Cetaceans	183 dB	88 m	88 m	87 m	73 m	73 m	72 m
		PW Pinnipeds	171 dB	930 m	930 m	930 m	810 m	810 m	810 m

Table A 20 Summary of the impact ranges for the NV West locations for TTS criteria from Southall et al. (2007) for maximum hammer blow energy

TTS – NV East				Monopile (5000 kJ)			Pin Pile (2700 kJ)		
				Max	Mean	Min	Max	Mean	Min
SW location	Unweighted SPL_{peak}	Cetaceans	224 dB	17 m	17 m	16 m	13 m	13 m	12 m
		Pinnipeds	212 dB	90 m	90 m	89 m	65 m	65 m	64 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	183 dB	370 m	370 m	370 m	270 m	270 m	260 m
		MF Cetaceans	183 dB	140 m	140 m	140 m	120 m	120 m	120 m
		HF Cetaceans	183 dB	110 m	110 m	110 m	94 m	94 m	93 m
		PW Pinnipeds	171 dB	1.2 km	1.2 km	1.2 km	1.0 km	1.0 km	1.0 km
NE location	Unweighted SPL_{peak}	Cetaceans	224 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Pinnipeds	212 dB	46 m	46 m	45 m	32 m	32 m	31 m
	M-Weighted single strike (SEL_{ss})	LF Cetaceans	183 dB	190 m	190 m	190 m	130 m	130 m	130 m
		MF Cetaceans	183 dB	72 m	72 m	71 m	61 m	61 m	60 m
		HF Cetaceans	183 dB	57 m	57 m	56 m	46 m	46 m	45 m
		PW Pinnipeds	171 dB	610 m	610 m	610 m	520 m	510 m	510 m

Table A 21 Summary of the impact ranges for the NV East locations for TTS criteria from Southall et al. (2007) for maximum hammer blow energy

Table A 22 and Table A 23 include only the behavioural response ranges for LF and MF cetaceans. The behavioural response ranges for HF cetaceans are given in Table A 24 and Table A 25 using the Lucke *et al.* (2009) criteria.

Behavioural – NV West				Monopile (5000 kJ)			Pin Pile (2700 kJ)		
				Max	Mean	Min	Max	Mean	Min
SW location	Likely Avoidance (SEL_{ss})	LF Cetaceans	152 dB	16 km	15 km	15 km	14 km	13 km	12 km
		MF Cetaceans	170 dB	2.3 km	2.3 km	2.3 km	1.7 km	1.7 km	1.7 km
	Possible Avoidance (SEL_{ss})	LF Cetaceans	142 dB	34 km	29 km	26 km	29 km	26 km	23 km
		MF Cetaceans	160 dB	7.7 km	7.5 km	7.2 km	6.0 km	5.9 km	5.7 km
NE location	Likely Avoidance (SEL_{ss})	LF Cetaceans	152 dB	12 km	12 km	12 km	10 km	9.7 km	9.5 km
		MF Cetaceans	170 dB	1.7 km	1.7 km	1.7 km	1.2 km	1.2 km	1.2 km
	Possible Avoidance (SEL_{ss})	LF Cetaceans	142 dB	25 km	24 km	22 km	22 km	20 km	19 km
		MF Cetaceans	160 dB	5.7 km	5.6 km	5.6 km	4.4 km	4.3 km	4.3 km

Table A 22 Summary of the impact ranges for the NV West locations for behavioural response criteria from Southall et al. (2007) for maximum hammer blow energy

Behavioural – NV East				Monopile (5000 kJ)			Pin Pile (2700 kJ)		
				Max	Mean	Min	Max	Mean	Min
SW location	Likely Avoidance (SEL_{ss})	LF Cetaceans	152 dB	15 km	15 km	14 km	13 km	12 km	12 km
		MF Cetaceans	170 dB	2.2 km	2.2 km	2.1 km	1.6 km	1.6 km	1.6 km
	Possible Avoidance (SEL_{ss})	LF Cetaceans	142 dB	31 km	28 km	26 km	27 km	25 km	23 km
		MF Cetaceans	160 dB	7.2 km	6.8 km	7.0 km	5.6 km	5.5 km	5.4 km
NE location	Likely Avoidance (SEL_{ss})	LF Cetaceans	152 dB	9.6 km	8.9 km	8.3 km	7.5 km	7.0 km	6.6 km
		MF Cetaceans	170 dB	1.1 km	1.1 km	1.1 km	800 m	800 m	800 m
	Possible Avoidance (SEL_{ss})	LF Cetaceans	142 dB	21 km	19 km	17 km	17 km	16 km	15 km
		MF Cetaceans	160 dB	4.1 km	4.0 km	3.8 km	3.0 km	2.9 km	2.8 km

Table A 23 Summary of the impact ranges for the NV East locations for behavioural response criteria from Southall et al. (2007) for maximum hammer blow energy

Lucke *et al*. (2009) results

Table A 24 and Table A 25 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. The criteria from Lucke *et al.* (2009) are all unweighted single strike SELs.

Lucke *et al*. (2009) – NV West			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
SW	Auditory injury (SEL_{ss})	179 dB	680 m	680 m	680 m	500 m	500 m	500 m
	TTS (SEL_{ss})	164 dB	4.9 km	4.8 km	4.7 km	3.7 km	3.7 km	3.6 km
	Behavioural (SEL_{ss})	145 dB	28 km	25 km	22 km	24 km	22 km	19 km
NE	Auditory injury (SEL_{ss})	179 dB	510 m	510 m	510 m	360 m	360 m	360 m
	TTS (SEL_{ss})	164 dB	3.6 km	3.6 km	3.6 km	2.7 km	2.7 km	2.7 km
	Behavioural (SEL_{ss})	145 dB	21 km	20 km	18 km	18 km	17 km	16 km

Table A 24 Summary of the impact ranges for the NV West locations for criteria from Lucke et al. (2009) for maximum hammer blow energy

Lucke *et al*. (2009) – NV East			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
SW	Auditory injury (SEL_{ss})	179 dB	640 m	640 m	640 m	470 m	470 m	470 m
	TTS (SEL_{ss})	164 dB	4.6 km	4.5 km	4.5 km	3.5 km	3.4 km	3.4 km
	Behavioural (SEL_{ss})	145 dB	25 km	24 km	22 km	22 km	21 km	20 km
NE	Auditory injury (SEL_{ss})	179 dB	330 m	330 m	330 m	230 m	230 m	230 m
	TTS (SEL_{ss})	164 dB	2.5 km	2.5 km	2.4 km	1.8 km	1.8 km	1.7 km
	Behavioural (SEL_{ss})	145 dB	17 km	16 km	14 km	14 km	13 km	12 km

Table A 25 Summary of the impact ranges for the NV East locations for criteria from Lucke et al. (2009) for maximum hammer blow energy

NMFS (2016) results

Predicted auditory injury and TTS impact ranges are given in Table A 26 to Table A 29 using the NMFS unweighted SPL_{peak} and weighted SEL_{cum} criteria from NMFS (2016).

Auditory Injury – NV West				Monopile (5000 kJ)			Pin Pile (2700 kJ)		
				Max	Mean	Min	Max	Mean	Min
SW location	Unweighted SPL_{peak}	LF Cetaceans	219 dB	36 m	36 m	35 m	26 m	26 m	25 m
		MF Cetaceans	230 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	202 dB	390 m	390 m	390 m	280 m	280 m	280 m
		PW Pinnipeds	218 dB	41 m	41 m	40 m	30 m	30 m	29 m
	Weighted	LF Cetaceans	183 dB	800 m	580 m	410 m	100 m	80 m	70 m

	SEL_{cum}	MF Cetaceans	185 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	155 dB	< 10 m	< 10 m	< 10 m	490 m	400 m	310 m
		PW Pinnipeds	185 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
NE location	**Unweighted SPL_{peak}**	LF Cetaceans	219 dB	27 m	27 m	26 m	19 m	19 m	18 m
		MF Cetaceans	230 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	202 dB	290 m	290 m	290 m	210 m	210 m	210 m
		PW Pinnipeds	218 dB	31 m	31 m	30 m	22 m	22 m	21 m
	Weighted SEL_{cum}	LF Cetaceans	183 dB	80 m	70 m	60 m	30 m	30 m	20 m
		MF Cetaceans	185 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	155 dB	< 10 m	< 10 m	< 10 m	30 m	30 m	20 m
		PW Pinnipeds	185 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m

Table A 26 Summary of the impact ranges at the for the NV West for auditory injury from NMFS (2016) for maximum hammer blow energy

Auditory Injury – NV East				**Monopile (5000 kJ)**			**Pin Pile (2700 kJ)**		
				Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
SW location	**Unweighted SPL_{peak}**	LF Cetaceans	219 dB	34 m	34 m	33 m	25 m	25 m	24 m
		MF Cetaceans	230 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	202 dB	370 m	370 m	370 m	270 m	270 m	270 m
		PW Pinnipeds	218 dB	39 m	39 m	38 m	28 m	28 m	27 m
	Weighted SEL_{cum}	LF Cetaceans	183 dB	420 m	340 m	260 m	70 m	60 m	50 m
		MF Cetaceans	185 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	155 dB	< 10 m	< 10 m	< 10 m	250 m	210 m	170 m
		PW Pinnipeds	185 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
NE location	**Unweighted SPL_{peak}**	LF Cetaceans	219 dB	18 m	18 m	17 m	13 m	13 m	12 m
		MF Cetaceans	230 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	202 dB	190 m	190 m	190 m	130 m	130 m	130 m
		PW Pinnipeds	218 dB	20 m	20 m	19 m	14 m	14 m	13 m
	Weighted SEL_{cum}	LF Cetaceans	183 dB	30 m	30 m	20 m	< 10 m	< 10 m	< 10 m
		MF Cetaceans	185 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	155 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		PW Pinnipeds	185 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m

Table A 27 Summary of the impact ranges at the for the NV East for auditory injury from NMFS (2016) for maximum hammer blow energy

TTS – NV West				Monopile (5000 kJ)			Pin Pile (2700 kJ)		
				Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
SW location	**Unweighted SPL$_{peak}$**	LF Cetaceans	213 dB	83 m	83 m	82m	60 m	60 m	59 m
		MF Cetaceans	224 dB	18 m	18 m	17 m	14 m	14 m	13 m
		HF Cetaceans	196 dB	900 m	900 m	900 m	660 m	660 m	660 m
		PW Pinnipeds	212 dB	95 m	95 m	94 m	69 m	69 m	68 m
	Weighted SEL$_{cum}$	LF Cetaceans	168 dB	23 km	18 km	15 km	18 km	15 km	13 km
		MF Cetaceans	170 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	140 dB	9.8 km	8.7 km	7.8 km	18 km	15 km	13 km
		PW Pinnipeds	170 dB	6.9 km	6.2 km	5.5 km	3.5 km	3.1 km	2.8 km
NE location	**Unweighted SPL$_{peak}$**	LF Cetaceans	213 dB	61 m	61 m	60 m	44 m	44 m	43 m
		MF Cetaceans	224 dB	14 m	14 m	13 m	10 m	10 m	< 10 m
		HF Cetaceans	196 dB	670 m	670 m	670 m	480 m	480 m	480 m
		PW Pinnipeds	212 dB	71 m	71 m	70 m	50 m	50 m	49 m
	Weighted SEL$_{cum}$	LF Cetaceans	168 dB	14 km	13 km	11 km	11 km	9.9 km	8.8 km
		MF Cetaceans	170 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	140 dB	5.6 km	5.3 km	4.9 km	11 km	10 km	9.5 km
		PW Pinnipeds	170 dB	3.5 km	3.3 km	3.1 km	1.2 km	1.2 km	1.1 km

Table A 28 Summary of the impact ranges at the for the NV West for TTS criteria from NMFS (2016) for maximum hammer blow energy

TTS – NV East				Monopile (5000 kJ)			Pin Pile (2700 kJ)		
				Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
SW location	**Unweighted SPL$_{peak}$**	LF Cetaceans	213 dB	78 m	78 m	77 m	56 m	56 m	55 m
		MF Cetaceans	224 dB	17 m	17 m	16 m	13 m	13 m	12 m
		HF Cetaceans	196 dB	850 m	850 m	840 m	620 m	620 m	620 m
		PW Pinnipeds	212 dB	90 m	90 m	89 m	65 m	65 m	64 m
	Weighted SEL$_{cum}$	LF Cetaceans	168 dB	20 km	17 km	15 km	16 km	14 km	13 km
		MF Cetaceans	170 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	140 dB	8.5 km	7.8 km	7.2 km	15 km	14 km	13 km
		PW Pinnipeds	170 dB	5.8 km	5.4 km	5.0 km	2.8 km	2.6 km	2.4 km
NE location	**Unweighted SPL$_{peak}$**	LF Cetaceans	213 dB	40 m	40 m	39 m	28 m	28 m	27 m
		MF Cetaceans	224 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	196 dB	440 m	440 m	430 m	300 m	300 m	300 m
		PW Pinnipeds	212 dB	46 m	46 m	45 m	32 m	32 m	31 m
	Weighted SEL$_{cum}$	LF Cetaceans	168 dB	9.6 km	8.1 km	6.9 km	6.8 km	5.6 km	4.7 km
		MF Cetaceans	170 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		HF Cetaceans	140 dB	3.0 km	2.5 km	2.2 km	7.4 km	6.4 km	5.8 km
		PW Pinnipeds	170 dB	1.4 km	1.1 km	930 m	70 m	60 m	40 m

Table A 29 Summary of the impact ranges at the for the NV East for TTS criteria from NMFS (2016) for maximum hammer blow energy

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 NV West 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.

The SEL$_{cum}$ results for HF cetaceans using the NMFS (2016) criteria (Table A 26 to Table A 29) 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 A 5) 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 A 2) 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 A 10 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 A 5 (shown faintly in Figure A 10). Overall, higher levels are present in the weighted pin pile spectrum.

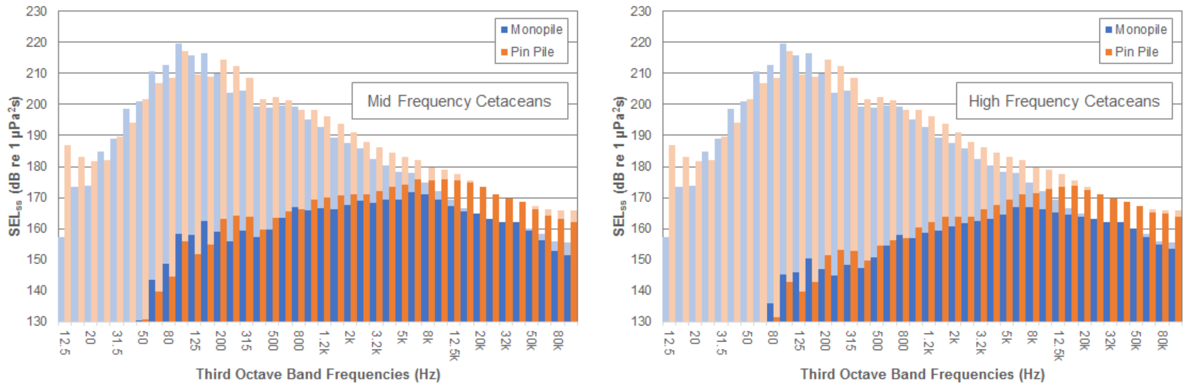

Figure A 10 Filtered noise inputs for monopiles and pin piles using the MF and HF cetacean filters from NMFS (2016). The lighter coloured bars show the unweighted third octave levels

Impacts on fish

Table A 30 to Table A 35 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 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 A 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 effect range will be somewhat lower.

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 8.8 km for TTS (SEL_{cum}).

Fish (no swim bladder) – NV West				Monopile (5000 kJ)			Pin Pile (2700 kJ)		
				Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
SW location	SPL_{peak}	Mortality and potential mortal injury	> 213 dB	83 m	83 m	82 m	60 m	60 m	59 m
		Recoverable injury	> 213 dB	83 m	83 m	82 m	60 m	60 m	59 m
	SEL_{cum}	Mortality and potential mortal injury	> 219 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Recoverable injury	> 216 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		TTS	>> 186 dB	8.8 km	7.8 km	7.0 km	4.6 km	4.1 km	3.7 km
NE location	SPL_{peak}	Mortality and potential mortal injury	> 213 dB	61 m	61 m	60 m	44 m	44 m	43 m
		Recoverable injury	> 213 dB	61 m	61 m	60 m	44 m	44 m	43 m
	SEL_{cum}	Mortality and potential mortal injury	> 219 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Recoverable injury	> 216 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		TTS	>> 186 dB	4.8 km	4.6 km	4.3 km	2.0 km	1.9 km	1.8 km

Table A 30 Summary of the impact ranges for the NV West locations for fish (no swim bladder) using the criteria from Popper et al. (2014) for maximum hammer blow energy

Fish (no swim bladder) – NV East				Monopile (5000 kJ)			Pin Pile (2700 kJ)		
				Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
SW location	SPL_{peak}	Mortality and potential mortal injury	> 213 dB	78 m	78 m	77 m	56 m	56 m	55 m
		Recoverable injury	> 213 dB	78 m	78 m	77 m	56 m	56 m	55 m
	SEL_{cum}	Mortality and potential mortal injury	> 219 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Recoverable injury	> 216 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		TTS	>> 186 dB	7.5 km	6.9 km	6.4 km	3.8 km	3.5 km	3.3 km
NE location	SPL_{peak}	Mortality and potential mortal injury	> 213 dB	40 m	40 m	39 m	28 m	28 m	27 m
		Recoverable injury	> 213 dB	40 m	40 m	39 m	28 m	28 m	27 m
	SEL_{cum}	Mortality and potential mortal injury	> 219 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Recoverable injury	> 216 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		TTS	>> 186 dB	2.4 km	2.0 km	1.7 km	320 m	230 m	150 m

Table A 31 Summary of the impact ranges for the NV East locations for fish (no swim bladder) using the criteria from Popper et al. (2014) for maximum hammer blow energy

Fish (swim bladder not involved in hearing) – NV West				Monopile (5000 kJ)			Pin Pile (2700 kJ)		
				Max	Mean	Min	Max	Mean	Min
SW location	**SPL$_{peak}$**	Mortality and potential mortal injury	> 207 dB	190 m	190 m	190 m	140 m	140 m	140 m
		Recoverable injury	> 207 dB	190 m	190 m	190 m	140 m	140 m	140 m
	SEL$_{cum}$	Mortality and potential mortal injury	210 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Recoverable injury	203 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		TTS	> 186 dB	8.8 km	7.8 km	7.0 km	4.6 km	4.1 km	3.7 km
NE location	**SPL$_{peak}$**	Mortality and potential mortal injury	> 207 dB	140 m	140 m	140 m	100 m	100 m	100 m
		Recoverable injury	> 207 dB	140 m	140 m	140 m	100 m	100 m	100 m
	SEL$_{cum}$	Mortality and potential mortal injury	210 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Recoverable injury	203 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		TTS	> 186 dB	4.8 km	4.6 km	4.3 km	2.0 km	1.9 km	1.8 km

Table A 32 Summary of the impact ranges for the NV West locations for fish (swim bladder not involved in hearing) using the criteria from Popper et al. (2014) for maximum hammer blow energy

Fish (swim bladder not involved in hearing) – NV East				Monopile (5000 kJ)			Pin Pile (2700 kJ)		
				Max	Mean	Min	Max	Mean	Min
SW location	**SPL$_{peak}$**	Mortality and potential mortal injury	> 207 dB	180 m	180 m	180 m	130 m	130 m	130 m
		Recoverable injury	> 207 dB	180 m	180 m	180 m	130 m	130 m	130 m
	SEL$_{cum}$	Mortality and potential mortal injury	210 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Recoverable injury	203 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		TTS	> 186 dB	7.5 km	6.9 km	6.4 km	3.8 km	3.5 km	3.3 km
NE location	**SPL$_{peak}$**	Mortality and potential mortal injury	> 207 dB	92 m	92 m	91 m	64 m	64 m	63 m
		Recoverable injury	> 207 dB	92 m	92 m	91 m	64 m	64 m	63 m
	SEL$_{cum}$	Mortality and potential mortal injury	210 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Recoverable injury	203 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		TTS	> 186 dB	2.4 km	2.0 km	1.7 km	320 m	230 m	150 m

Table A 33 Summary of the impact ranges for the NV East locations for fish (swim bladder not involved in hearing) using the criteria from Popper et al. (2014) for maximum hammer blow energy

Fish (swim bladder involved in hearing) – NV West				Monopile (5000 kJ)			Pin Pile (2700 kJ)		
				Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
SW location	**SPL$_{peak}$**	Mortality and potential mortal injury	> 207 dB	190 m	190 m	190 m	140 m	140 m	140 m
		Recoverable injury	> 207 dB	190 m	190 m	190 m	140 m	140 m	140 m
	SEL$_{cum}$	Mortality and potential mortal injury	207 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Recoverable injury	203 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		TTS	186 dB	8.8 km	7.8 km	7.0 km	4.6 km	4.1 km	3.7 km
NE location	**SPL$_{peak}$**	Mortality and potential mortal injury	> 207 dB	140 m	140 m	140 m	100 m	100 m	100 m
		Recoverable injury	> 207 dB	140 m	140 m	140 m	100 m	100 m	100 m
	SEL$_{cum}$	Mortality and potential mortal injury	207 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Recoverable injury	203 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		TTS	186 dB	4.8 km	4.6 km	4.3 km	2.0 km	1.9 km	1.8 km

Table A 34 Summary of the impact ranges for the NV West locations for fish (swim bladder involved in hearing) using the criteria from Popper et al. (2014) for maximum hammer blow energy

Fish (swim bladder involved in hearing) – NV East				Monopile (5000 kJ)			Pin Pile (2700 kJ)		
				Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
SW location	**SPL$_{peak}$**	Mortality and potential mortal injury	> 207 dB	180 m	180 m	180 m	130 m	130 m	130 m
		Recoverable injury	> 207 dB	180 m	180 m	180 m	130 m	130 m	130 m
	SEL$_{cum}$	Mortality and potential mortal injury	207 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Recoverable injury	203 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		TTS	186 dB	7.5 km	6.9 km	6.4 km	3.8 km	3.5 km	3.3 km
NE location	**SPL$_{peak}$**	Mortality and potential mortal injury	> 207 dB	92 m	92 m	91 m	64 m	64 m	63 m
		Recoverable injury	> 207 dB	92 m	92 m	91 m	64 m	64 m	63 m
	SEL$_{cum}$	Mortality and potential mortal injury	207 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		Recoverable injury	203 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
		TTS	186 dB	2.4 km	2.0 km	1.7 km	320 m	230 m	150 m

Table A 35 Summary of the impact ranges for the NV East locations for fish (swim bladder involved in hearing) using the criteria from Popper et al. (2014) for maximum hammer blow energy

A.6 Summary and conclusions

Subacoustech Environmental has undertaken a study on behalf of Royal HaskoningDHV to assess the effect of impact piling noise during construction of the Norfolk Vanguard Offshore Wind Farm.

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 Norfolk Vanguard East and the Norfolk Vanguard West 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.

Results using the Parvin *et al*. (2007) criteria show that lethal effect and physical injury in all marine species are likely to only be at close range, out to a few tens of metres.

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 A 36 below. For most cases the SW location at NV West provided the largest impact ranges.

Criteria	Effect	Species	Monopile (5000 kJ)	Pin Pile (2700 kJ)
Southall *et al*. (2007)	Auditory Injury (SEL_{cum})	LF Cetaceans	< 10 m	< 10 m
		MF Cetaceans	< 10 m	< 10 m
		HF Cetaceans	< 10 m	< 10 m
		PW Pinnipeds	4.5 km	2.6 km
	TTS (SEL_{ss})	LF Cetaceans	390 m	280 m
		MF Cetaceans	150 m	130 m
		HF Cetaceans	120 m	100 m
		PW Pinnipeds	1.3 km	1.1 km
	Behavioural (SEL_{ss})	LF Cetaceans	16 – 34 km	14 – 29 km
		MF Cetaceans	2.3 – 7.7 km	1.7 – 6.0 km
Lucke *et al*. (2009)	Auditory injury (SEL_{ss})	Harbour porpoise	680 m	500 m
	TTS (SEL_{ss})		4.9 km	3.7 km
	Behavioural (SEL_{ss})		28 km	24 km
NMFS (2016)	Auditory injury (SEL_{cum})	LF Cetaceans	800 m	100 m
		MF Cetaceans	< 10 m	< 10 m
		HF Cetaceans	< 10 m	490 m
		PW Pinnipeds	< 10 m	< 10 m
	TTS (SEL_{cum})	LF Cetaceans	23 km	18 km
		MF Cetaceans	< 10 m	< 10 m
		HF Cetaceans	9.8 km	18 km
		PW Pinnipeds	6.9 km	3.5 km

Table A 36 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 190 m for injury and out to 8.8 km for TTS at the maximum blow energies, when considering monopiles at the SW modelling location of NV West.

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