Hornsea Project Four: Environmental Statement (ES)

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Volume A4, Annex 4.5: Subsea Noise Technical Report Part 1

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Glossary

Term	Definition
Ambient noise	Normal background noise in the environment, unaffected by the project-related activities.
Decibel	A customary scale most commonly used (in various ways) for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be 10 $\log_{10}$(actual/reference), where (actual/reference) is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is 20$\log_{10}$(actual pressure/reference pressure). As noted above, the standard reference for underwater sound pressure is 1 micro-Pascal (μPa). The dB unit is followed by a value identifying the specific reference pressure (i.e. re 1 μPa).
Hornsea Project Four Offshore Wind Farm	The term covers all elements of the project (i.e. both the offshore and onshore). Hornsea Four infrastructure will include offshore generating stations (wind turbines), electrical export cables to landfall, and connection to the electricity transmission network. Hereafter referred to as Hornsea Four.
Maximum Design Scenario	The maximum design parameters of each Hornsea Four asset (both on and offshore) considered to be a worst case for any given assessment. The modelling scenarios undertaken that consider all the maximum design modelling parameters possible at Hornsea Four. However, by considering all parameters as maximum design it is possible that the resulting scenario is impossible to occur, which is why most-likely modelling scenarios have also been included, based on engineering predictions.
Order Limits	The limits within which Hornsea Four (the authorised project) may be carried out.
Orsted Hornsea Project Four Ltd	The Applicant for the proposed Hornsea Project Four Offshore Wind Farm Development Consent Order (DCO).
Peak pressure	The greatest pressure above or below zero that is associated with a sound wave.
Peak-to-peak pressure	The sum of the greatest positive and negative pressures that is associated with a sound wave.
Permanent Threshold Shift (PTS)	A total or partial permanent loss of hearing caused by some kind of acoustic or drug trauma. PTS results in irreversible damage to the sensory hair cells of the ear, and thus a permanent reduction of hearing acuity.
Sound Exposure Level (SEL)	The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.
Sound Pressure Level (SPL)	The sound pressure level or SPL is an expression of the sound pressure using the decibel (dB) scale and the standard reference pressures of 1 μPa for water, and 20 μPa for air.
Temporary Threshold Shift (TTS)	Temporary loss of hearing as a result of exposure to sound over time. Exposure to high levels of sound over relatively short time periods will cause the same amount of TTS as exposure to lower levels of sound over longer

Term	Definition
	time periods. The duration of TTS varies depending on the nature of the stimulus, but there is generally recovery of full hearing over time.
Threshold	The threshold generally represents the lowest signal level an animal will detect in some statistically predetermined percent of presentations of a signal.
Unweighted sound level	Sound levels which are 'raw' or have not been adjusted in any way, for example to account for the hearing ability of a species.
Weighted sound level	A sound level which has been adjusted with respect to a 'weighting envelope' in the frequency domain, typically to make an unweighted level relevant to a particular species. Examples of this are the dB(A), where the overall sound level has been adjusted to account for the hearing ability of humans, or the filters used by Southall et al. (2019) for marine mammals.

Acronyms

Acronym	Definition
AfL	Agreement for Lease
DCO	Development Consent Order
E	East modelling location
EIA	Environmental Impact Assessment
GIS	Geographic Information System
HF	High-Frequency Cetaceans (Southall et al. (2019) marine mammal hearing group)
HVAC	High Voltage Alternative Current
INSPIRE	Impulse Noise Sound Propagation and Impact Range Estimator (Subacoustech Environmental's noise modelling software)
LF	Low-Frequency Cetaceans (Southall et al. (2019) marine mammal hearing group)
MDS	Maximum Design Scenario
MF	Mid-Frequency Cetaceans (NMFS (2018) marine mammal hearing group)
MMO	Marine Management Organisation
NMFS	National Marine Fisheries Service
NPL	National Physical Laboratory
NW	North West modelling location
PCW	Phocid Carnivores in Water (Southall et al. (2019) marine mammal hearing group)
PEIR	Preliminary Environmental Information Report
PTS	Permanent Threshold Shift
RMS	Root Mean Square
S	South modelling location
SE	Sound Exposure
SEL	Sound Exposure Level
SEL_{cum}	Cumulative Sound Exposure Level
SEL_{ss}	Single Strike Sound Exposure Level
SPL	Sound Pressure Level
SPL_{peak}	Peak Sound Pressure Level
$SPL_{peak-to-peak}$	Peak-to-peak Sound Pressure Level
TL	Transmission Loss
TTS	Temporary Threshold Shift
UXO	Unexploded Ordinance

Acronym	Definition
VHF	Very High-Frequency Cetaceans (Southall et al. (2019) marine mammal hearing group)
WTG	Wind Turbine Generator

Units

Unit	Definition
dB	Decibel (sound pressure)
Hz	Hertz (frequency)
kHz	Kilohertz (frequency)
kJ	Kilojoule (energy)
km	Kilometres (distance)
km^2	Kilometres squared (area)
knot	Knot (speed, at sea)
m	Metres (distance)
ms^{-1}	Metres per second (speed)
μPa	Micropascal (pressure)

1 Introduction

1.1 Project background

1.1.1.1 Orsted Hornsea Project Four Limited (hereafter 'the Applicant') is proposing to develop Hornsea Project Four Offshore Wind Farm (hereafter 'Hornsea Four'). Hornsea Four will be located approximately 69 km offshore the East Riding of Yorkshire in the Southern North Sea and will be the fourth project to be developed in the former Hornsea Zone (please see **Volume A1, Chapter 1: Introduction** for further details on the Hornsea Zone). Hornsea Four will include both offshore and onshore infrastructure including an offshore generating station (wind farm), export cables to landfall, and connection to the electricity transmission network (please see **Volume A1, Chapter 4: Project Description** for full details on the Project Design). The location of Hornsea Four is illustrated in **Figure 1**. The Order Limits combine the search areas for the onshore and offshore infrastructure.

1.1.1.2 The Hornsea Four Agreement for Lease (AfL) area was 846 km^2 at the Scoping phase of project development. In the spirit of keeping with Hornsea Four's approach to Proportionate Environmental Impact Assessment (EIA), the project has due consideration to the size and location (within the existing AfL area) of the final project that is being taken forward to Development Consent Order (DCO) application. This consideration is captured internally as the "Developable Area Process", which includes Physical, Biological and Human constraints in refining the developable area, balancing consenting and commercial considerations with technical feasibility for construction.

1.1.1.3 The combination of Hornsea Four's Proportionality in EIA and Developable Area process has resulted in a marked reduction in the array area taken forward at the point of DCO application. Hornsea Four adopted a major site reduction from the array area presented at Scoping (846 km^2) to the Preliminary Environmental Information Report (PEIR) boundary (600 km^2), with a further reduction adopted for the Environmental Statement (ES) and DCO application (468 km^2) due to the results of the PEIR, technical considerations and stakeholder feedback. The evolution of the Hornsea Four Order Limits is detailed in **Volume A1, Chapter 3: Site Selection and Consideration of Alternatives** and **Volume A4, Annex 3.2: Selection and Refinement of the Offshore Infrastructure**.

1.1.1.4 Subacoustech Environmental Ltd was commissioned by the Applicant to undertake a study of potential underwater noise related to the construction, operation, and eventual decommissioning of Hornsea Four, focussing on modelling results for impact piling and other noise sources relating to the construction and lifecycle of Hornsea Four.

1.1.1.5 The consideration of subsea noise for Hornsea Four has been discussed with consultees through the Hornsea Four Evidence Plan process; specifically with the Marine Mammals and Marine Ecology & Processes Evidence Plan Technical Panels. Agreements made with consultees within the Evidence Plan process are set out in the topic specific Evidence Plan Logs which are appendices to the Hornsea Four Evidence Plan (**Volume B1, Annex 1.1: Evidence Plan**), an annex of the Hornsea Four Consultation Report (**Volume B1, Chapter 1: Consultation Report**). All agreements within the Evidence Plan Logs have unique identifier codes which have been used throughout this document to signpost to the specific agreements made (e.g. OFF-ME&P-2.1).

Hornsea Four

Figure 1

Hornsea Four and the surrounding bathymetry

🟥 Order Limits
⬚ Array Area
▭ HVAC Booster Station Works Area
🟨 Offshore Export Cable Corridor

Value
0
80

(EMODnet Bathymetry, resolution c.115m)

Coordinate system: ETRS 1989 UTM Zone 31N
Scale@A3: 1:600,000

0 10 20 Kilometres

0 5 10 Nautical Miles

REV	REMARK	DATE
....	First Issue fo PEIR	17/06/2019
A	Updated following PEIR consultations, for DCO	30/07/2021

Hornsea Four Location
and Bathymetry
Document no: HOW04GB0089
Created by: BPHB
Checked by: RM
Approved by: LK

Date: 30/07/2021 Author: BenBlakeman Name: HOW04GB0089_AC_Location_and_Bathymetry_RevA

1.2 Noise modelling

1.2.1 Introduction

1.2.1.1 This report focuses on pile driving activities during construction of Hornsea Four and also considers other noise sources that are likely to be present during the development lifecycle. Underwater noise modelling has been carried out in two parts. Impact piling has been considered using Subacoustech Environmental's INSPIRE (Impulse Noise Sound Propagation and Impact Range Estimator) subsea noise propagation and prediction software. Other noise sources have been considered using a high-level, simple modelling approach.

1.2.2 Impact piling

1.2.2.1 Impact piling has been proposed as a method for installing foundation piles into the seabed for wind turbine generators (WTGs), substations and accommodation platforms. Both monopile and pin pile (jacket) foundation options have been considered.

1.2.2.2 The impact piling technique involves a large weight or hammer being dropped or driven onto the top of the pile, forcing the pile 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 (e.g. Würsig et al. 2000; Caltrans 2001; Nedwell et al. 2003b and 2007; Parvin et al. 2006; and Thomsen et al. 2006).

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

1.2.3 Other sources of noise

1.2.3.1 Although impact piling is expected to be the greatest source of noise during construction (Bailey et al. 2014; Bergström et al. 2014), several other noise sources associated with the development of Hornsea Four may also be present. These include dredging (for seabed preparation for foundations and/or sandwave clearance for cable installation), drilling of foundation piles, cable laying, rock placement, trenching, vessel noise and noise from the operational WTGs. These noise sources have been considered using a simple modelling approach due to the relative levels of noise and available information from these activities. A high-level review of noise from decommissioning techniques has also been included.

1.3 Aims and objectives

1.3.1.1 This report presents detailed modelling study of the potential underwater noise from impact piling and other noise sources relating to the construction, operation, and decommissioning of Hornsea Four 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 aid assessment of possible environmental effects in marine receptors (**Section 2**);
- A brief description of baseline ambient noise (**Section 3**);

- Discussion of the approach, input parameters and assumptions for the impact piling noise modelling undertaken (**Section 4**);
- Presentation of detailed subsea noise modelling results for impact piling using unweighted metrics (**Section 5.1**);
- Presentation 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**);
- Presentation of modelling results for two impact piling installations occurring simultaneously (**Section 5.3**)
- Summary of the predicted noise levels from the simple modelling approach for dredging, drilling, cable laying, rock placement, trenching, vessel noise, noise from operational wind turbines, and a high-level review of decommissioning techniques (**Section 5.3**); and
- Summary of the results (**Section 7**).

2 Measurement of Noise

2.1 Underwater Noise

2.1.1 Background

2.1.1.1 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).

2.1.1.2 It should be noted that stated underwater noise levels should not be confused with the noise levels in air, which use a different scale.

2.1.2 Units of measurement

2.1.2.1 Sound measurements underwater are usually expressed using the 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".

2.1.2.2 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.

2.1.2.3 The dB scale represents a ratio. 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 example, a reference quantity of 20 µPa is used for sound in air since this is the threshold of human hearing.

2.1.2.4 When used with sound pressure, the pressure value is squared. 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:

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

2.1.2.5 For underwater sound, typically a unit of 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.

2.1.2.6 Unless otherwise defined, all noise levels in this report are referenced to 1 µPa. It is recognised that ISO 18405 (2017) defines SPL in reference to the unit 1 μPa^2. As the key publications used in this assessment use the unit 1 µPa, this terminology will also be used in this report. This will not affect any results or values.

2.1.3 Sound pressure level (SPL)

2.1.3.1 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 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.

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

2.1.4 Peak sound pressure level (SPL_{peak})

2.1.4.1 Peak SPLs are often used to characterise sound transients from impulsive sources, such as percussive impact piling and seismic airgun sources. SPL_{peak} 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.

2.1.4.2 A further variation of this is the peak-to-peak SPL ($SPL_{peak\text{-}to\text{-}peak}$) where the maximum variation of the pressure from positive to negative within the wave is considered. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak level will be twice the peak level, or 6 dB higher (see **Section 2.1.2**).

2.1.5 Sound exposure level (SEL)

2.1.5.1 When considering 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. Currently the SEL metric has been used to develop criteria for assessing the injury range from fish for various noise sources (Popper et al. 2014).

2.1.5.2 The 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^{2}s).

2.1.5.3 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:

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

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

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

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

2.1.5.5 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).

2.1.5.6 Weighted metrics for marine mammals have been proposed by Southall et al., (2019). These assign a frequency response to groups of marine mammals and are discussed in the following section.

2.2 Analysis of environmental effects

2.2.1 Background

2.2.1.1 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 interest in chronic noise exposure is increasing.

2.2.1.2 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.

2.2.1.3 The following sections discuss the underwater noise criteria used in this study.

2.2.2 Criteria to be used

2.2.2.1 The main metrics and criteria that have been used in this study to aid assessment of environmental effect come from two key papers covering underwater noise and its effects:

- Southall et al. (2019) marine mammal noise exposure criteria; and
- Sound exposure guidelines for fishes by Popper et al. (2014).

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

Marine mammals

2.2.2.3 The Southall et al. (2019) paper is effectively an update of the previous Southall et al. (2007) criteria and gives identical thresholds to those from the National Marine Fisheries Service (NMFS) (2018) guidance for marine mammals.

2.2.2.4 The Southall et al. (2019) guidance groups marine mammals into groups of similar species and applies filters to the unweighted noise to approximate the hearing sensitivity of the receptor. The hearing groups given in the Southall et al. (2019) are summarised in **Table 1** and **Figure 2**. Further groups for sirenians and other marine carnivores in water are also given in the guidance, but this has not been used in this study as those species are not commonly found in the North Sea.

Table 1: Marine mammal hearing groups (from Southall et al. 2019).

Hearing group	Generalised hearing range	Example species
Low-frequency cetaceans (LF)	7 Hz to 35 kHz	Baleen whales
High-frequency cetaceans (HF)	150 Hz to 160 kHz	Dolphins, toothed whales, beaked whales, bottlenose whales (including bottlenose dolphin)
Very high-frequency cetaceans (VHF)	275 Hz to 160 kHz	True porpoises (including harbour porpoises)
Phocid carnivores in water (PCW)	50 Hz to 86 kHz	True seals (including harbour seal)

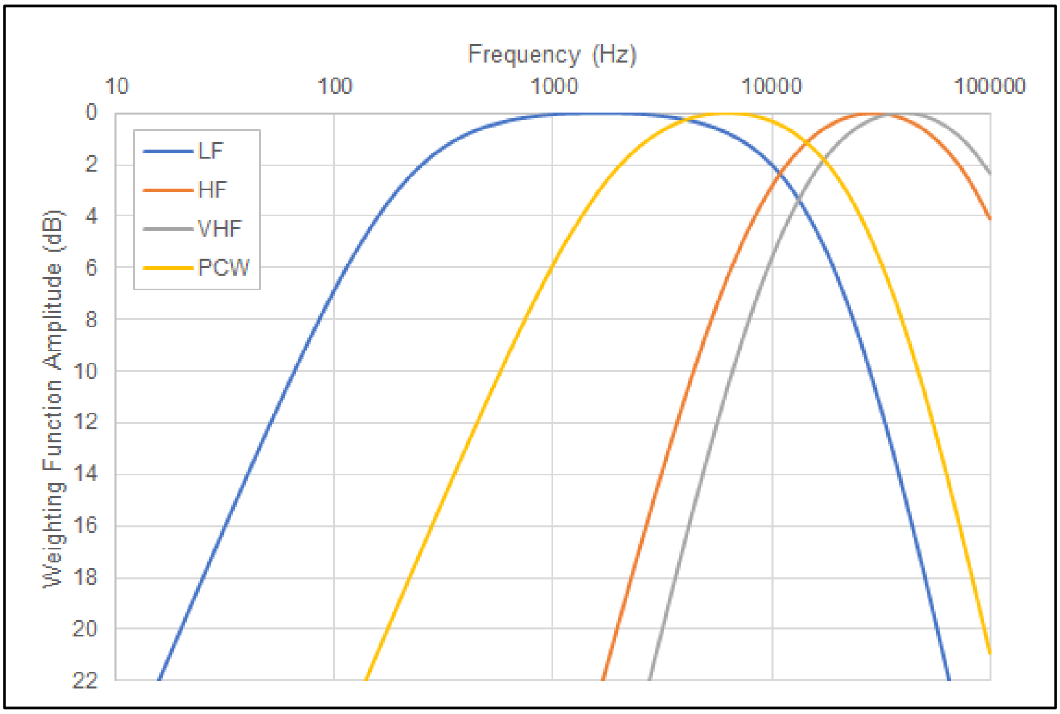


Figure 2: Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al. 2019).

2.2.2.5 It should also be noted that the criteria in NMFS (2018), although numerically identical, apply different names to the marine mammal groupings and weightings. For example, what Southall et al. (2019) calls high-frequency cetaceans (HF), NMFS (2018) calls mid-frequency cetaceans (MF) and what Southall et al. (2019) calls very high-frequency cetaceans (VHF), NMFS (2018) refers to as high-frequency cetaceans. As such, great care should be taken when comparing results using the Southall et al. (2019) and NMFS (2018) criteria, especially as the HF groupings and criteria cover different species depending on which study is being used.

2.2.2.6 The Southall et al. (2019) criteria has been used for this study as it is a peer-reviewed and published paper in a reputable journal, whereas NMFS (2018) is a guidance document from a government agency and as such could be subject to changes at any point.

2.2.2.7 Southall et al. (2019) also gives individual criteria based on whether the noise source is considered impulsive or non-impulsive. Southall et al. (2019) categorises impulsive noises as having high peak sound pressure, short duration, fast rise-time and broad frequency content at source, and non-impulsive sources as steady-state noise. Explosives, impact piling and seismic airguns are considered impulsive noise sources, and sonars, vibropiling and other low-level continuous noises are considered non-impulsive. A non-impulsive sound does not necessarily have to have a long duration.

2.2.2.8 Southall et al. (2019) 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. These dual criteria are only used for impulsive noise – the criteria set giving the greatest calculated range is used as the PTS impact range.

2.2.2.9 As sound pulses propagate through the environment and dissipate, they also lose their most injurious characteristics (e.g. rapid pulse rise time, high peak sound pressure) and become more like a "non-pulse" at greater distances. Southall et al. (2019) briefly discusses this. Active research is currently underway into the identification of the distance at which the pulse can be considered effectively non-impulsive, and Hastie et al. (2019) analysed a series of impulsive noise data to investigate this.

2.2.2.10 Although the situation is complex, the paper reported that most of the signals analysed crossed their threshold for rapid rise time and high peak pressure characteristics associated with impulsive noise dissipated at around 3.5 km from the source. At this stage we cannot definitively say that signals beyond 3.5 km should all be considered non-impulsive, but it is suggested that, beyond this point, signals will increasingly be better represented using the non-impulsive criteria.

2.2.2.11 **Table 2** and **Table 3** present the Southall et al. (2019) criteria for onset of risk of PTS and TTS for each of the key marine mammal hearing groups considering impulsive and non-impulsive noise sources.

Table 2: SPL$_{peak}$ criteria for PTS and TTS in marine mammals (Southall et al. 2019).

Southall et al. (2019)	Unweighted SPL$_{peak}$ (dB re 1 µPa)	
	Impulsive	
	PTS	TTS
Low-frequency cetaceans (LF)	219	213
High-frequency cetaceans (HF)	230	224
Very high-frequency cetaceans (VHF)	202	196
Phocid carnivores in water (PCW)	218	212

Table 3: SEL$_{cum}$ and SEL$_{ss}$ criteria for PTS and TTS in marine mammals (Southall et al. 2019).

Southall et al. (2019)	Weighted SEL$_{cum}$ and SEL$_{ss}$ (dB re 1 µPa^{2}s)			
	Impulsive		Non-impulsive	
	PTS	TTS	PTS	TTS
Low-frequency cetaceans (LF)	183	168	199	179
High-frequency cetaceans (HF)	185	170	198	178
Very high-frequency cetaceans (VHF)	155	140	173	153
Phocid carnivores in water (PCW)	185	170	201	181

2.2.2.12 Where SEL$_{cum}$ are required, a fleeing animal model has been used for marine mammals. This assumes that the receptor, when 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 cetaceans (LF) groups (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 for fleeing, 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 modelling assumes that when a fleeing receptor reaches the coast it receives no more noise, as it is likely that the receptor will fleeing along the coast (rather than staying in a single location at the shore), and at this distance from Hornsea Four, the receptor will, in any case, be far enough from the piling that it will have received the majority of its expected noise exposure.

2.2.2.13 The stationary animal model assumes that a receptor will stay at the same distance from a noise source for the entire duration that the source is present, which for low-level sources (i.e., compared to impact piling) such as those being considered herein, can provide useful impact range results. However, basing the modelling on a stationary (zero flee speed) receptor is likely to greatly overestimate the potential risk to a receptor, assuming that an individual would remain in the high noise level region of the water column, especially when considering the precautionary nature of the parameters already built into the cumulative exposure calculations.

Fish

2.2.2.14 The large number of, and variation in, fish species leads to a greater challenge in the production of a generic noise criterion, or range of criteria, for the assessment of noise impacts. Whereas previous studies 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 fish exposure to sound and uses categories for fish that are representative of the species present in UK waters.

2.2.2.15 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 unweighted SPL$_{peak}$ and unweighted SEL$_{cum}$ values) for a variety of noise sources; in this case, impact piling and continuous noise sources have been considered.

2.2.2.16 The criteria used for modelling are summarised in **Table 4** and **paragraph 2.2.2.18**.

2.2.2.17 In a similar fashion to marine mammals, a fleeing animal model has been used assuming a fish flees from the noise source at a constant rate of 1.5 ms^{-1}, based on data from Hirata (1999). This speed is the slowest of all species identified and as such is considered to be a worst-case assumption for flee speed. A stationary animal model has also been considered for fish, assuming that a fish remains still when exposed to the high noise levels. This is discussed further below.

Table 4: Criteria for mortality and potential mortal injury, recoverable injury and TTS in species of fish from impact piling noise (Popper et al. 2014).

Impact piling	Mortality and potential mortal injury	Impairment	
		Recoverable injury	TTS
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 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$_{cum}$

2.2.2.18 Fish eggs and larvae are also included in the assessment and have the same criteria as "Fish: swim bladder not involved in hearing", for mortality and potential mortal injury.

Table 5: Criteria for recoverable injury and TTS in species of fish from continuous noise sources (Popper et al. 2014).

Shipping and continuous sounds	Impairment	
	Recoverable injury	TTS
Fish: swim bladder involved in hearing	170 dB RMS for 48 hours	158 dB RMS for 12 hours

2.2.2.19 A further set of criteria also exists for turtles, which are not present at this site, and as such these have not been considered as part of this study.

2.2.2.20 Where insufficient data is available, Popper et al. (2014) also give qualitative criteria that summarise the effect of the noise as having either a high, moderate, or low effect on an individual in either the near-field (tens of metres), intermediate-field (hundreds of metres), or far-field (thousands of metres). These qualitative effects are reproduced in Table 6 and Table 7.

Table 6: Summary of the qualitative effects on fish from impact piling from Popper et al. (2014) (N=Near-field, I=Intermediate-field, F=Far-field).

Impact piling	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	See Table 4	See Table 4	See Table 4	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder not involved in hearing	See Table 4	See Table 4	See Table 4	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder involved in hearing	See Table 4	See Table 4	See Table 4	(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate

2.2.2.21 The thresholds for eggs and larvae in "Impairment" categories are all qualitative and have the values (N) Moderate, (I) Low and (F) Low.

Table 7: Summary of the qualitative effects on fish from continuous noise from Popper et al. (2014) (N=Near-field, I=Intermediate-field, F=Far-field).

Shipping and continuous sounds	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder not involved in hearing	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder involved in hearing	(N) Low (I) Low (F) Low	See paragraph 2.2.2.18 and Table 5	See paragraph 2.2.2.18 and Table 5	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low

2.2.2.22 Both a fleeing animal and stationary animal model have been modelled to cover the SEL_{cum} criteria for fish. It is recognised that there is limited evidence for fish fleeing from high noise sources in the wild and it would reasonably be expected that the reaction would differ between species. Most species are likely to move away from a sound that is loud enough to cause harm (Dahl et al. 2015; Popper et al. 2014), some may seek protection in the sediment and others may dive deeper in the water column. The flee speed chosen for this study of 1.5 ms^{-1} is relatively slow in relation to the data in Hirata (1999) and thus is considered somewhat conservative.

2.2.2.23 Although it is feasible that some species will not flee, those that are likely to remain are thought more likely be benthic species or species without a swim bladder; these are the least sensitive species. For example, from Popper et al. (2014): "There is evidence (e.g. Goertner et al. 1994; Stephenson et al. 2010; Halvorsen et al. 2012) that little or no damage occurs to fishes without a swim bladder except at very short ranges from an in-water explosive event. Goertner (1978) showed that the range from an explosive event over which damage may occur to a non-swim bladder fish is in the order of 100 times less than that for swim bladder fish."

2.2.2.24 Stationary animal modelling has been included in this study, based on research from Hawkins et al. (2014). However, basing the modelling on a stationary (zero flee speed) receptor is likely to greatly overestimate the potential risk to fish species, especially when considering the precautionary nature of the parameters already built into the cumulative exposure model.

3 Baseline Ambient Noise

3.1.1.1 The baseline noise level in open water, in the absence of any 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 mammals and fish vocalisation, as well as an element from invertebrates.

3.1.1.2 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 aggregate dredgers and small fishing boats have a lower overall contribution. There are no dredging areas, active dredge zones, or dredging application option and prospecting areas within or in close proximity to the Hornsea Four project area.

3.1.1.3 Other sources of anthropogenic noise include oil and gas platforms and other drilling activity and military exercises. Drilling, including oil and gas drilling, may contribute some low frequency noise in the wind farm site, although due to its low-level nature (see **Section 5.3**), this is unlikely to contribute significantly to the overall ambient 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.

3.1.1.4 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 is, however, not currently available.

3.1.1.5 Typical underwater noise levels show a frequency dependency in relation to different noise sources; the classic curves for this are given in Wenz (1962) and are reproduced in Figure 3 below. Figure 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 to 1,000 Hz region, but to a lesser extent will also extend into higher and lower frequencies.

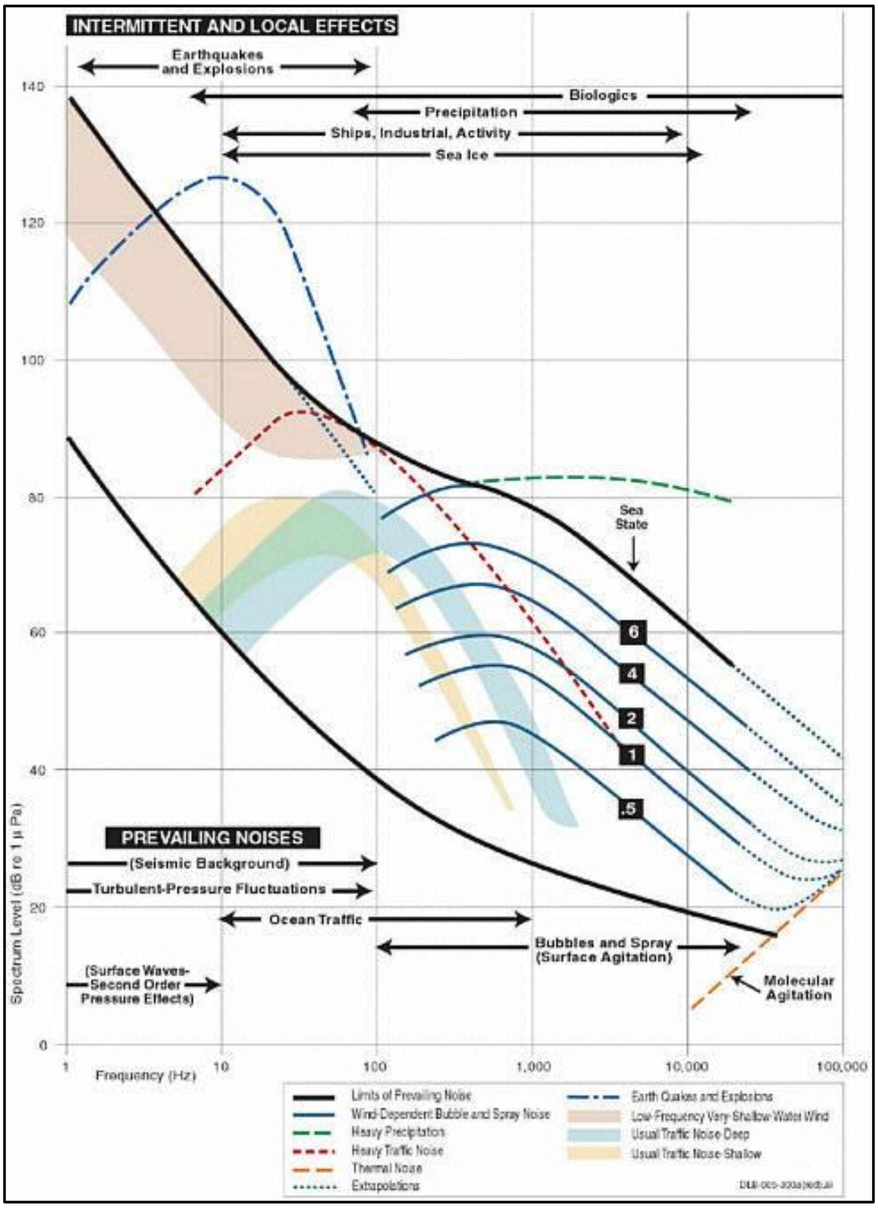


Figure 3: Ambient underwater noise, following Wenz (1962), showing frequency dependency from different noise sources.

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

3.1.1.7 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, although they 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 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 typical and realistic.

3.1.1.8 In principle, when noise introduced by anthropogenic sources propagates far enough it will reduce to the level of natural 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

4.1.1.1 The noise modelling methodology set out in this section has been discussed and agreed with both the Marine Ecology and Processes and Marine Mammals Evidence Plan Technical Panels (OFF-ME&P-2.1 and OFF-MM-2.5, respectively).

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

4.1.1.3 The modelling of impact piling has been undertaken using the INSPIRE noise model. The INSPIRE model (currently version 4.0) is a semi-empirical underwater noise propagation model based around a combination of numerical modelling and actual measured data. It is designed to calculate the propagation of noise in shallow, mixed water, typical of the conditions around the UK and very well suited to the region around Hornsea Four. The model has been tuned for accuracy using over 50 datasets of underwater noise propagation from monitoring around offshore piling activities.

4.1.1.4 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 two degrees). 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 can then be plotted over digital bathymetry data so that impact ranges can be clearly visualised as necessary. INSPIRE also produces these contours as Geographic Information System (GIS) shapefiles.

4.1.1.5 INSPIRE considers a wide array of input parameters, including variations in bathymetry and source frequency content to ensure accurate results are produced specific to the location and nature of the piling operation. It should also be noted that the results presented in this study should be considered conservative as what are considered to be maximum design parameters have been selected in the model for:

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

4.1.1.6 A simple modelling approach has been used for the other noise sources that may be present during the construction and lifecycle of Hornsea Four. These are discussed in **Section 5.3**.

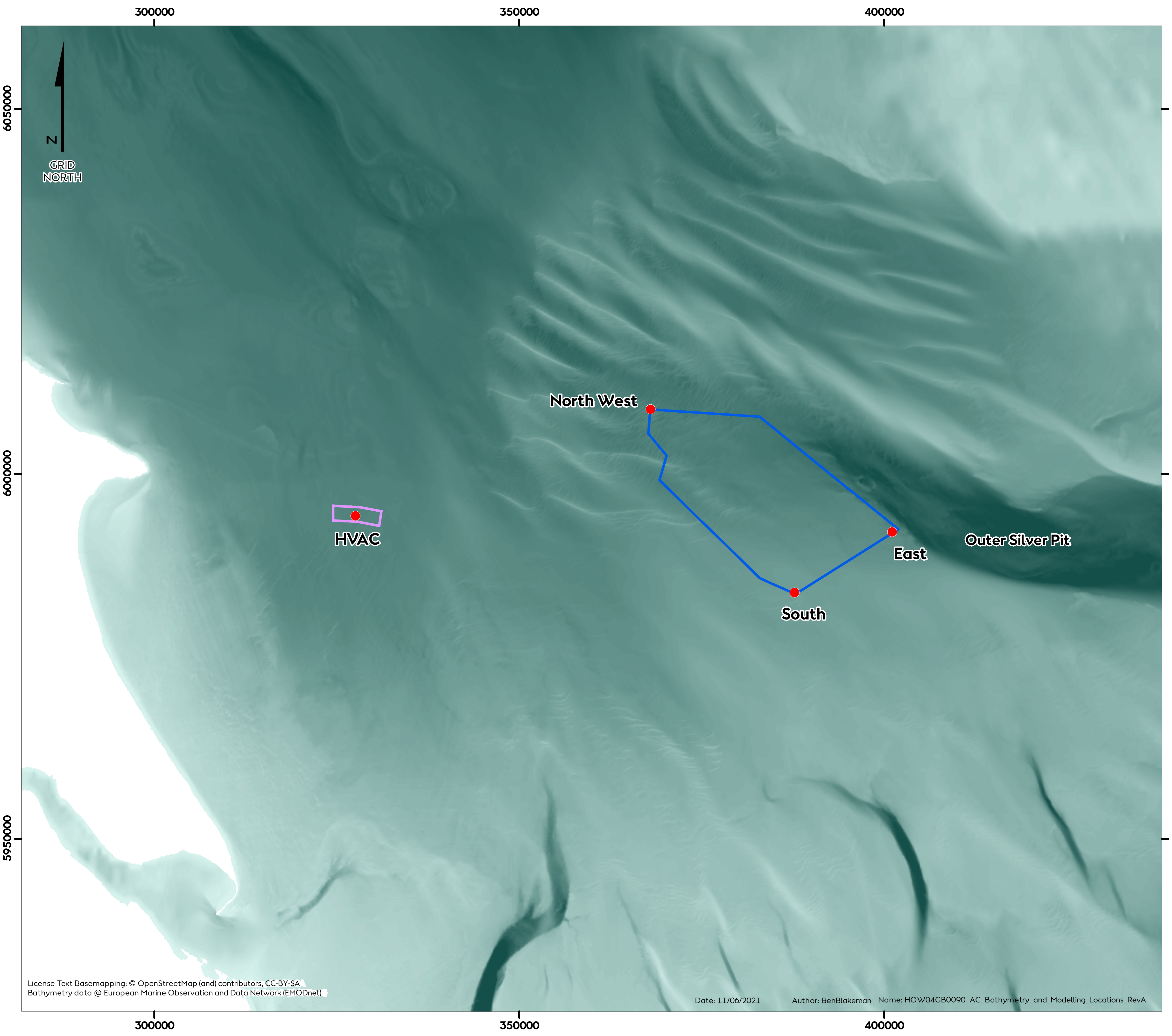
4.1.1.7 The input parameters for the impact piling modelling using INSPIRE are detailed in the following sections.

4.2 Locations

4.2.1.1 Modelling has been undertaken at four representative locations at Hornsea Four, covering the extents of the wind farm array and the High Voltage Alternative Current (HVAC) booster station search area to encompass variations in bathymetry in and around Hornsea Four. Locations in the north west, east and south of the PEIR boundary for the array area as well as a point within the HVAC booster station search area were agreed with stakeholders through the Evidence Plan process (OFF-ME&P-2.1 and OFF-MM-2.5). Since these discussions took place, the array area has been reduced, with the east and south modelling locations no longer falling within the Order Limits for the DCO application. As such, the east and south modelling locations have been moved to corresponding locations within the updated Order Limits. The chosen locations are shown in **Figure 4** and summarised in **Table 8**.

Table 8: Summary of the underwater noise modelling locations at Hornsea Four.

Modelling locations	North West (NW)	East (E)	South (S)	HVAC
Latitude	54° 12.6191′ N	54° 04.0150 N	53° 59.3713′ N	54° 04.0376′ N
Longitude	00° 58.5183′ E	01° 29.3022 E	01° 17.2580 E	00° 21.8970′ E
Water depth (mean tide)	50.4 m	47.9 m	37.9 m	50.9 m



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Hornsea Four

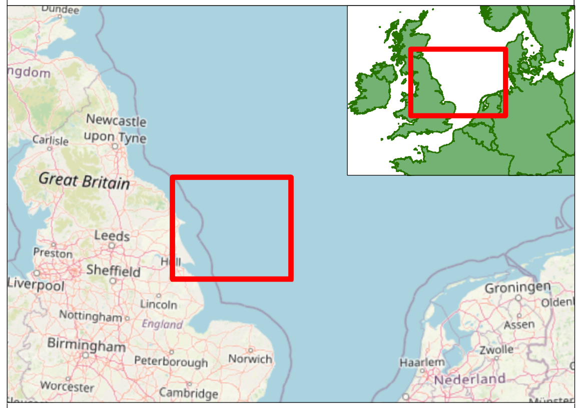
Figure 4

Underwater noise modelling locations at Hornsea Four

🟦 Array Area
🟪 HVAC Booster Station Works Area
● Modelling Locations

Water Depth (m below CD)
0
80

(EMODnet Bathymetry, resolution c.115m)



Coordinate system: ETRS 1989 UTM Zone 31N
Scale@A3: 1:500,000

0 10 20 Kilometres
0 5 10 Nautical Miles

REV	REMARK	DATE
....	First Issue fo PEIR	17/06/2019
A	Updated following PEIR consultations, for DCO	11/06/2021

Bathymetry and
Modelling Locations
Document no: HOW04GB0090
Created by: BPHB
Checked by: RM
Approved by: LK

4.3 Input parameters

4.3.1 Introduction

4.3.1.1 The modelling takes full account of the environmental parameters within and around Hornsea Four and the characteristics of the noise source. The following parameters have been assumed for modelling.

4.3.2 Impact piling parameters

4.3.2.1 Four piling source scenarios have been modelled to include monopile and pin pile foundations for WTGs and HVAC booster stations at Hornsea Four. This covers both the maximum design and most-likely installation scenarios. The maximum design installation scenarios consider the maximum possible blow energies and piling durations, which may prove to be highly unlikely due to hammer capacity or pile fatigue. The most-likely installation scenarios use more realistic blow energies and durations, which have been chosen based on other wind farm installations and reasonable predictions. The modelled scenarios are:

- Maximum design scenario monopile – up to 15 m diameter, installed using a maximum blow energy of 5,000 kJ;
- Most-likely scenario monopile – up to 15 m diameter, installed using a maximum blow energy of 4,000 kJ;
- Maximum design scenario pin pile – up to 4.6 m diameter, installed using a maximum blow energy of 3,000 kJ; and
- Most-likely scenario pin pile – up to 4.6 m diameter, installed using a maximum blow energy of 1,750 kJ.

4.3.2.2 For cumulative SEL, the soft start and ramp up of blow energies along with total duration and strike rate have also been considered. These vary for the maximum design and most-likely scenarios. The soft start and ramp up scenarios for this modelling have been summarised in **Table 9** to **Table 10**.

4.3.2.3 The modelled scenarios contain a total of 6,603 strikes over 262.5 minutes (maximum design) or 2,553 strikes over 127.5 minutes (most-likely) inclusive of soft start and ramp up. Both monopile and pin pile scenarios assume the same number of strikes, total duration, and strike rates.

Table 9: Summary of the maximum design ramp up scenario used for calculating SEL_{cum} for monopiles and pin piles.

Percentage of maximum hammer energy	20%	40%	60%	80%	100%
Monopile blow energy	1,000 kJ	2,000 kJ	3,000 kJ	4,000 kJ	5,000 kJ
Pin pile blow energy	600 kJ	1,200 kJ	1,800 kJ	2,400 kJ	3000kJ
Number of strikes	3	75	112	113	6,300
Duration	30 minutes	7.5 minutes	7.5 minutes	7.5 minutes	210 minutes
Strike rate	1 strike every 10 min	10 strikes/min	15 strikes/min		30 strikes/min

Table 10: Summary of the most-likely soft start and ramp up scenario used for calculating SEL_{cum} for monopiles and pin piles.

Percentage of maximum hammer energy	20%	40%	60%	80%	100%
Monopile blow energy	800 kJ	1,600 kJ	2,400 kJ	3,200 kJ	4,000 kJ
Pin pile blow energy	350 kJ	700 kJ	1,050 kJ	1,400 kJ	1,750 kJ
Number of strikes	3	75	112	113	2,250
Duration	30 minutes	7.5 minutes	7.5 minutes	7.5 minutes	75 minutes
Strike rate	1 strike every 10 min	10 strikes/min	15 strikes/min		30 strikes/min

4.3.2.4 A further cumulative modelling scenario has been included where three pin piles are installed one after the other, in a single 24-hour period, using the maximum design scenario at the NW location.

4.3.3 Source levels

4.3.3.1 Noise modelling requires knowledge of the source level, which is the theoretical noise level at one metre from the noise source.

4.3.3.2 The INSPIRE model assumes that the noise source, the hammer striking the pile, acts as a single point, as it will appear at distance. The source level is estimated based on the blow energy imparted on the pile by the hammer. This is then adjusted depending on the water depth at the modelling location to allow for the length of the pile in contact with the water, which can affect the amount of noise that is transmitted from the pile into its surroundings.

4.3.3.3 It is recognised that the "source level" concept technically does not exist in the context of shallow water piling (Heaney et al. 2020). In practice, in underwater noise modelling, it is simply a value that can be used to produce correct noise levels at range (for a specific model), as required in impact assessments.

4.3.3.4 The unweighted single strike SPL_{peak} and SEL_{ss} source levels estimated for this study are provided in **Table 11** and **Table 12**. These figures are presented on request, although as noted above they are not intended to be compatible or comparable with any other model or predicted source levels.

Table 11: Summary of the unweighted SPL_{peak} source levels used for modelling at Hornsea Four.

SPL_{peak} source levels	Location	Monopile	Pin Pile
Maximum design *Monopile: 5,000 kJ* *Pin Pile: 3,000 kJ*	NW	244.8 dB re 1 µPa @ 1 m	242.8 dB re 1 µPa @ 1 m
	E	244.8 dB re 1 µPa @ 1 m	242.8 dB re 1 µPa @ 1 m
	S	243.9 dB re 1 µPa @ 1 m	241.8 dB re 1 µPa @ 1 m
	HVAC	244.8 dB re 1 µPa @ 1 m	242.8 dB re 1 µPa @ 1 m
Most-likely *Monopile: 4,000 kJ* *Pin Pile: 1,750 kJ*	NW	244.0 dB re 1 µPa @ 1 m	240.2 dB re 1 µPa @ 1 m
	E	244.0 dB re 1 µPa @ 1 m	240.2 dB re 1 µPa @ 1 m
	S	243.0 dB re 1 µPa @ 1 m	239.2 dB re 1 µPa @ 1 m
	HVAC	244.0 dB re 1 µPa @ 1 m	240.2 dB re 1 µPa @ 1 m

Table 12: Summary of the unweighted SEL$_{ss}$ source levels used for modelling at Hornsea Four.

SEL$_{ss}$ source levels	Location	Monopile	Pin Pile
Maximum design *Monopile: 5,000 kJ* *Pin Pile: 3,000 kJ*	NW	218.8 dB re 1 µPa^{2}s @ 1 m	216.8 dB re 1 µPa^{2}s @ 1 m
	E	218.8 dB re 1 µPa^{2}s @ 1 m	216.8 dB re 1 µPa^{2}s @ 1 m
	S	217.9 dB re 1 µPa^{2}s @ 1 m	215.8 dB re 1 µPa^{2}s @ 1 m
	HVAC	218.8 dB re 1 µPa^{2}s @ 1 m	216.8 dB re 1 µPa^{2}s @ 1 m
Most-likely *Monopile: 4,000 kJ* *Pin Pile: 1,750 kJ*	NW	218.0 dB re 1 µPa^{2}s @ 1 m	214.2 dB re 1 µPa^{2}s @ 1 m
	E	218.0 dB re 1 µPa^{2}s @ 1 m	214.2 dB re 1 µPa^{2}s @ 1 m
	S	217.0 dB re 1 µPa^{2}s @ 1 m	213.2 dB re 1 µPa^{2}s @ 1 m
	HVAC	218.0 dB re 1 µPa^{2}s @ 1 m	214.2 dB re 1 µPa^{2}s @ 1 m

4.3.4 Frequency content

4.3.4.1 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 Environmental's noise measurement database to obtain representative one-third octave band frequency spectrum levels (i.e. the frequency breakdown of a noise level) for installing monopiles and pin piles. The one-third octave band levels for maximum hammer energy used for modelling are illustrated in Figure 5; the shape of each spectrum is the same for all the other locations and blow energies, with the overall source levels adjusted depending on these parameters. This is particularly important when considering marine mammal species that are more sensitive to a particular frequency of sound than others.

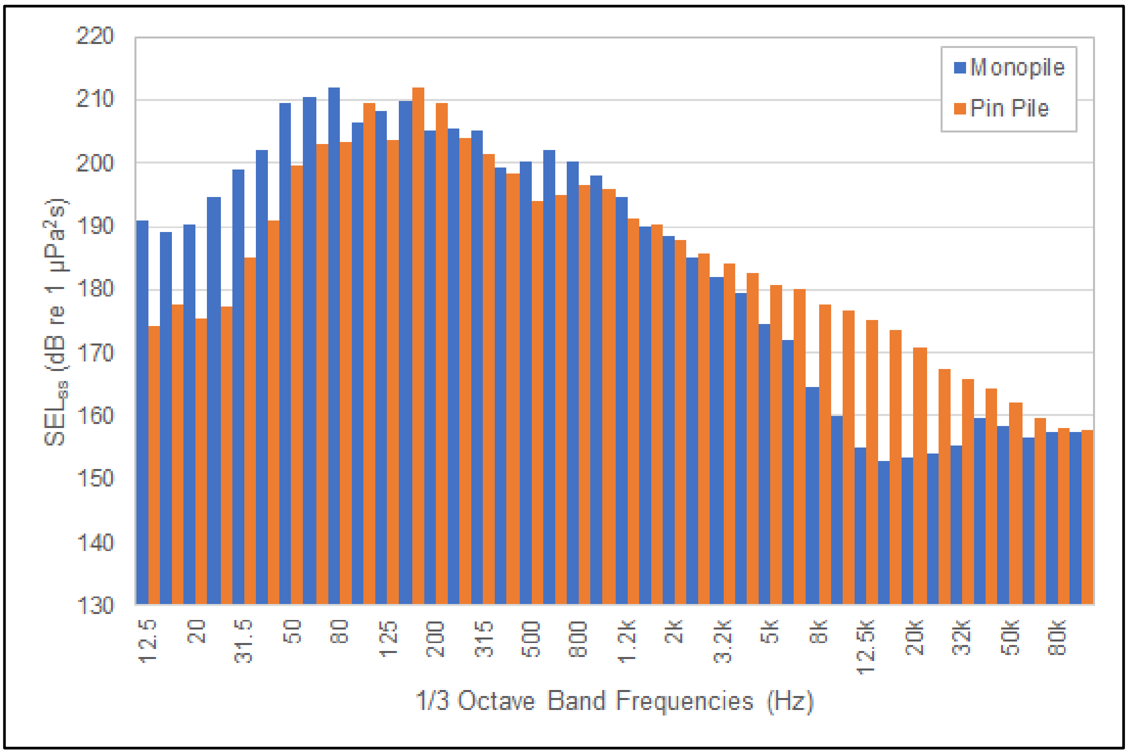


Figure 5: One-third octave source level frequency spectra for the maximum hammer blow energy at the NW modelling location (as unweighted SEL$_{ss}$).

4.3.4.2 Frequency spectra for piles of over seven metres in diameter, one of the largest with measured data available, have been used for the monopile modelling, and piles of approximately four metres in diameter (near the top end of the pin pile options being considered) have been used for pin pile modelling. It is worth noting that the monopile spectra contain more lower frequency content (approximately 25 to 160 Hz) 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 Hornsea Four. A larger diameter would be expected to move the dominant frequency of the sound produced (i.e. the frequency where the highest levels are present) lower, further below the frequencies of greatest hearing sensitivity of marine mammals. Thus, the sound would appear slightly quieter to a receptor more sensitive to higher frequencies such as dolphins and porpoises (HF and VHF cetaceans in Southall et al., 2019) and the spectrum used is likely to be precautionary. Marine mammal hearing sensitivity is covered in **Section 2.2**.

4.3.5 Other environmental conditions

4.3.5.1 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 Hornsea Four as it is based on over 50 datasets of measured impact piling noise in coastal and offshore waters surrounding the UK.

4.3.5.2 Mean tidal depth has been used for the depth of water across the site as the tidal state will fluctuate throughout installation of the WTG foundations.

4.4 Modelling confidence

4.4.1.1 As discussed in **Section 4.1**, INSPIRE is a semi-empirical model based around a combination of numerical modelling and actual measured data. The INSPIRE model has always endeavoured to give a conservative estimate of underwater noise levels from impact piling noise. There is always some variability with underwater noise measurements, even when considering measurements of pile strikes at the same blow energy taken at the same range. For example, there can be big variations in noise level, sometimes up to 5 or even 10 dB, as seen in Bailey et al. (2010) and the data shown in **Figure 6**. The INSPIRE model always assumes the highest of these measured noise levels at any range.

4.4.1.2 This version of INSPIRE is the product of re-analysing the impact piling noise measurements in Subacoustech Environmental's measurement database and cross-referencing it with blow energy data from piling logs, giving a database of single strike noise levels referenced to a specific blow energy at a specific range. This analysis showed that the previous versions of INSPIRE overestimated the range of noise levels with blow energy, meaning that low blow energies were previously being underestimated. This led to underestimations in predicted levels, particularly for cumulative SELs.

4.4.1.3 As INSPIRE is semi-empirical, a validation process is inherently built into the development process. Whenever a new set of good, reliable impact piling measurement data is gathered through offshore surveys, it is compared against the outputted levels from INSPIRE and, if differences show that refinements need to be made to the model, it can go under further development to account for the new data. Over 50 separate impact piling noise datasets from all around the UK have been used as part of the development for this version of

INSPIRE, and in each case, a conservative fit to the data is used. This is the same process that has been used for previous iterations of INSPIRE, however with each new version more measurement data is included.

4.4.1.4 Figure 6 presents a small selection of measured impact piling noise data plotted against outputs from INSPIRE version 4.0. The plots show data points from measured data (in red) plotted alongside modelled data (in green) using INSPIRE version 4.0, matching the pile size, blow energy and range from the measured data. These show the conservative fit to data, with the INSPIRE modelled data points sitting at the higher end of the measured noise levels at each range.

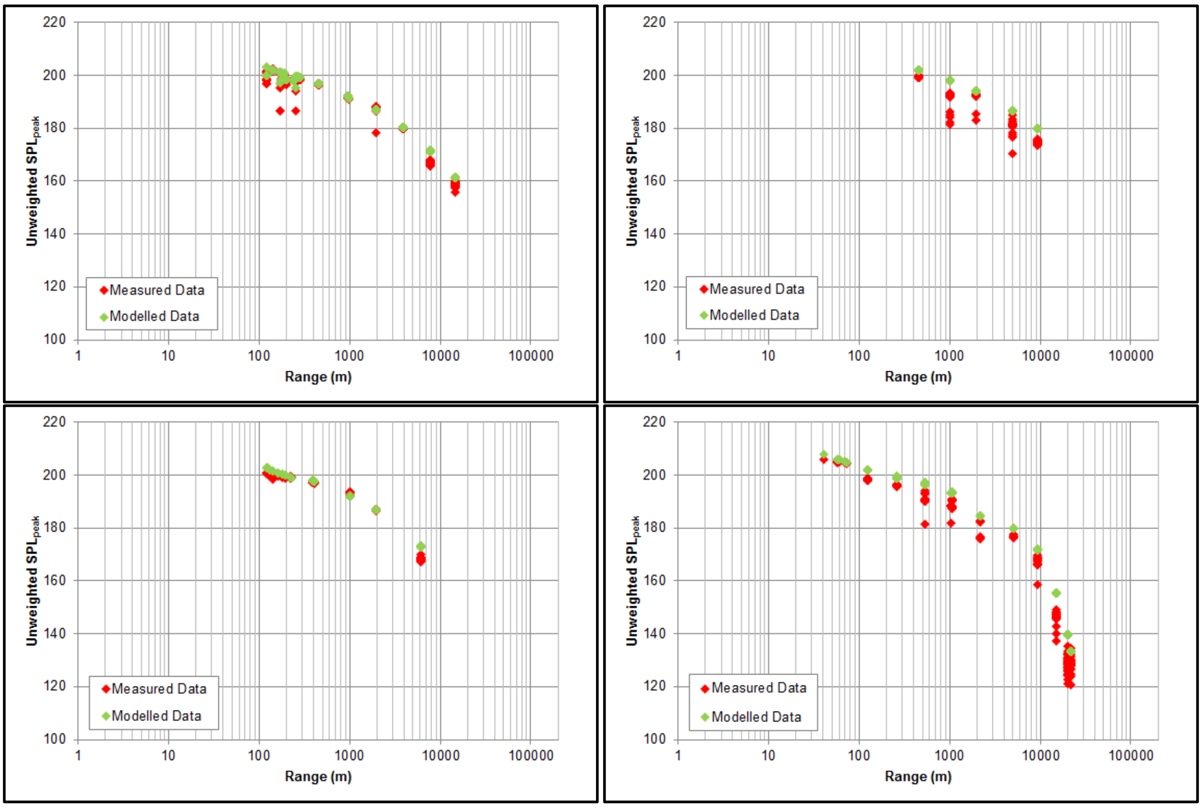


Figure 6: Comparison between example measured data (red points) and modelled data using INSPIRE version 4.0 (green points).

4.4.1.5 Due to the conservatism of the INSPIRE model, along with the upper-end parameters used for modelling, there is an inherent precaution built into the model. This includes the conservative fit to data shown in Figure 6, the assumed maximum blow energies and ramp-up scenarios considered for modelling in Section 4.3.2, the flee speeds considered for receptors and the modelling locations chosen. All of these factors are compounded when considering cumulative exposure calculations. When all these factors are considered individually, they can be reasonable and realistic, however when they are considered together, they can result in an overestimating in noise levels, and ultimately lead to a maximum design scenario (MDS) that is highly unlikely to occur in practice.