

DOGGER BANK D WIND FARM

Preliminary Environmental Information Report

Volume 2

Appendix 12.3 Underwater Noise Modelling Report

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APPENDIX 12.3 UNDERWATER NOISE MODELLING REPORT

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Executive Summary

Subacoustech Environmental Ltd., on behalf of Royal HaskoningDHV, has undertaken a study in order to assess the potential underwater noise and its effects during the construction and operation of the proposed Dogger Bank D Offshore Wind Farm.

Modelling of underwater noise generated by impact piling for various turbine foundation types was undertaken at four representative locations, with the loudest levels of noise and the greatest impact ranges predicted for the monopile foundation scenario due to the larger pile diameter and hammer blow energies used.

The modelling results were analysed in terms of relevant noise metrics and criteria to assess the effects of impact piling noise on marine mammals and fish, which have been used to aid biological assessments. For marine mammals, the largest permanent threshold shift (PTS) impact ranges were predicted for animals in the Low-Frequency (LF) cetacean category with maximum ranges of 9.5km. For fish, the largest recoverable injury ranges were predicted to be 12km for a stationary receptor, reducing to around 350m when considering a moving receptor.

Noise sources other than impact piling, including drilling, alternative non-piled foundation options, rock placement, vessel movements and operational wind turbine generator (WTG) noise, were all predicted to be much lower than those predicted for impact piling noise. Noise from unexploded ordnance (UXO) clearance showed there is a risk of PTS up to 15km from detonation of the largest UXO device considered (907kg + donor charge), using the unweighted $L_{p,pk}$ criteria for Very High-Frequency (VHF) cetaceans. However, this is likely to be highly precautionary as the impact range is based on a worst-case criterion and calculation methodology that does not account for any smoothing of the pulse over long ranges, which would reduce the pulse peak and other characteristics of the sound that cause injury. It also does not take into account the expected use of deflagration techniques for UXO disposal.

It should be stressed that, due to the nature of modelling, while the results present specific ranges at which each impact threshold is met, the ranges should be taken as indicative and worst case in determining where environmental effects may occur in receptors during the proposed operations.

The outputs of this modelling have been used to inform analysis of the impacts of underwater noise on marine mammals and fish in their respective reports.

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Terminology

Decibel (dB)	A customary scale commonly used (in various ways) for reporting levels of sound. The dB represents a ratio/comparison of a sound measurement (e.g., sound pressure) over a fixed reference level. The dB symbol is followed by a reference value (e.g., re 1μPa).
Peak pressure	The highest pressure above or below ambient that is associated with a sound wave.
Peak-to-peak pressure	The sum of the highest positive and negative pressures that are associated with a sound wave.
Permanent Threshold Shift (PTS)	Noise threshold that represents the onset level of a permanent impairment hearing caused by acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the ear, and thus a permanent reduction of hearing acuity.
Root Mean Square (RMS)	The square root of the arithmetic average of a set of squared instantaneous values. Used for presentation of an average sound pressure level.
Sound Exposure Level (SEL or $L_{E,p}$)	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 Exposure Level, cumulative (SEL_{cum} or $L_{E,p,t}$)	Single value for the collected, combined total of sound exposure over a specified time or multiple instances of a noise source.
Sound Exposure Level, single strike (SEL_{ss})	Calculation of the sound exposure level representative of a single noise impulse, typically a pile strike.
Sound Pressure Level (SPL or L_p)	The sound pressure level is an expression of sound pressure using the decibel (dB) scale; the standard frequency pressures of which are 1μPa for water and 20μPa for air.
Sound Pressure Level Peak (SPL_{peak} or $L_{p,pk}$)	The highest (zero-peak) positive or negative sound pressure, in decibels.
Temporary Threshold Shift (TTS)	Onset threshold level for a temporary reduction of hearing acuity caused by exposure to sound over time.
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.

Acronyms

ADD	Acoustic Deterrent Device
BGS	British Geological Survey
EIA	Environmental Impact Assessment
EEZ	Exclusive Economic Zone
EMODnet	European Marine Observation and Data Network
GIS	Geographic Information System
HE	High Explosive
HF	High-Frequency Cetaceans
INSPIRE	Impulsive Noise Sound Propagation and Impact Range Estimator
ISO	International Organisation for Standardisation
LF	Low-Frequency Cetaceans
MTD	Marine Technical Directorate
NEQ	Net Explosive Quantity
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPL	National Physical Laboratory
OSP	Offshore Platform
PCW	Phocid Carnivores in Water
PPV	Peak Particle Velocity
PTS	Permanent Threshold Shift
RMS	Root Mean Square
SE	Sound Exposure
SEL ($L_{E,p}$)	Sound Exposure Level
SEL _{cum} ($L_{E,p,t}$)	Cumulative Sound Exposure Level
SEL _{ss} ($L_{E,p,ss}$)	Single Strike Sound Exposure Level
SPL	Sound Pressure Level
SPL _{peak} ($L_{p,pk}$)	Peak Sound Pressure Level
SPL _{RMS} (L_p)	Root Mean Square Sound Pressure Level
TNT	Trinitrotoluene (explosive)
TTS	Temporary Threshold Shift
UXO	Unexploded Ordnance
VHF	Very High-Frequency Cetaceans
WTG	Wind Turbine Generator

Units

dB	Decibel (sound pressure)
GW	Gigawatt (power)
g	Gram (mass)
Hz	Hertz (frequency)
kg	Kilogram (mass)
kHz	Kilohertz (frequency)
kJ	Kilojoule (energy)
km	Kilometre (distance)
km ²	Square kilometres (area)
kW	Kilowatt (power)
m	Metre (distance)
mm/s	Millimetres per second (particle velocity)
m/s	Metres per second (speed)
MW	Megawatt (power)
Pa	Pascal (pressure)
Pa ² s	Pascal squared seconds (acoustic energy)
μPa	Micropascal (pressure)

1 Introduction

The Dogger Bank D Offshore Wind Farm (OWF) is a proposed fourth phase of the Dogger Bank Wind Farm in the North Sea, England. As part of the Environmental Impact Assessment (EIA) process, Subacoustech Environmental Ltd. has undertaken detailed modelling and analysis in relation to the effect of underwater noise on marine mammals and fish during the construction and operation of Dogger Bank D.

The array area covers an approximate area of 262 km², is situated approximately 210km off the Yorkshire coast at its closest point to shore and is located immediately adjacent to the Dogger Bank C project and the UK Exclusive Economic Zone (EEZ) boundary. Dogger Bank D has a proposed capacity of up to 113 wind turbine generators (WTGs). The location of Dogger Bank D, alongside other nearby wind farm developments, is shown in Figure 1-1.

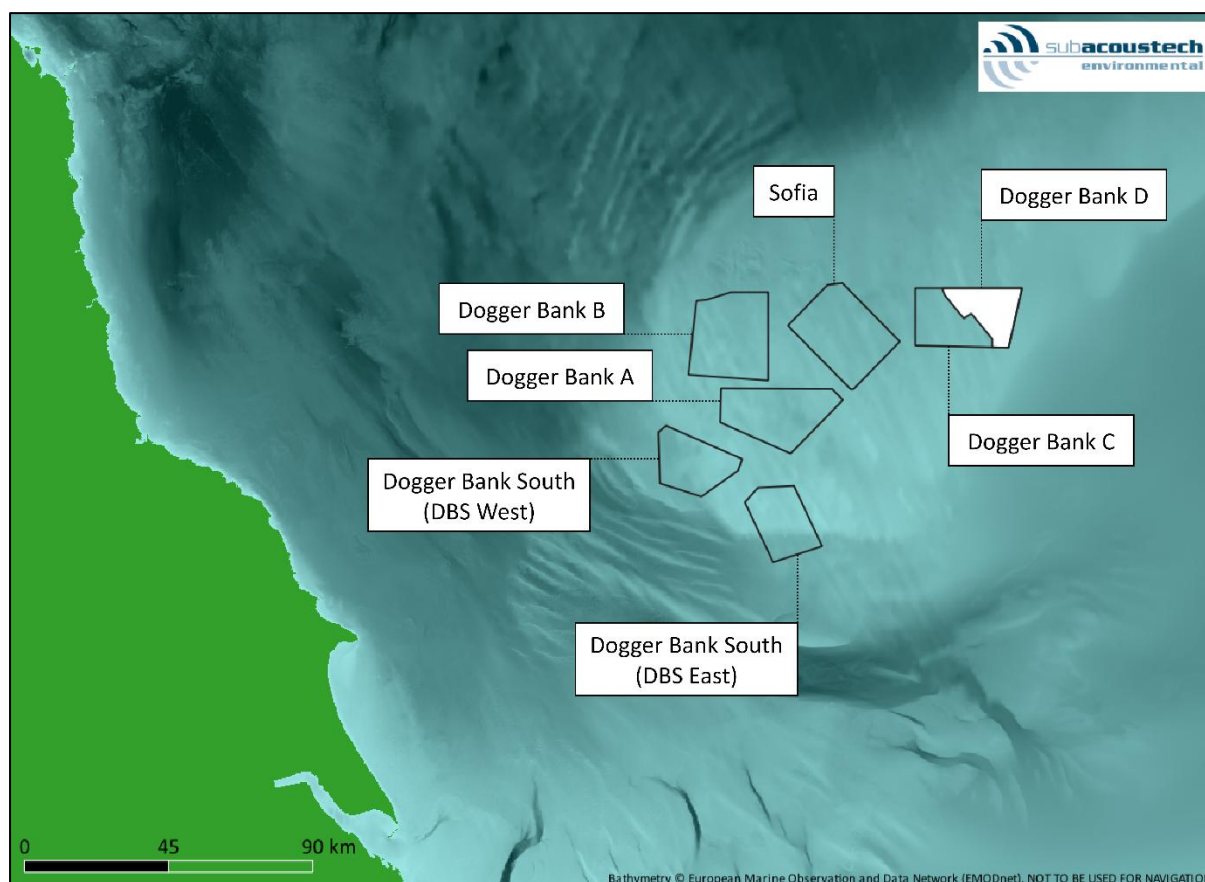


Figure 1-1: Overview map showing the Dogger Bank D boundary, its location on the Dogger Bank, other nearby wind farm developments and the surrounding bathymetry.

This report presents a detailed assessment of the potential underwater noise generated during the construction and operation of Dogger Bank D, and includes the following:

- Background information covering the units for measuring and assessing underwater noise, and a review of the underwater noise metrics and criteria used to assess the possible environmental effects in marine receptors (section 2).
- Discussion of the approach, input parameters, and assumptions for the detailed modelling undertaken (section 3).

- Presentation and interpretation of the detailed subsea noise modelling for impact piling with regards to its effect on marine mammals and fish (section 4).
- Noise modelling of other noise sources expected around the construction and operation of Dogger Bank D, including drilling, alternative non-piled foundation options, rock placement, vessel noise, operational WTG noise, and unexploded ordnance (UXO) clearance (section 5).
- Summary and conclusions (section 6).

Further modelling results using an alternative impact range prediction methodology, discussed in section 2.2.1, are presented in Appendix A.

2 Background to underwater noise metrics

2.1 Underwater noise

Sound travels much faster in water (approximately 1,500m/s) than in air (340m/s). Since water is a relatively incompressible, dense medium, the pressure associated with underwater sound tends to be much higher than in air. It should be noted that stated underwater noise levels are different to those stated for airborne noise levels, as a different scale is used between in water and in air measurements. Therefore, noise measurements in air are generally incomparable to noise measurements underwater.

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, as this better reflects how sound is perceived. For example, equal increments of sound levels do not have an equal increase in the perceived sound. Instead, each doubling of sound level will cause a roughly equal increase of loudness. Any quantity expressed in this dB scale is termed a “level.” For example, if the unit is sound pressure, it will be termed a “sound pressure level” on the dB scale.

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. 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 20µPa is used for sound in air since that is the lower threshold of human hearing.

When used with sound pressure, the pressure value is squared. So that variations in the units agree, the sound pressure must be specified as units of Root Mean Square (RMS) pressure squared. This is equivalent to expressing the sound as:

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

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

2.1.2 Sound pressure level (L_p or SPL)

The Sound Pressure Level (SPL or L_p) is normally used to characterise noise 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 ($L_{p,RMS}$) 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 impact piling, seismic airgun or underwater blasting, it is critical that the period over which the RMS level is calculated is quoted e.g., $L_{p,125ms}$. For instance, in the case of a pile strike lasting a tenth of a second, the mean taken over a tenth of a second will be ten times higher than the mean averaged over one second. Often, transient sounds such as these are quantified using “peak” SPLs ($L_{p,pk}$) or Sound Exposure Levels (SELs, L_E).

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

2.1.3 Peak sound pressure level ($L_{p,pk}$ or SPL_{peak})

The peak SPL, or $L_{p,pk}$, is often used to characterise transient sound from impulsive sources, such as percussive impact piling. $L_{p,pk}$ 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 Sound exposure level ($L_{E,p,t}$ or SEL)

When considering the noise from transient sources, 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, 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 injury ranges for fish and marine mammals from various noise sources (Popper *et al.*, 2014; Southall *et al.*, 2019).

The SEL ($L_{E,p}$) sums the acoustic energy over a measurement period (t), and effectively takes account of both the SPL of the sound and the duration it 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 Pa, T is the total duration of sound in seconds, and t is time in seconds. The SE is a measurement 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 must be compared with a reference acoustic energy (p_{ref}^2) and a reference time (T_{ref}). The $L_{E,p,t}$ is then defined by:

$$L_{E,p} = 10 \times \log_{10} \left(\frac{\int_0^T p^2(t) dt}{p_{ref}^2 T_{ref}} \right)$$

By using a common reference pressure (p_{ref}) of 1 μPa for assessments of underwater noise, the $L_{E,p}$ and L_p can be compared using the expression:

$$L_{E,p} = L_p + 10 \times \log_{10} T$$

where L_p is a measure of the average level of broadband noise and the $L_{E,p}$ sums the cumulative broadband noise energy.

This means that, for continuous sounds of less than (i.e., fractions of) one second, the $L_{E,p,1s}$ will be lower than the L_p . For periods greater than one second, the $L_{E,p}$ will be numerically greater than the L_p (i.e., for a continuous sound of 10 seconds duration, the $L_{E,p,10s}$ will be 10dB higher than the L_p ; for a sound of 100 seconds duration the $L_{E,p,100s}$ will be 20dB higher than the L_p , and so on).

Where a single impulse noise such as the soundwave from a pile strike is considered in isolation, this can be represented by a "single strike" $L_{E,p}$ or SEL_{ss} . A cumulative $L_{E,p,t}$ or SEL_{cum} , accounts for the exposure from multiple impulses or pile strikes over time, where the number of impulses replaces the T in the equation above, leading to:

$$L_{E,p,t} = L_E + 10 \times \log_{10} X$$

where L_E is the sound exposure level of one impulse and X is the total number of impulses or strikes. Unless otherwise defined, all L_E noise levels in this report are references to $1\mu\text{Pa}^2\text{s}$.

2.2 Properties of sound

2.2.1 *Impulsive and non-impulsive noise*

Sound can be categorised loosely into two types: impulsive noise and non-impulsive noise. Non-impulsive noise can be defined as a steady-state noise which does not necessarily have a long duration (e.g., vibropiling, drilling). Impulsive noise can be defined as a sound with a high peak sound pressure, short duration, fast rise-time and a broad frequency content at the source (e.g., seismic airguns, explosives, impact piling).

These differences are important to consider regarding the potential for auditory injury, as impulsive noise is generally more injurious than non-impulsive noise.

Due to the differences between impulsive and non-impulsive noise sources, different metrics are appropriate for describing these different sound sources. For example:

- Impulsive noises: Use peak SPL ($L_{p,pk}$) and cumulative SEL ($L_{E,p,t}$)
- Non-impulsive noises: cumulative SEL ($L_{E,p,t}$)

Objective categorisation of noise as impulsive or non-impulsive can sometimes be challenging. This is particularly the case if a sound is travelling over long distances. For example, if an impulsive sound propagates through an environment, the energy within the sound wave will also dissipate and becomes less impulsive with distance from the noise source. This is important to consider regarding auditory injury and impact range calculations, as noise will become less injurious if it becomes less impulsive.

Active research is currently underway to define the range-dependant transition from impulsive and non-impulsive noise (see Martin *et al.*, 2020). Although the situation is complex, Hastie *et al.* (2019) concluded that an impulsive sound can be considered effectively non-impulsive 3.5km from the source. Using these findings, Southall (2021) suggests that noise should be considered non-impulsive when there is no longer energy content above 10kHz.

The recent study by Matei *et al.* (2024) concludes that there is still insufficient evidence to clearly define a transition point suitable for an assessment such as this, although the paper makes it clear that there is a substantial reduction in impulsiveness within the first 5km. Due to the uncertainty, no presumption of a change in impulsiveness has been made in this report, although non-pulse should be considered more relevant where PTS ranges are calculated above 5km. Results in respect of both impulsive and non-impulsive criteria have been presented for piling noise sources.

2.2.2 *Particle motion*

The motion of the particles that make up a medium is an important component of sound. Particle motion is present wherever there is sound, and it describes the back-and-forth movement of particles in water, which in the context of underwater noise, are caused by a sound wave passing through the water column. This back-and-forth movement means that, unlike sound pressure at a single point, particle motion always contains directional information (Hawkins and Popper, 2017). Regarding quantifying particle motion, it is usually defined in reference to the velocity of the particle (often a peak particle velocity, PPV), but sometimes the related acceleration or displacement of the particle is used.

It has been identified by several researchers that many fish species, (e.g., Popper and Hawkins, 2019; Nedelec *et al.*, 2016; Radford *et al.*, 2012), as well as marine invertebrates (see Solé *et al.*, 2023) are sensitive to particle motion. However, sound pressure metrics are still preferred and more widely used than particle motion due to

a lack of supporting data (Popper and Hawkins, 2018). There continue to be calls for additional research on the levels of and effects with respect to particle motion. Subsequently, particle motion is not considered further in this report.

2.3 Analysis of environmental effects: Assessment criteria

Over the last 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 adverse impacts in species is dependent upon the incident sound level, source 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 seismic airguns, impact piling and blasting 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.

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); or
- Disturbance and behavioural responses.

The following sections discuss the underwater noise criteria used in this study with respect to species of marine mammals and fish that may be present around the study area at Dogger Bank D.

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

- Southall *et al.* (2019) marine mammal exposure criteria;
- Popper *et al.* (2014) sound exposure guidelines for fishes and sea turtles.

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

2.3.1 Marine mammals

The Southall *et al.* (2019) paper is the most used and recognised reference for marine mammal hearing thresholds. It provides identical thresholds to those from the National Marine Fisheries Service (NMFS) (2018) guidance for marine mammals. It should be noted that, despite the identical thresholds, the marine mammal hearing groups are described slightly differently in the Southall *et al.* (2019) paper to the NMFS (2018) guidance. Therefore, care should be taken if comparing results using the Southall *et al.* (2019) to NMFS (2018) criteria.

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

It should be noted that despite Southall *et al.* (2019) referring to peak SPL as SPL_{peak} , this notation has since been deprecated (ISO 18405:2017) and will be referred to as $L_{p,pk}$ in the rest of this report.

Table 2-1: Marine mammal hearing groups (from Southall *et al.*, 2019).

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

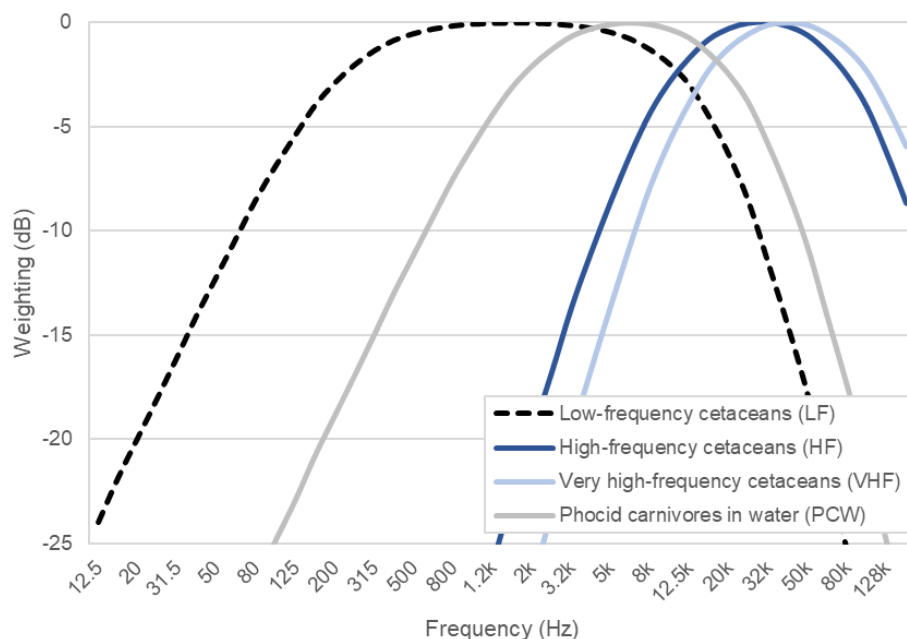


Figure 2-1: Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall *et al.*, 2019).

Southall *et al.* (2019) considers the nature of the sound in the context of whether it is an impulsive or non-impulsive noise source (see section 2.2.1 for details).

Although the use of impact ranges derived using the impulsive criteria are recommended for all but clearly defined non-impulsive sources, it should be recognised that where calculated ranges are beyond 3.5 km (see section 2.2.1), the impact range is likely to be somewhere between the impulsive and non-impulsive impact criteria. Therefore, if the modelled impact range of an impulsive noise has been predicted to be greater than 3.5 km, the non-impulsive impact range should also be considered. Both impulsive and non-impulsive criteria have been presented in this study.

Table 2-2 and Table 2-3 present the impulsive and non-impulsive criteria set out by Southall *et al.* (2019) for Permanent Threshold Shift (PTS) and Temporary Threshold Shift (TTS) in marine mammals used in this study.

Table 2-2: $L_{p,pk}$ unweighted criteria for PTS and TTS in marine mammals (Southall *et al.*, 2019).

Southall <i>et al.</i> (2019)	$L_{p,pk}$ (dB re 1 μ Pa)	
	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 2-3: $L_{E,p,24h,wtd}$ weighted criteria for PTS and TTS in marine mammals (Southall *et al.*, 2019).

Southall <i>et al.</i> (2019)	$L_{E,p,24h,wtd}$ (dB re 1 μ Pa 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

Where $L_{E,p,t}$ thresholds are required for marine mammals, a fleeing animal model has been used. This assumes that a receptor, when exposed to high noise levels, will swim away from the noise source. A constant fleeing speed of 3.25m/s has been assumed for the low-frequency cetaceans (LF) group (Blix and Folkow, 1995), based on data for minke whale, and for other receptors, a constant rate of 1.5m/s has been assumed for fleeing, which is a cruising speed for a harbour porpoise (Otani *et al.*, 2000). These are considered worst case assumptions as marine mammals are expected to be able to swim much faster under stress conditions (Kastelein *et al.* 2018), especially at the start of any noisy process when the receptor will be closest.

2.3.2 Fish

The Popper *et al.* (2014) guidelines are recognised as a suitable reference for underwater noise impacts on marine fauna (aside from marine mammals) in UK waters. Popper *et al.* (2014) provides a summary of the latest research and guidelines for fish (and other marine fauna) exposed to sound and uses categories for fish that are representative of the species present around the Dogger Bank D array area.

The Popper *et al.* (2014) guidelines present criteria dependent on the type of noise source, species of marine fauna and their hearing capabilities, and impact type. Noise sources considered in the guidance include explosions, pile driving, seismic airguns, sonar, and shipping and continuous noise. For this study, criteria for pile driving, explosions, and shipping and continuous noise have been used.

For each sound source, the marine fauna is categorised into groups of fish, sea turtles, and eggs and larvae. Due to their diversity and quantity, fish are categorised further into three groups depending on their hearing capabilities, which can be indicated by whether they possess a swim bladder or not, and whether the swim bladder is involved in hearing.

Popper *et al.* (2014) provides separate criteria, depending on the species and the noise source, for various impacts associated with noise exposure. These are mortality and potential mortal injury, impairment (split into recoverable injury, TTS, and masking), and behavioural effects.

Depending on the noise source, quantitative criteria are given in appropriate metrics ($L_{p,pk}$, $L_{E,p,24h}$, etc.), which can then be used as thresholds for the onsets of listed impacts. Where insufficient data is available, Popper *et al.* (2014) also gives a qualitative description. This summarises the effect of the noise as having either a high, moderate or low relative risk of an effect on an individual in either near (tens of meters), intermediate (hundreds of meters) or far (thousands of meters) from the source.

Where $L_{E,p,t}$ thresholds are required for fish, both a stationary and fleeing animal model has been used. This is due to the diversity of species considered under this criterion, and as a result, both models encompass the diversity of responses to noise.

Most species described by Popper *et al.* (2014) are likely to move away from a sound that is loud enough to cause harm (Dahl *et al.*, 2015; Popper *et al.*, 2014). For those species that flee, a speed of 1.5m/s (based on Hirata, 1999) is considered a conservative speed at which to base a fleeing animal model. However, considering the diversity of species described by Popper *et al.* (2014), whether an animal flees or remains stationary in response to a loud noise will differ between species. It is recognised that there is limited evidence for fish fleeing from high level noise sources in the wild. Those species that are likely to remain stationary are thought more likely to be benthic species or species without a swim bladder, due to their reduced hearing capabilities making these species the least sensitive to noise (e.g., Goertner *et al.*, 1994; Goertner *et al.*, 1978; Stephenson *et al.*, 2010; Halvorsen *et al.*, 2012). Hubert *et al.* (2024) noted that pelagic fish did not clearly flee on exposure to sound, albeit at sound pressure levels far lower than piling noise and did not rule out the possibility that a flee response could occur at higher levels. Despite this, including only a stationary animal model as a worst-case scenario is likely to overestimate the potential risk to fish species, and so a combined approach is recommended, which considers impact ranges from both fleeing and stationary receptors. Impact ranges from both stationary and fleeing receptors are therefore included in this report.

The quantitative and qualitative thresholds from the Popper *et al.* (2014) used in this study are reproduced in Table 2-4 to Table 2-6, covering pile driving, explosions, and shipping and continuous noise. Similar to the Southall *et al.* (2019) criteria in section 2.3.1, the Popper *et al.* (2014) criteria use the deprecated SPL_{peak} , SPL_{RMS} and SEL_{cum} notation, and this report will use respectively the $L_{p,pk}$, L_p , and $L_{E,p,t}$ notation from ISO 18405:2017 from hereon.

Table 2-4: Recommended guidelines for pile driving according to Popper et al. (2014) for species of fish, sea turtles, and eggs and larvae (N = near-field; I = intermediate-field, F = far-field).

Popper et al. (2014) criteria for pile driving					
Receptor	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	> 219dB $L_{E,p,24h}$ > 213dB $L_{p,pk}$	> 216dB $L_{E,p,24h}$ > 213dB $L_{p,pk}$	>> 186dB $L_{E,p,24h}$	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder not involved in hearing	210dB $L_{E,p,24h}$ > 207dB $L_{p,pk}$	203dB $L_{E,p,24h}$ > 207dB $L_{p,pk}$	> 186dB $L_{E,p,24h}$	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder involved in hearing	207dB $L_{E,p,24h}$ > 207dB $L_{p,pk}$	203dB $L_{E,p,24h}$ > 207dB $L_{p,pk}$	186dB $L_{E,p,24h}$	(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate
Sea turtles	> 210dB $L_{E,p,24h}$ > 207dB $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) High (I) Moderate (F) Low
Eggs and larvae	> 210dB $L_{E,p,24h}$ > 207dB $L_{p,pk}$	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low

Table 2-5: Recommended guidelines for explosions according to Popper et al. (2014) for species of fish, sea turtles, and eggs and larvae (N = near-field; I = intermediate-field, F = far-field).

Popper et al. (2014) criteria for explosions					
Receptor	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	229 – 234dB $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) Moderate (F) Low
Fish: swim bladder not involved in hearing	229 – 234dB $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) Low (F) Low
Fish: swim bladder involved in hearing	229 – 234dB $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low
Sea turtles	229 – 234dB $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low
Eggs and larvae	> 13mm/s peak velocity	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low

Table 2-6: Recommended guidelines for shipping and continuous sounds according to Popper *et al.* (2014) for species of fish, sea turtles, and eggs and larvae (N = near-field; I = intermediate-field, F = far-field).

Popper <i>et al.</i> (2014) criteria for shipping and continuous					
Receptor	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	(N) Low	(N) Low	(N) Moderate	(N) High	(N) Moderate
	(I) Low	(I) Low	(I) Low	(I) High	(I) Moderate
	(F) Low	(F) Low	(F) Low	(F) Moderate	(F) Low
Fish: swim bladder not involved in hearing	(N) Low	(N) Low	(N) Moderate	(N) High	(N) Moderate
	(I) Low	(I) Low	(I) Low	(I) High	(I) Moderate
	(F) Low	(F) Low	(F) Low	(F) Moderate	(F) Low
Fish: swim bladder involved in hearing	(N) Low	170dB L _{p,48h}	158dB L _{p,12h}	(N) High	(N) High
	(I) Low			(I) High	(I) Moderate
	(F) Low			(F) High	(F) Low
Sea turtles	(N) Low	(N) Low	(N) Moderate	(N) High	(N) High
	(I) Low	(I) Low	(I) Low	(I) High	(I) Moderate
	(F) Low	(F) Low	(F) Low	(F) Moderate	(F) Low
Eggs and larvae	(N) Low	(N) Low	(N) Low	(N) High	(N) Moderate
	(I) Low	(I) Low	(I) Low	(I) Moderate	(I) Moderate
	(F) Low	(F) Low	(F) Low	(F) Low	(F) Low

It is important to note that despite the emerging evidence that fish are sensitive to particle motion (see section 2.2.2), the Popper *et al.* (2014) guidance defines noise impacts in terms of sound pressure or sound pressure-associated functions (i.e., L_{E,p,t}).

It has been suggested that the criteria set out by Popper *et al.* (2014) could have been derived from unmeasured particle motion, as well as sound pressure. Whilst this may be true, sound pressure remains the preferred metric in the criteria due to a lack of data surrounding particle motion (Popper and Hawkins, 2018), particularly in regarding the ability to predict the consequences of the particle motion of a noise source, and the sensitivity of fish to a specific particle motion value. Therefore, as stated by Popper and Hawkins (2019): “since there is an immediate need for updated criteria and guidelines on potential effects of anthropogenic sound on fishes, we recommend, as do our colleagues in Sweden (Andersson *et al.*, 2017), that the criteria proposed by Popper *et al.* (2014) should be used.”

2.3.3 Marine invertebrates

A review by Solé *et al.* (2023) highlights the increasing evidence that some types of anthropogenic noise can negatively impact a variety of marine invertebrate taxa. These impacts include changes in behaviour, physiology, and rate of mortality, as well as physical impairment, at the individual, population, or ecosystem level. Much of the damage from exposure to noise comes from vibration of the invertebrate body (André *et al.*, 2016) caused by the passage of sound.

Comparatively, the studies described by Solé *et al.* (2023) show a general inconsistency in the way noise impacts have been quantified for marine invertebrates. For example, Hubert *et al.* (2021) notes behavioural changes in blue mussels to 150 and 300Hz tones, whereas Spiga *et al.* (2016) describes behavioural changes in the same species at L_{E,p} (single pulse) 153.47dB re 1µPa. These inconsistencies make it difficult to generate accurate thresholds for the onset of any impact for species. A notable exception is the cephalopods group, in which several studies, mainly by Solé *et al.* (2013, 2018, 2019) and André *et al.* (2011) show a consistent threshold for auditory damage on various species of cephalopod at 157dB re 1µPa. While further research is needed even on this group to ensure accurate thresholds which are satisfactory to regulators, the current state of research on

cephalopods sets a goal for the research required for other marine invertebrate groups, if they are to be used usefully as impact thresholds.

The meta-analysis conducted by Solé *et al.* (2023) also reveals inconsistencies in the responses of taxonomically near species of marine invertebrates to the effect of anthropogenic noise. For example, Fields *et al.* (2019) demonstrates low mortality of zooplankton during seismic airguns, whereas for the same noise source, McCauley *et al.* (2017) showed mass mortality of krill larvae. Clearly, the effect of noise on one species may not necessarily be applicable on another species despite being taxonomically near, which again makes it difficult to generate a generalised impact threshold that can confidently be applied to different taxonomic groups of marine invertebrates.

In its current state, research on the effects of anthropogenic noise on marine invertebrates is emerging, but more slowly than for marine mammals and fish. At this time, this research is in too early a stage to be used to accurately generate impact thresholds which would be satisfactory to assess with sufficient level of rigour and therefore are not discussed further.

3 Modelling methodology

To estimate the underwater noise levels likely to arise during the construction and operation of Dogger Bank D, predictive noise modelling has been undertaken. The methods described in this section, and used 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).

Of those considered, the noise source most important to consider is impact piling due to the noise level and duration it will be present (Bailey *et al.*, 2014), and as such, the noise related to impact piling activity is the primary focus of this study.

The modelling of impact piling has been undertaken using the INSPIRE (Impulsive Noise Sound Propagation and Impact Range Estimator) underwater noise model, which has been widely used for wind farm assessments around the UK. The INSPIRE model (currently version 5.2) is a semi-empirical underwater noise propagation model based around a combination of numerical modelling, a combined geometric and energy flow/hysteresis loss method, and actual measured data. It is designed to calculate the propagation of noise in shallow (i.e., less than 100m), mixed water, typical of the conditions around the UK and well suited for use in the North Sea. The model has been tuned for accuracy using over 80 datasets of underwater noise propagation from monitoring around offshore piling activities.

The model provides estimates of unweighted $L_{p,pk}$, $L_{E,p,ss}$ and $L_{E,p,t}$ noise levels, as well as 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 GIS shapefiles.

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

- Piling hammer blow energies
- Soft start, hammer energy ramp up, and strike rate
- Total duration of piling, and
- Receptor swim speeds.

Simpler modelling approaches have been used for noise sources other than piling that may be present during the construction and operation of Dogger Bank D, these are discussed in section 5.

3.1 Modelling confidence

INSPIRE is semi-empirical and as such 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, either by Subacoustech or a third party, it is compared against the outputted levels from INSPIRE and, if necessary, the model can be adjusted. Currently over 80 separate impact piling noise datasets primarily from the Irish and North Sea have been used as part of the development for the latest version of INSPIRE, and in each case, an average fit is used. The largest pile diameter included in the analysis was of 9.5m, and the highest blow energy included was 3,000kJ.

INSPIRE is designed to predict trends in the effect of increasing parameters beyond empirical data, and uses the data combined with standard acoustic theory to predict the effect of blow energies, large piles and deep water.

In addition, INSPIRE is also validated by comparing the noise levels outputted from the model with measurements and modelling undertaken by third parties, for example Thompson *et al.* (2013).

The version of INSPIRE used at Dogger Bank D (version 5.2) is the product of reanalysing all the impact piling noise in Subacoustech Environmental's measurement database and any other data available and cross-referencing it with blow energy data from piling logs. This gives a database of single strike noise levels referenced to a specific blow energy at a specific range and environmental conditions, primarily water depth.

Previous iterations of the INSPIRE model have endeavoured to give a worst-case estimate of underwater noise levels produced by various permutations of impact piling parameters. There is always some natural variability with underwater noise measurements, even when considering measurements of pile strikes under the same conditions (i.e., at the same blow energy, taken at the same range). For example, there can be variations in noise level of up to five or even 10 dB, as seen in Bailey *et al.* (2010) and the data shown in Figure 3-1 and Figure 3-2. When modelling using the upper bounds of this range, in combination with other worst-case parameter selections, conservatism can be compounded to create excessively overcautious predictions, especially when calculating $L_{E,p,t}$. With this in mind, the current version of INSPIRE attempts to calculate closer to the average fit of the measured noise levels at all ranges, which maintains an additional degree of precaution in the estimation.

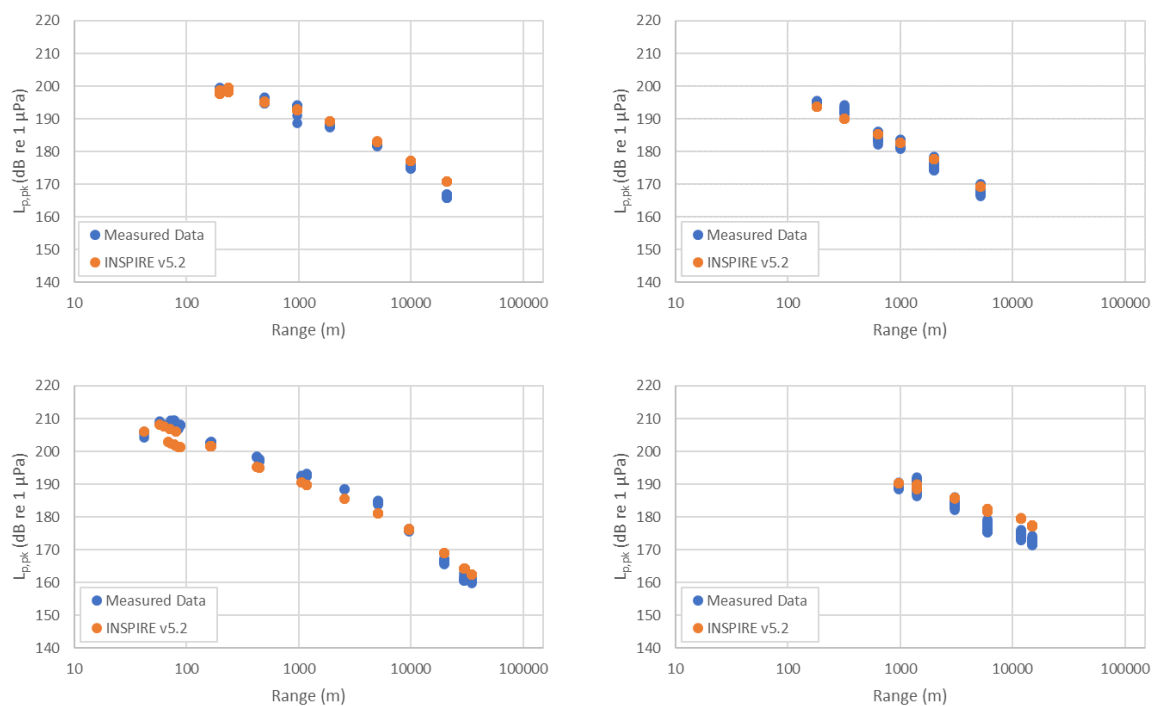


Figure 3-1: Comparison between example measured $L_{p,pk}$ impact piling data (blue points) and modelled data using INSPIRE version 5.2 (orange points)¹.

¹ Top Left: 6.0m pile, 1,010kJ max hammer energy, off the Suffolk coast, North Sea, 2009; Top Right: 1.8m pile, 260kJ max hammer energy, West of Barrow-in-Furness, Irish Sea, 2010; Bottom Left: 5.3m pile, 1,560kJ max hammer energy, off the North Welsh coast, 2012; Bottom Right: 9.5m pile, 1,600kJ max hammer energy, North Sea, 2020.

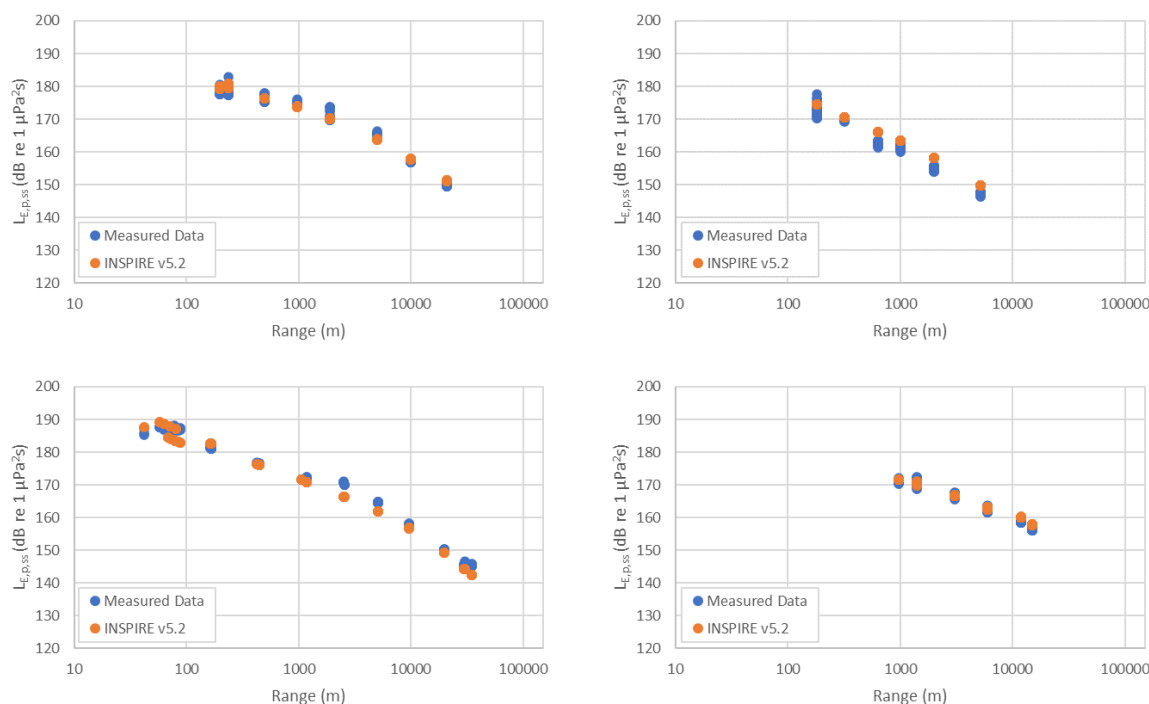


Figure 3-2: Comparison between example measured $L_{E,p,ss}$ impact piling data (blue points) and modelled data using INSPIRE version 5.2 (orange points)².

Figure 3-1 and Figure 3-2 present a small selection of the measured impact piling noise data plotted against outputs from INSPIRE. The plots show data points from measured data (in blue) plotted alongside modelled data (in orange) using INSPIRE v5.2, matching the pile size, blow energy and position of the measured data. These show the fit to the data, with the INSPIRE data points sitting, more or less, in the middle of the measured noise levels at each range. When combined with the worst-case assumptions in parameter selection, modelled results will remain precautionary.

The greatest deviations from the model tend to be at the greatest distances, where, due to the lower levels, the influence on the $L_{E,p,t}$ will be small.

Additional validation has been undertaken using data presented by von Pein *et al.* (2022), which studied trends in noise level with changes in piling parameters using data primarily acquired in the North Sea and Baltic Sea. The data showed a strong correlation with blow energy, and a lower correlation with pile diameter, which Subacoustech agrees with, although the calculated correlation based on that data appears to overestimate its trend. Figure 3-3 and Figure 3-4 are adapted from von Pein *et al.* (2022), replicating their results and overlaying with measured data from Subacoustech (selecting samples taken at the reference distance) and results at equivalent datapoints using INSPIRE v5.2.

This shows a very good agreement with Subacoustech's data (relating to blow energy), although von Pein *et al.* (2022) may overestimate the noise level at low blow energies. It should be noted that the upper and lower bounds showing a correlation of noise level with pile diameter, based on the von Pein *et al.* (2022) data alone,

² Top Left: 6.0m pile, 1,010kJ max hammer energy, off the Suffolk coast, North Sea, 2009; Top Right: 1.8m pile, 260kJ max hammer energy, West of Barrow-in-Furness, Irish Sea, 2010; Bottom Left: 5.3m pile, 1,560kJ max hammer energy, off the North Welsh coast, 2012; Bottom Right: 9.5m pile, 1,600kJ max hammer energy, North Sea, 2020.

could easily be close to horizontal; there is also no control for blow energy, which is not constant. With the inclusion of Subacoustech's data, there is little correlation at greater pile diameters, and it can be seen that the variations at a single pile diameter are largely controlled by changes in blow energy.

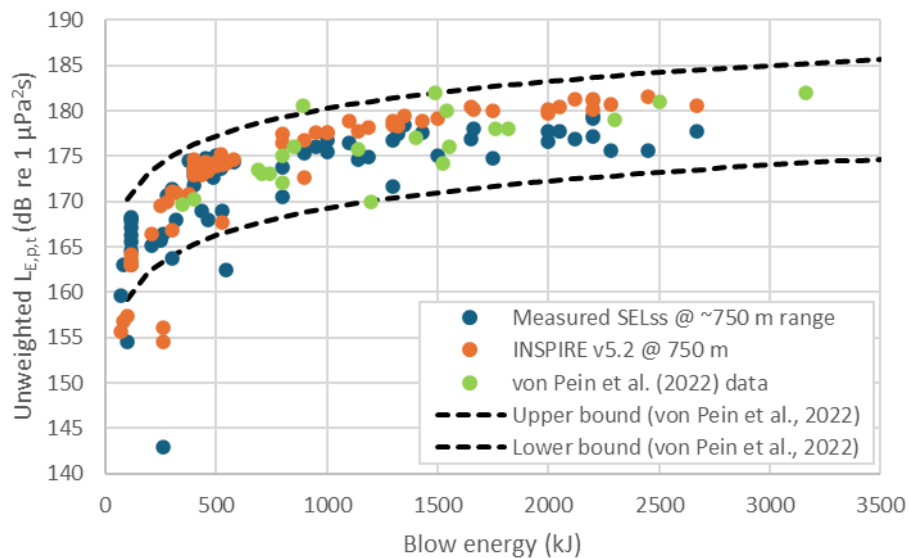


Figure 3-3: Data relating blow energy to noise level ($L_{E,p,t}$) adapted from von Pein (2022) (green) overlaid with Subacoustech measured data (blue) and INSPIRE v5.2 predictions. Upper and Lower bounds from von Pein (2022).

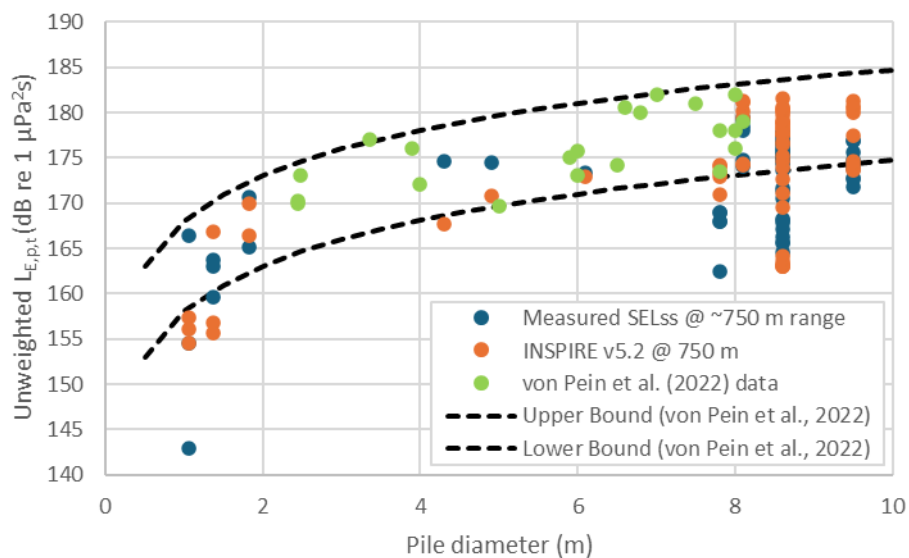


Figure 3-4: Data relating pile diameter to noise level ($L_{E,p,t}$) adapted from von Pein (2022) (green) overlaid with Subacoustech measured data (blue) and INSPIRE v5.2 predictions. Upper and Lower bounds from von Pein (2022).

3.2 Modelling parameters

3.2.1 Modelling locations

Modelling for foundation impact piling has been undertaken at four representative locations covering the extents of the Dogger Bank D site, three locations at the corners of the site give the greatest spatial variation, along with a central location for the Offshore Platform (OSP) to give a worst case spread for impacts, specifically a spread of various water depths, distances to shore and transmission into deeper water to the northwest and southeast of the array area.

These locations are summarised in Table 3-1 and illustrated in Figure 3-5.

Table 3-1: Summary of the underwater noise modelling locations used for this study.

Modelling locations	Latitude	Longitude	Water depth
NE corner	55.1186°N	003.098896°W	26.6m
NW corner	55.11828°N	002.706941°W	23.8m
SE corner	54.95485°N	003.031866°W	21.5m
Centre (OSP)	55.0593°N	002.935394°W	26.2m

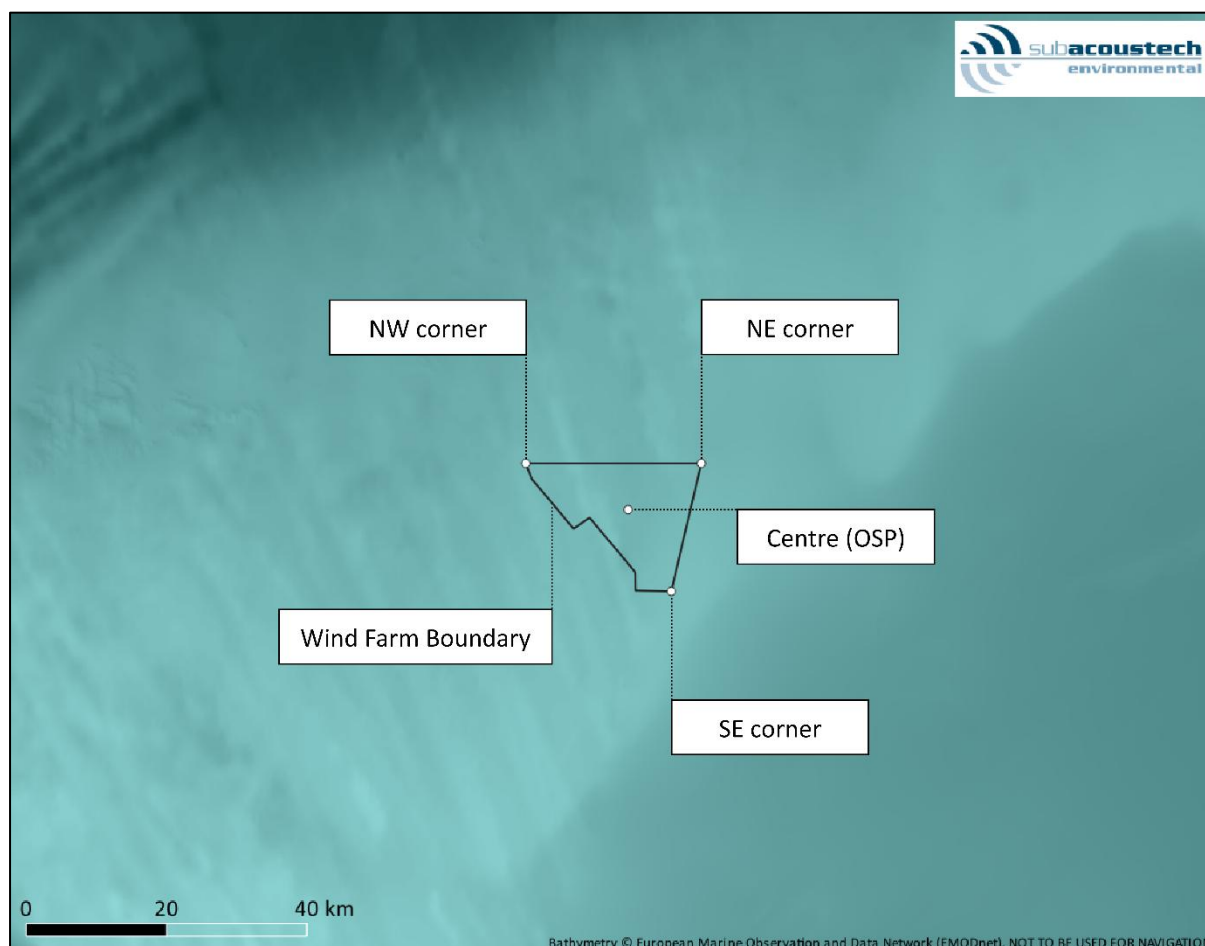


Figure 3-5: Approximate positions of the modelling locations at Dogger Bank D.

3.2.2 *Impact piling parameters*

Two foundation designs have been considered for this study:

- A monopile foundation scenario, installing an 18m diameter pile with a maximum energy of 8,000kJ, and
- A multi-leg jacket pile foundation scenario, installing 5m diameter piles with a maximum energy of 5,000kJ.

Both scenarios have been considered at the NE, NW and SE corner modelling locations; at the Centre (OSP) location only monopile foundations have been considered, as this is a single location and the worst-case scenario is covered by the monopile scenario.

For $L_{E,p,t}$ criteria, the soft start and ramp up of blow energies along with the total duration of piling and strike rate must also be considered. These are summarised for the two foundation scenarios in Table 3-2 and Table 3-3.

In a 24-hour period, it is expected that up to two monopiles or four jacket piles can be installed sequentially from the same piling vessel, which has been taken into consideration for the modelling. There is also the possibility that two piling vessels could be operational simultaneously across the Dogger Bank D array area (each installing two monopiles, totalling four per day); this has also been modelled and is considered in section 4.2. Where multiple sequential piles are modelled, no break has been assumed between each one, as a worst-case scenario.

Table 3-2: Summary of the soft start and ramp up scenario used for the monopile foundation modelling.

Monopile foundation	10% (800kJ)	Gradual ramp-up	100% (8,000kJ)
No. of strikes	600	1800	7200
Duration	20 minutes	1 hour	4 hours
Strike rate (bl/min)	30	30	30
9,600 strikes over 5 hours, 20 minutes per pile 19,200 strikes over 10 hours, 40 minutes for two piles			

Table 3-3: Summary of the soft start and ramp up scenario used for the multi-leg jacket pile foundation modelling.

Monopile foundation	10% (500kJ)	Gradual ramp-up	100% (5,000kJ)
No. of strikes	600	1800	7200
Duration	20 minutes	1 hour	4 hours
Strike rate (bl/min)	30	30	30
9,600 strikes over 5 hours, 20 minutes per pile 38,400 strikes over 21 hours, 20 minutes for four piles			

3.2.3 *Apparent source levels*

Noise modelling requires knowledge of a source level, which is the theoretical noise level at one metre from the noise source. It is worth noting that the 'source level' technically does not exist in the context of many shallow water (< 100m) noise sources (Heaney *et al.*, 2020). The noise level at one metre from the pile will be highly complex and vary up and down the water column by the pile, which is a long, extended noise source, rather than being one simple noise level. In practice, for underwater noise modelling such as this, it is effectively an

‘apparent source level’ that is used, essentially a value that can be used to produce correct noise levels at range (for a specific model), as required in impact assessments.

The INSPIRE model requires an apparent source level, which is estimated based on the pile diameter and the blow energy imparted on the pile by the hammer. This is adjusted depending on the water depth at the modelling location to allow for the length of the pile (and effective surface area) in contact with the water, which can affect the amount of noise that is transmitted from the pile into its surroundings. The unweighted, single strike $L_{p,pk}$ and $L_{E,p,ss}$ apparent source levels estimated for this study are provided in Table 3-4. These figures are presented in accordance with requests commonly made by regulatory authorities, although as indicated above, they are not necessarily compatible with any other model or predicted apparent source level. In each case, the differences in apparent source level for each location are minimal as the water depths and other noise-affecting conditions are all similar.

Table 3-4: Summary of the maximum unweighted apparent source levels used for modelling.

Source levels	Modelling location	$L_{p,pk}$ @ 1m	$L_{E,p,ss}$ @ 1m
Monopile foundation (18m diameter pile / 8,000kJ maximum energy)	NE corner	243.3dB re 1μPa @ 1m	224.6dB re 1μPa ² s @ 1m
	NW corner	243.3dB re 1μPa @ 1m	224.6dB re 1μPa ² s @ 1m
	SE corner	243.3dB re 1μPa @ 1m	224.6dB re 1μPa ² s @ 1m
	Centre (OSP)	243.3dB re 1μPa @ 1m	224.6dB re 1μPa ² s @ 1m
Multi-leg jacket pile foundations (5m diameter pile / 5,000kJ maximum energy)	NE corner	242.6dB re 1μPa @ 1m	223.7dB re 1μPa ² s @ 1m
	NW corner	242.6dB re 1μPa @ 1m	223.6dB re 1μPa ² s @ 1m
	SE corner	242.6dB re 1μPa @ 1m	223.6dB re 1μPa ² s @ 1m

3.2.4 Predicted noise levels at 750m from the noise source

In addition to the apparent source levels given in the previous section, it is useful to look at the potential noise levels at a range of 750m from the noise source, which is a common feature of underwater noise studies for where the primary consideration is impact piling. This has the added advantage of being comparable with other modelling or measurements, where the source level (or apparent source level) may not. A summary of the modelled unweighted levels at a range of 750m, are given in Table 3-5 considering the transect with the greatest noise transmission at each location while piling at the maximum hammer blow energy.

Table 3-5: Summary of the maximum predicted $L_{p,pk}$ and $L_{E,p,ss}$ (single strike) noise levels at a range of 750 m from the noise source when considering the maximum hammer blow energy.

Predicted levels at 750 m range	Modelling location	$L_{p,pk}$ @ 750m	$L_{E,p,ss}$ @ 750m
Monopile foundation (18 m diameter pile / 8,000 kJ maximum energy)	NE corner	201.5dB re 1μPa	182.9dB re 1μPa ² s
	NW corner	201.1dB re 1μPa	182.5dB re 1μPa ² s
	SE corner	200.6dB re 1μPa	182.0dB re 1μPa ² s
	Centre (OSP)	201.5dB re 1μPa	182.9dB re 1μPa ² s
Multi-leg jacket pile foundations (5 m diameter pile / 5,000 kJ maximum energy)	NE corner	200.8dB re 1μPa	181.9dB re 1μPa ² s
	NW corner	200.4dB re 1μPa	181.5dB re 1μPa ² s
	SE corner	199.8dB re 1μPa	181.0dB re 1μPa ² s

3.2.5 Predicted noise levels against range

Figure 3-6 presents the predicted unweighted $L_{p,pk}$ and $L_{E,p,ss}$ noise levels from the modelled NE location during the maximum blow energy of the monopile scenario (18m diameter pile, 8,000kJ blow energy), against range, over the longest calculated transect: 324° (NW). This is provided on regulatory request. This plot has been presented in order to show the noise transmission, which can be used as a basis to compare and validate the

levels against any future noise monitoring. It should not be assumed necessarily comparable to any other transect or blow energy.

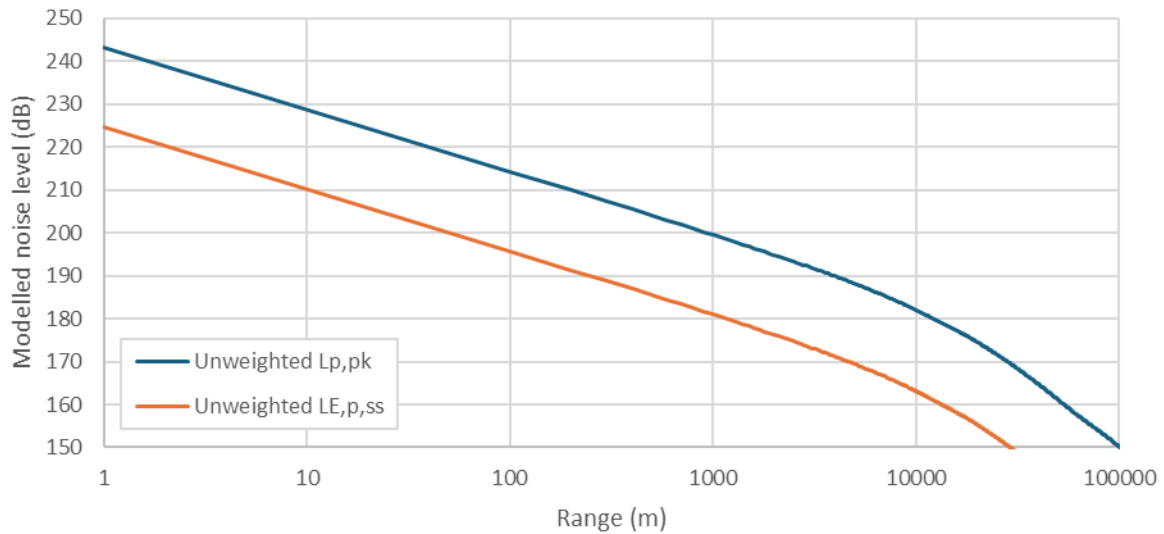


Figure 3-6: Modelled unweighted $L_{p,pk}$ and $L_{E,p,ss}$ noise levels with range for the maximum monopile blow energy from the NE corner along a 324° transect.

3.2.6 Environmental conditions

With the inclusion of measured noise propagation data for similar offshore piling operations in UK waters, the INSPIRE model intrinsically accounts for various environmental conditions. This includes the differences that can occur with the temperature and salinity of the water, as well as the sediment type in and around the site. Data from the British Geological Survey (BGS) show that the seabed in and around Dogger Bank D is generally made up of various combinations of sand and gravelly sand.

Digital bathymetry from the European Marine Observation and Data Network (EMODnet) has been used for this modelling. Mean tidal depth has been assumed throughout.

3.3 $L_{E,p,t}$ and fleeing receptors

Expanding on the information contained in section 2.3 regarding $L_{E,p,t}$ and the fleeing animal assumptions used for modelling, it is important to understand the meaning of the results presented in the following sections.

When an $L_{E,p,t}$ impact range is presented for a fleeing animal, this range can be considered a starting position (at the commencement of piling) for the fleeing receptor. For example, if a receptor began to flee in a straight line from the noise source, starting at the position (distance from a pile) denoted by a modelled PTS contour, the receptor would receive exactly the noise exposure as per the PTS onset criterion under consideration.

When considering a stationary receptor (i.e., one that stays at the same position throughout piling, with no flee response), calculating the $L_{E,p,t}$ is straightforward: all the noise levels produced and received at a single point along a transect are aggregated to calculate the $L_{E,p,t}$. If this calculated level is greater than the threshold being modelled, the model steps away from the noise source and the noise levels from that new location are aggregated to calculate a new $L_{E,p,t}$. This continues outward until the threshold is met.

For a fleeing animal, the receptor's distance from the noise source while moving away also needs to be considered. To model this, a starting point close to the source is chosen and the received noise level for each noise event (e.g., pile strike) is noted; the receptor moves away from the source at a defined speed. For example, if a noise event (i.e., a pulse from a pile strike) occurs every six seconds, and an animal is fleeing at a rate of 1.5m/s, it is 9m further from the source after each noise pulse, resulting in a slightly reduced noise level each time. These values are then aggregated into an $L_{E,p,t}$ value over the entire operation. The faster an animal is fleeing, the greater the distance travelled between noise events. The impact range outputted by the model for this situation is the distance the receptor must be at the start of the operation to exactly meet the exposure threshold.

As an example, the graphs Figure 3-7 and Figure 3-8 show the difference in the received $L_{E,p,t}$ from a stationary receptor and a fleeing receptor travelling at a constant speed of 1.5m/s, using the monopile foundation scenario at the NE corner for a single pile installation.

The received single strike $L_{E,p,ss}$ from the stationary receptor, as illustrated in Figure 3-7, shows the noise level gradually increasing as the blow energy increases throughout the piling operation. These step changes are also visible for the fleeing receptor, but as the receptor is further from the noise source by the time the levels increase, the total received exposure reduces, resulting in progressively lower received noise levels. As an example, for the first 20 minutes of piling, where the blow energy for the monopile is 800kJ (10% of maximum energy), fleeing at a rate of 1.5m/s, a receptor has the potential to move 1.8km from the noise source. After the full installation or just 5 hours 20 minutes, the receptor has the potential to be over 28km from the noise source.

Figure 3-8 shows the effect these different received levels have when calculating the $L_{E,p,t}$, clearly showing the difference in the cumulative levels between a receptor remaining still, as opposed to fleeing. To use an extreme example, starting at a range of 1m, the first strike results in a received level of 218.2dB re $1\mu\text{Pa}^2\text{s}$. If the receptor were to remain stationary throughout the piling operation, it would receive a cumulative level of 264.0dB re $1\mu\text{Pa}^2\text{s}$, whereas when fleeing at 1.5m/s over the same scenario, a cumulative received level of just 220.0dB re $1\mu\text{Pa}^2\text{s}$ is achieved.

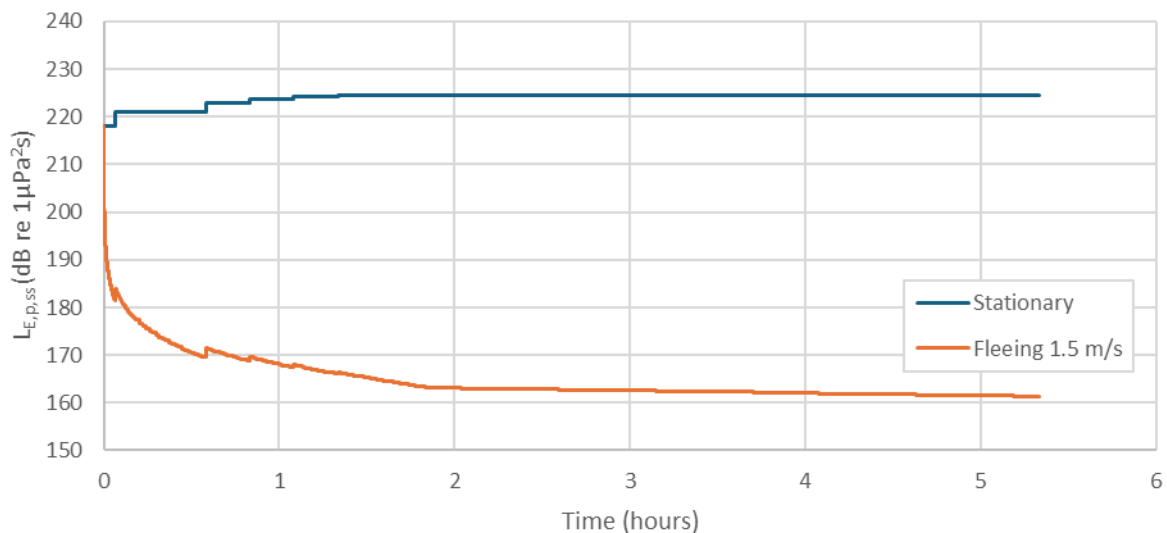


Figure 3-7 Received single strike noise levels ($L_{E,p,ss}$) for receptors during the monopile foundation installation at the NE corner, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source.

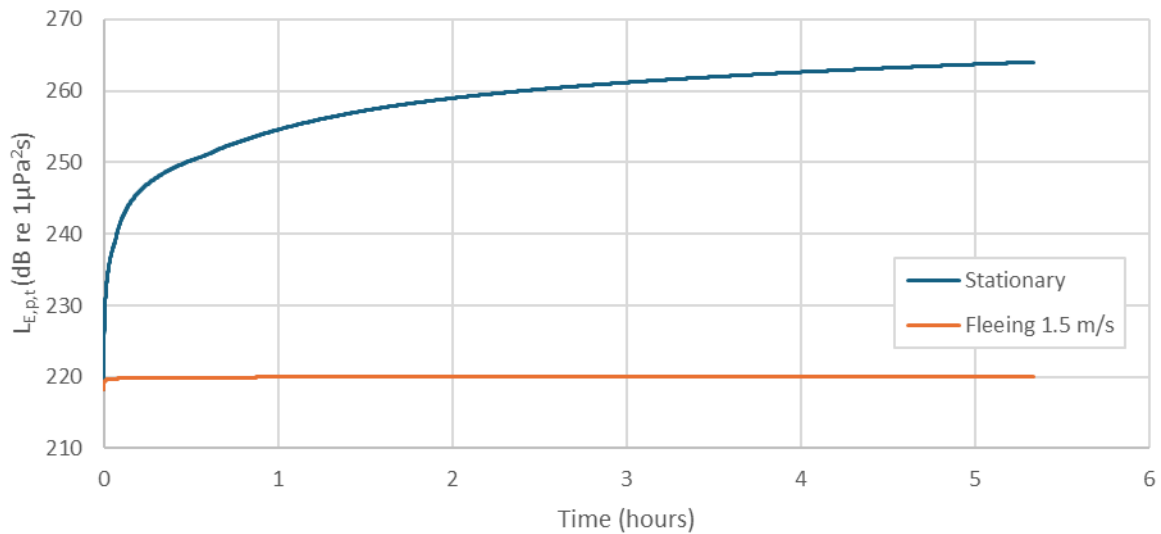


Figure 3-8 Cumulative received noise level ($L_{E,p,t}$) for receptors during monopile foundation installation at the NE corner, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source.

To summarise, if the receptor were to start fleeing in a straight line from the noise source starting at a range closer than the modelled value, it would receive a noise exposure in excess of the criterion, and if the receptor were to start fleeing from a range further than the modelled value, it would receive a noise exposure below the criterion. This is illustrated in Figure 3-9.

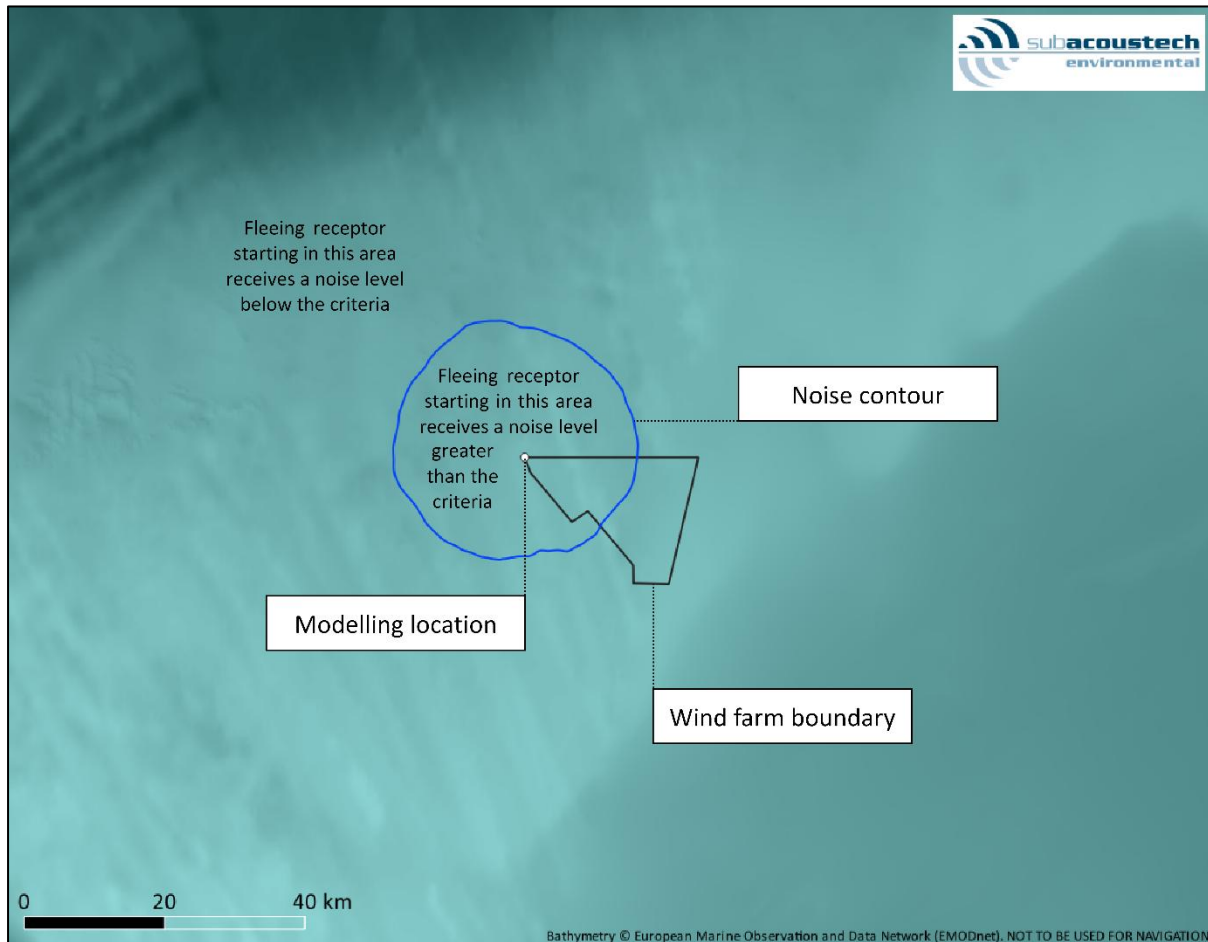


Figure 3-9: Example plot showing a fleeing animal $L_{E,p,t}$ criteria contour and the areas where the cumulative noise exposure will exceed an impact criteria.

Some modelling approaches include the effects of Acoustic Deterrent Devices (ADDs) that cause receptors to flee from the immediate area around the pile before activity commences. Subacoustech Environmental's approach does not include this, however the efficacy of using an ADD can still be inferred from the results. For example, if a receptor were to flee for 20 minutes from an ADD at a rate of 1.5m/s, it would travel 1.8km before piling begins. If a calculated cumulative $L_{E,p,t}$ impact range was below 1.8km, it can be assumed that the ADD will be effective in eliminating the risk of exceedance of the threshold. The noise from an ADD is of a much lower level than impact piling, and as such its effect on the total $L_{E,p,t}$ exposure would be minimal.

3.3.1 The effects of input parameters on $L_{E,p,t}$ and fleeing receptors

As discussed in section 3.2.2, parameters such as bathymetry, hammer blow energies, piling ramp up, strike rate and duration all have an effect on predicted noise levels. When considering $L_{E,p,t}$ and a fleeing animal model, some of these parameters can have a greater influence on the predicted noise levels than others.

Parameters like hammer blow energy can have a clear effect on the impact ranges, with higher energies resulting in high apparent source noise levels and therefore larger impact ranges. When considering cumulative noise levels, these higher levels are compounded, sometimes thousands of times, due to the number of pile strikes. With this in mind, the ramp up from lower to higher blow energies requires careful consideration for fleeing receptors, as levels while the receptor is closer to the noise source will have a greater effect on the overall cumulative exposure level.

Linked to the effect of the ramp up is the strike rate, as the more pile strikes that occur while the receptor is close to the noise source, the greater the exposure and the greater effect it will have to the $L_{E,p,t}$. The faster the strike rate, the shorter the distance the receptor can flee between each pile strike, which leads to a greater exposure overall.

In general, the greatest contribution to the receptors' exposure is found when it is close to the noise source. If high blow energies or a fast strike rate are implemented at the start of piling activities, it will tend to make impact ranges worse.

Another factor that can cause big differences in calculated impact ranges is the bathymetry, as deeper water results in a slower attenuation of noise (i.e., levels remain higher for greater distances). However, it is not always feasible to limit piling activity in or near to deep water.

3.4 Precaution in underwater noise modelling

It is worth reiterating the precaution that is included in the modelling when calculating environmental impacts. In an effort to minimise the risk of under-prediction for the potential impact ranges that occur in respect of sensitive marine mammal and fish receptors, conservative parameters are included for every element, which can be broken down into three basic steps for acoustic modelling. The possibility that the worst-case conservative parameters could all occur together is highly unlikely, but necessary for the purposes of the assessment.

3.4.1 Source

The modelling locations were chosen to provide the greatest extents of the site, and specifically the locations likely to lead to maximum underwater noise transmission. The largest diameter for all types of piles has been used for the worst case. The maximum blow energies were used for a duration unlikely to occur in practice. A fast strike rate has been included for much of the ramp-up. The total piling duration is at the top of expectations and not expected to be exceeded on site.

3.4.2 Transmission

Sound attenuates over distance from the source. The model considers fundamental noise spreading predictions adjusted to empirical data, accounting for frequency content, water depth, and other environmental factors, but fits to this data still err on the side of caution.

3.4.3 Receiver

The thresholds used for the sensitivity of marine mammals and fish are based on respective guidance for species groups (e.g., Southall *et al.*, 2019; Popper *et al.*, 2014). However, these tend to be precautionary in themselves. Frequency specific hearing thresholds are not used for fish as they are with marine mammals, effectively assuming that fish are sensitive to sound at all frequencies, which is not the case. The thresholds calculated for PTS and TTS are the 'onset' to these effects for both fish and marine mammals, which means that this is the threshold at which the effect starts to be detected in test species, rather than where this effect is widespread.

4 Modelling results

This section presents the modelled impact ranges from impact piling noise at Dogger Bank D following the parameters detailed in section 3.2, covering the Southall *et al.* (2019) marine mammal criteria (section 2.3.1), and the Popper *et al.* (2014) fish criteria (section 2.3.2). To aid navigation, Table 4-1 consists of a list of the modelling results tables included in section 4.1. Modelling covering concurrent piling at multiple locations is covered in section 4.2.

Throughout this report, any predicted ranges smaller than 0.05km and areas less than 0.01km² for single strike criteria and ranges smaller than 0.1km and areas less than 0.1km² for cumulative criteria have not been presented in detail. At ranges this close to the noise source, the modelling processes are unable to model to a sufficient level of accuracy due to complex acoustic effects present near the source. These ranges are given as “less than” this limit (e.g., < 0.1km).

Additionally, the modelling results for the Southall *et al.* (2019) non-impulsive criteria are presented in Appendix A.

Table 4-1 Summary of the single location impact piling modelling results presented in section 4.1.

Table (page)	Parameters (section)		Criteria	
Table 4-2 (p32)	NE corner (4.1.1)	Monopile (4.1.1.1)	Southall <i>et al.</i> (2019)	L _{p,pk} (Impulsive)
Table 4-3 (p32)				L _{E,p,24h,wtd} (Impulsive)
Table 4-4 (p32)			Popper <i>et al.</i> (2014)	L _{p,pk} (Pile driving)
Table 4-5 (p33)				L _{E,p,24h} (Pile driving)
Table 4-6 (p33)		Jacket pile (4.1.1.2)	Southall <i>et al.</i> (2019)	L _{p,pk} (Impulsive)
Table 4-7 (p33)				L _{E,p,24h,wtd} (Impulsive)
Table 4-8 (p34)			Popper <i>et al.</i> (2014)	L _{p,pk} (Pile driving)
Table 4-9 (p34)				L _{E,p,24h} (Pile driving)
Table 4-10 (p34)	NW corner (4.1.2)	Monopile (4.1.2.1)	Southall <i>et al.</i> (2019)	L _{p,pk} (Impulsive)
Table 4-11 (p35)				L _{E,p,24h,wtd} (Impulsive)
Table 4-12 (p35)			Popper <i>et al.</i> (2014)	L _{p,pk} (Pile driving)
Table 4-13 (p35)				L _{E,p,24h} (Pile driving)
Table 4-14 (p36)		Jacket pile (4.1.2.2)	Southall <i>et al.</i> (2019)	L _{p,pk} (Impulsive)
Table 4-15 (p36)				L _{E,p,24h,wtd} (Impulsive)
Table 4-16 (p36)			Popper <i>et al.</i> (2014)	L _{p,pk} (Pile driving)
Table 4-17 (p37)				L _{E,p,24h} (Pile driving)
Table 4-18 (p37)	SE corner (4.1.3)	Monopile (4.1.3.1)	Southall <i>et al.</i> (2019)	L _{p,pk} (Impulsive)
Table 4-19 (p37)				L _{E,p,24h,wtd} (Impulsive)
Table 4-20 (p38)			Popper <i>et al.</i> (2014)	L _{p,pk} (Pile driving)
Table 4-21 (p38)				L _{E,p,24h} (Pile driving)
Table 4-22 (p38)		Jacket pile (4.1.3.2)	Southall <i>et al.</i> (2019)	L _{p,pk} (Impulsive)
Table 4-23 (p39)				L _{E,p,24h,wtd} (Impulsive)
Table 4-24 (p39)			Popper <i>et al.</i> (2014)	L _{p,pk} (Pile driving)
Table 4-25 (p39)				L _{E,p,24h} (Pile driving)
Table 4-26 (p40)	Centre (OSP) (4.1.4)	Monopile (4.1.4.1)	Southall <i>et al.</i> (2019)	L _{p,pk} (Impulsive)
Table 4-27 (p40)				L _{E,p,24h,wtd} (Impulsive)
Table 4-28 (p40)			Popper <i>et al.</i> (2014)	L _{p,pk} (Pile driving)
Table 4-29 (p41)				L _{E,p,24h} (Pile driving)

4.1 Single location modelling

Table 4-2 to Table 4-29 present the modelling results for the single location scenarios, covering monopile and jacket pile foundation scenarios, for these scenarios, the largest marine mammal impact ranges are predicted for the monopile foundation scenario. Maximum marine mammal PTS ranges are predicted for LF cetaceans out to 9.5km, reducing to <100m with the non-impulsive criteria. For fish, the largest recoverable injury ranges (203dB $L_{E,p,24h}$) are predicted out to 12km when considering a stationary receptor, reducing to 350m when a fleeing animal is assumed.

4.1.1 NE corner

4.1.1.1 Monopile foundations

Table 4-2: Summary of the unweighted $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum blow energy used during monopile foundation modelling at the NE corner modelling location.

Southall et al. (2019) Unweighted $L_{p,pk}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219dB)	0.01km ²	< 0.05km	< 0.05km	< 0.05km
	HF (230dB)	< 0.01km ²	< 0.05km	< 0.05km	< 0.05km
	VHF (202dB)	1.5km ²	0.69km	0.69km	0.69km
	PCW (218dB)	0.01km ²	0.06km	0.06km	0.06km
TTS (Impulsive)	LF (213dB)	0.05km ²	0.13km	0.12km	0.13km
	HF (224dB)	< 0.01km ²	< 0.05km	< 0.05km	< 0.05km
	VHF (196dB)	9.1km ²	1.7km	1.7km	1.7km
	PCW (212dB)	0.07km ²	0.15 km	0.15km	0.15km

Table 4-3: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the monopile foundation modelling for two sequentially installed piles at the NE corner modelling location.

Southall et al. (2019) Weighted $L_{E,p,t}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183dB)	220km ²	9.1km	7.2km	8.5km
	HF (185dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (155dB)	140km ²	7km	5.9km	6.6km
	PCW (185dB)	1.6km ²	0.73km	0.68km	0.71km
TTS (Impulsive)	LF (168dB)	4,500km ²	45km	27km	38km
	HF (170dB)	0.92km ²	0.58km	0.53km	0.54km
	VHF (140dB)	2,900km ²	35km	24km	30km
	PCW (170dB)	900km ²	19km	14km	17km

Table 4-4 Summary of the unweighted $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum blow energy used during monopile foundation modelling at the NE corner modelling location.

Popper et al. (2014) $L_{p,pk}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213dB	0.05km ²	0.13km	0.12km	0.13km
	207dB	0.32km ²	0.32km	0.32km	0.32km

Table 4-5 Summary of the unweighted $L_{E,p,24h}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the monopile foundation modelling for two sequentially installed piles at the NE corner modelling location, assuming both fleeing and stationary animals.

Popper et al. (2014) $L_{E,p,24h}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	216dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	210dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	207dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	203dB	0.22km ²	0.28km	0.25km	0.26km
	186dB	540km ²	14km	12km	13km
Stationary (0 m/s)	219dB	2.5km ²	0.9km	0.88km	0.89km
	216dB	5.9km ²	1.4km	1.4km	1.4km
	210dB	32km ²	3.2km	3.2km	3.2km
	207dB	69km ²	4.8km	4.6km	4.7km
	203dB	170km ²	7.7km	7.3km	7.5km
	186dB	2,900km ²	33km	26km	30km

4.1.1.2 Jacket pile foundations

Table 4-6: Summary of the unweighted $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum blow energy used during jacket pile foundation modelling at the NE corner modelling location.

Southall et al. (2019) Unweighted $L_{p,pk}$		Jacket pile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219dB)	0.01km ²	< 0.05km	< 0.05km	< 0.05km
	HF (230dB)	< 0.01km ²	< 0.05km	< 0.05km	< 0.05km
	VHF (202dB)	1.2km ²	0.63km	0.62km	0.62km
	PCW (218dB)	0.01km ²	0.05km	0.05km	0.05km
TTS (Impulsive)	LF (213dB)	0.04km ²	0.11km	0.11km	0.11km
	HF (224dB)	< 0.01km ²	< 0.05km	< 0.05km	< 0.05km
	VHF (196dB)	7.4km ²	1.6km	1.5km	1.5km
	PCW (212dB)	0.05km ²	0.13km	0.13km	0.13km

Table 4-7: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the jacket pile foundation modelling for four sequentially installed piles at the NE corner modelling location.

Southall et al. (2019) Weighted $L_{E,p,t}$		Jacket pile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183dB)	130km ²	7.0km	5.4km	6.5km
	HF (185dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (155dB)	91km ²	5.8km	4.9km	5.4km
	PCW (185dB)	0.53km ²	0.43km	0.4km	0.41km
TTS (Impulsive)	LF (168dB)	3,800km ²	42km	25km	35km
	HF (170dB)	0.24km ²	0.3km	0.25km	0.28km
	VHF (140dB)	2,600km ²	33km	22km	28km
	PCW (170dB)	800km ²	18km	13km	16km

Table 4-8 Summary of the unweighted $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum blow energy used during jacket pile foundation modelling at the NE corner modelling location.

Popper et al. (2014) $L_{p,pk}$		Jacket pile foundation			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213dB	0.04km ²	0.11km	0.11km	0.11km
	207dB	0.26km ²	0.29km	0.29km	0.29km

Table 4-9 Summary of the unweighted $L_{E,p,24h}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the jacket pile foundation modelling for four sequentially installed piles at the NE corner modelling location, assuming both fleeing and stationary animals.

Popper et al. (2014) $L_{E,p,24h}$		Jacket pile foundation			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	216dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	210dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	207dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	203dB	< 0.1km ²	0.15km	0.13km	0.13km
	186dB	770km ²	17km	13km	16km
Stationary (0 m/s)	219dB	8.6km ²	1.7km	1.7km	1.7km
	216dB	20km ²	2.6km	2.5km	2.5km
	210dB	94km ²	5.6km	5.4km	5.5km
	207dB	190km ²	8km	7.6km	7.7km
	203dB	420km ²	12km	11km	12km
	186dB	4,800km ²	43km	33km	39km

4.1.2 NW corner

4.1.2.1 Monopile foundations

Table 4-10: Summary of the unweighted $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum blow energy used during monopile foundation modelling at the NW corner modelling location.

Southall et al. (2019) Unweighted $L_{p,pk}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219dB)	0.01km ²	< 0.05km	< 0.05km	< 0.05km
	HF (230dB)	< 0.01km ²	< 0.05km	< 0.05km	< 0.05km
	VHF (202dB)	1.3km ²	0.65km	0.65km	0.65km
	PCW (218dB)	0.01km ²	0.06km	0.05km	0.06km
TTS (Impulsive)	LF (213dB)	0.04km ²	0.12km	0.12km	0.12km
	HF (224dB)	< 0.01km ²	< 0.05km	< 0.05km	< 0.05km
	VHF (196dB)	7.9km ²	1.6km	1.6km	1.6km
	PCW (212dB)	0.06km ²	0.14km	0.14km	0.14km

Table 4-11: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the monopile foundation modelling for two sequentially installed piles at the NW corner modelling location.

Southall et al. (2019) Weighted $L_{E,p,t}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183dB)	200km ²	9.5km	6.4km	7.9km
	HF (185dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (155dB)	120km ²	6.9km	5.4km	6.2km
	PCW (185dB)	1km ²	0.6km	0.55km	0.57km
TTS (Impulsive)	LF (168dB)	4,200km ²	54km	23km	36km
	HF (170dB)	0.67km ²	0.5km	0.45km	0.46km
	VHF (140dB)	2,700km ²	38km	23km	29km
	PCW (170dB)	820km ²	19km	13km	16km

Table 4-12 Summary of the unweighted $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum blow energy used during monopile foundation modelling at the NW corner modelling location.

Popper et al. (2014) $L_{p,pk}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213dB	0.04 km ²	0.12km	0.12km	0.12km
	207dB	0.28 km ²	0.3km	0.3km	0.3km

Table 4-13 Summary of the unweighted $L_{E,p,24h}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the monopile foundation modelling for two sequentially installed piles at the NW corner modelling location, assuming both fleeing and stationary animals.

Popper et al. (2014) $L_{E,p,24h}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	216dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	210dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	207dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	203dB	0.26km ²	0.33km	0.28km	0.29km
	186dB	920km ²	21km	14km	17km
Stationary (0 m/s)	219dB	4.3km ²	1.2km	1.2km	1.2km
	216dB	10km ²	1.8km	1.8km	1.8km
	210dB	51km ²	4.1km	4km	4km
	207dB	110km ²	6km	5.7km	5.9km
	203dB	260km ²	9.4km	8.7km	9.1km
	186dB	3,600km ²	39km	28km	34km

4.1.2.2 Jacket pile foundations

Table 4-14: Summary of the unweighted $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum blow energy used during jacket pile foundation modelling at the NW corner modelling location.

Southall et al. (2019) Unweighted $L_{p,pk}$		Jacket pile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219dB)	0.01km ²	< 0.05km	< 0.05km	< 0.05km
	HF (230dB)	< 0.01km ²	< 0.05km	< 0.05km	< 0.05km
	VHF (202dB)	1.1km ²	0.59km	0.58km	0.59km
	PCW (218dB)	0.01km ²	0.05km	< 0.05km	0.05km
TTS (Impulsive)	LF (213dB)	0.04km ²	0.11km	0.11km	0.11km
	HF (224dB)	< 0.01km ²	< 0.05km	< 0.05km	< 0.05km
	VHF (196dB)	6.5km ²	1.4km	1.4km	1.4km
	PCW (212dB)	0.05km ²	0.13km	0.12km	0.13km

Table 4-15: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the jacket pile foundation modelling for four sequentially installed piles at the NW corner modelling location.

Southall et al. (2019) Weighted $L_{E,p,t}$		Jacket pile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	HF (185dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (155dB)	80km ²	5.7km	4.3km	5.1km
	PCW (185dB)	0.32km ²	0.35km	0.3km	0.32km
TTS (Impulsive)	LF (168dB)	690km ²	29km	5.4km	14km
	HF (170dB)	0.17km ²	0.25km	0.23km	0.24km
	VHF (140dB)	2,400km ²	36km	21km	28km
	PCW (170dB)	730km ²	18km	12km	15km

Table 4-16 Summary of the unweighted $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum blow energy used during jacket pile foundation modelling at the NW corner modelling location.

Popper et al. (2014) $L_{p,pk}$		Jacket pile foundation			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213dB	0.04km ²	0.11km	0.11km	0.11km
	207dB	0.23km ²	0.27km	0.27km	0.27km

Table 4-17 Summary of the unweighted $L_{E,p,24h}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the jacket pile foundation modelling for four sequentially installed piles at the NW corner modelling location, assuming both fleeing and stationary animals.

Popper et al. (2014) $L_{E,p,24h}$		Jacket pile foundation			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	216dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	210dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	207dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	203dB	< 0.1km ²	0.13km	0.10km	0.11km
	186dB	710km ²	18km	12km	15km
Stationary (0 m/s)	219dB	7.6km ²	1.6km	1.5km	1.6km
	216dB	17km ²	2.4km	2.3km	2.4km
	210dB	83km ²	5.3km	5.1km	5.2km
	207dB	170km ²	7.5km	7.1km	7.3km
	203dB	380km ²	12km	10km	11km
	186dB	4,500km ²	44km	31km	38km

4.1.3 SE corner

4.1.3.1 Monopile foundations

Table 4-18: Summary of the unweighted $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum blow energy used during monopile foundation modelling at the SE corner modelling location.

Southall et al. (2019) Unweighted $L_{p,pk}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219dB)	0.01km ²	< 0.05km	< 0.05km	< 0.05km
	HF (230dB)	< 0.01km ²	< 0.05km	< 0.05km	< 0.05km
	VHF (202dB)	1.1km ²	0.61km	0.6km	0.6km
	PCW (218dB)	0.01km ²	0.05km	0.05km	0.05km
TTS (Impulsive)	LF (213dB)	0.04km ²	0.11km	0.11km	0.11km
	HF (224dB)	< 0.01km ²	< 0.05km	< 0.05km	< 0.05km
	VHF (196dB)	6.6km ²	1.5km	1.4km	1.5km
	PCW (212dB)	0.05km ²	0.13km	0.13km	0.13km

Table 4-19: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the monopile foundation modelling for two sequentially installed piles at the SE corner modelling location.

Southall et al. (2019) Weighted $L_{E,p,t}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183dB)	130km ²	7.6km	5.3km	6.3km
	HF (185dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (155dB)	80km ²	5.6km	4.5km	5km
	PCW (185dB)	0.51km ²	0.43km	0.38km	0.4km
TTS (Impulsive)	LF (168dB)	3,500km ²	44km	23km	33km
	HF (170dB)	0.4km ²	0.38km	0.35km	0.36km
	VHF (140dB)	2,300km ²	34km	20km	27km
	PCW (170dB)	570km ²	17km	11km	13km

Table 4-20 Summary of the unweighted $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum blow energy used during monopile foundation modelling at the SE corner modelling location.

Popper et al. (2014) $L_{p,pk}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213dB	0.04km ²	0.11km	0.11km	0.11km
	207dB	0.25km ²	0.28km	0.28km	0.28km

Table 4-21 Summary of the unweighted $L_{E,p,24h}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the monopile foundation modelling for two sequentially installed piles at the SE corner modelling location. assuming both fleeing and stationary animals.

Popper et al. (2014) $L_{E,p,24h}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	216dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	210dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	207dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	203dB	0.14km ²	0.2km	0.2km	0.21km
	186dB	680km ²	18km	12km	15km
Stationary (0 m/s)	219dB	3.7km ²	1.1km	1.1km	1.1km
	216dB	8.5km ²	1.7km	1.6km	1.6km
	210dB	41km ²	3.7km	3.6km	3.6km
	207dB	84km ²	5.3km	5.1km	5.2km
	203dB	200km ²	8.3km	7.8km	8km
	186dB	3,100km ²	37km	26km	31km

4.1.3.2 Jacket pile foundations

Table 4-22: Summary of the unweighted $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum blow energy used during jacket pile foundation modelling at the SE corner modelling location.

Southall et al. (2019) Unweighted $L_{p,pk}$		Jacket pile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219dB)	0.01km ²	< 0.05km	< 0.05km	< 0.05km
	HF (230dB)	< 0.01km ²	< 0.05km	< 0.05km	< 0.05km
	VHF (202dB)	0.92km ²	0.54km	0.54km	0.54km
	PCW (218dB)	0.01km ²	< 0.05km	< 0.05km	< 0.05km
TTS (Impulsive)	LF (213dB)	0.03km ²	0.1km	0.1km	0.1km
	HF (224dB)	< 0.01km ²	< 0.05km	< 0.05km	< 0.05km
	VHF (196dB)	5.4km ²	1.3km	1.3km	1.3km
	PCW (212dB)	0.04km ²	0.12km	0.12km	0.12km

Table 4-23: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the jacket pile foundation modelling for four sequentially installed piles at the SE corner modelling location.

Southall et al. (2019) Weighted $L_{E,p,t}$		Jacket pile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	HF (185dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (155dB)	50km ²	4.5km	3.6km	4km
	PCW (185dB)	0.16km ²	0.25km	0.20km	0.22km
TTS (Impulsive)	LF (168dB)	430km ²	20km	3.5km	11km
	HF (170dB)	0.11km ²	0.2km	0.18km	0.19km
	VHF (140dB)	2,000km ²	32km	19km	25km
	PCW (170dB)	500km ²	15km	10km	12km

Table 4-24 Summary of the unweighted $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum blow energy used during jacket pile foundation modelling at the SE corner modelling location.

Popper et al. (2014) $L_{p,pk}$		Jacket pile foundation			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213dB	0.03km ²	0.1km	0.1km	0.1km
	207dB	0.2km ²	0.26km	0.25km	0.25km

Table 4-25 Summary of the unweighted $L_{E,p,24h}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria covering the jacket pile foundation modelling for four sequentially installed piles at the SE corner modelling location. assuming both fleeing and stationary animals.

Popper et al. (2014) $L_{E,p,24h}$		Jacket pile foundation			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	216dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	210dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	207dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	203dB	< 0.1km ²	0.1km	< 0.1km	< 0.1km
	186dB	510km ²	16km	10km	13km
Stationary (0 m/s)	219dB	6.3km ²	1.5km	1.4km	1.4km
	216dB	14km ²	2.2km	2.1km	2.1km
	210dB	66km ²	4.7km	4.6km	4.6km
	207dB	130km ²	6.6km	6.3km	6.4km
	203dB	300km ²	10km	9.3km	9.7km
	186dB	3,900km ²	42km	29km	35km

4.1.4 Centre (OSP)

4.1.4.1 Monopile foundations

Table 4-26: Summary of the unweighted $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum blow energy used during monopile foundation modelling at the Centre (OSP) modelling location.

Southall et al. (2019) Unweighted $L_{p,pk}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219dB)	0.01km ²	< 0.05km	< 0.05km	< 0.05km
	HF (230dB)	< 0.01km ²	< 0.05km	< 0.05km	< 0.05km
	VHF (202dB)	1.5km ²	0.69km	0.69km	0.69km
	PCW (218dB)	0.01km ²	0.06km	0.06km	0.06km
TTS (Impulsive)	LF (213dB)	0.05km ²	0.13km	0.12km	0.12km
	HF (224dB)	< 0.01km ²	< 0.05km	< 0.05km	< 0.05km
	VHF (196dB)	9.0km ²	1.7km	1.7km	1.7km
	PCW (212dB)	0.07km ²	0.15km	0.14km	0.15km

Table 4-27: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria covering the monopile foundation modelling for two sequentially installed piles at the Centre (OSP) modelling location.

Southall et al. (2019) Weighted $L_{E,p,t}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183dB)	200km ²	9.5km	6.8km	7.9km
	HF (185dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (155dB)	120km ²	7.2km	5.6km	6.2km
	PCW (185dB)	1.4km ²	0.73km	0.63km	0.68km
TTS (Impulsive)	LF (168dB)	3,900km ²	44km	26km	35km
	HF (170dB)	0.86km ²	0.55km	0.48km	0.53km
	VHF (140dB)	2,600km ²	34km	23km	29km
	PCW (170dB)	790km ²	19km	14km	16km

Table 4-28 Summary of the unweighted $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum blow energy used during monopile foundation modelling at the Centre (OSP) modelling location.

Popper et al. (2014) $L_{p,pk}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213dB	0.05km ²	0.13km	0.12km	0.12km
	207dB	0.31km ²	0.32km	0.32km	0.32km

Table 4-29 Summary of the unweighted $L_{E,p,24h}$ impact ranges for fish using the Popper *et al.* (2014) pile driving criteria covering the monopile foundation modelling for two sequentially installed piles at the Centre (OSP) modelling location. assuming both fleeing and stationary animals.

Popper <i>et al.</i> (2014) $L_{E,p,24h}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	216dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	210dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	207dB	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	203dB	0.36km ²	0.35km	0.3km	0.34km
	186dB	860km ²	20km	14km	17km
Stationary (0 m/s)	219dB	4.8km ²	1.3km	1.2km	1.2km
	216dB	11km ²	1.9km	1.9km	1.9km
	210dB	57km ²	4.4km	4.2km	4.3km
	207dB	120km ²	6.3km	5.8km	6.1km
	203dB	270km ²	9.9km	8.9km	9.4km
	186dB	3,500km ²	37km	29km	33km

4.2 Multiple location modelling

Modelling has been carried out to investigate the potential impacts of multiple piling vessels installing foundations simultaneously at separate locations. A scenario covering simultaneous piling at the NW and SE corners of Dogger Bank D has been chosen to represent the worst-case piling parameters in a 24-hour period, using the monopile scenario from the previous sections (two vessels, each installing two piles sequentially, resulting in four monopile foundations installed in a 24-hour period).

When considering $L_{E,p,t}$ modelling, piling from multiple sources can increase impact ranges significantly as, in this case, it introduces noise from twice the number of pile strikes to the water. Unlike the sequential piling investigated in section 4.1, fleeing receptors can be closer to a source for a higher number of the pile strikes, taking into account a second piling location, which results in higher cumulative noise exposures. Figure 4-1 shows the TTS contour for fish from Popper *et al.* (2014) (186dB $L_{E,p,24h}$) for a fleeing receptor as an example. The red contours show the impact from each location modelled individually (as presented in section 4.1), and the blue contour shows the increase in the predicted impacts when multiple sources are active simultaneously, resulting in a contour encircling both red contours.

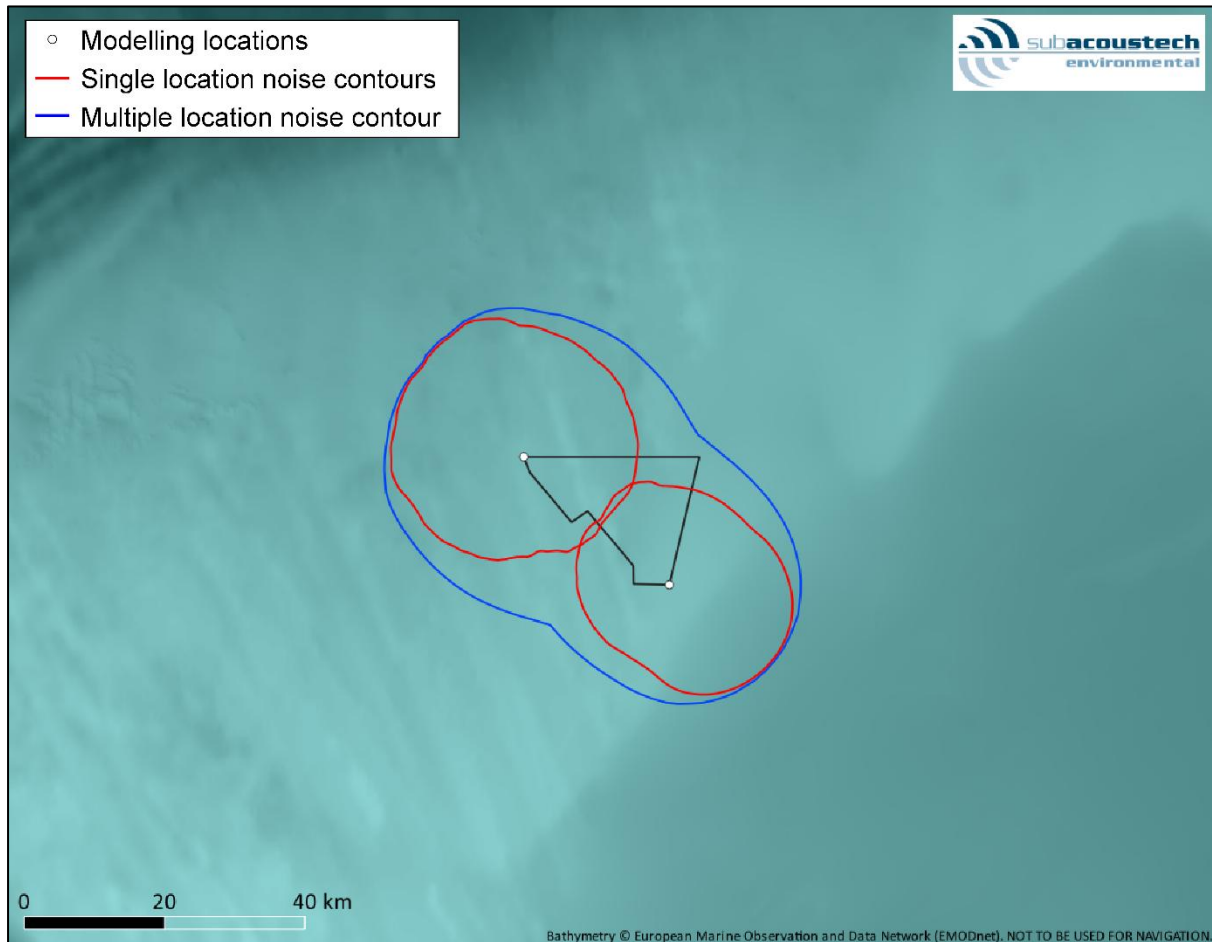


Figure 4-1 Example contour plot showing the interaction between two noise sources occurring simultaneously (TTS in fish, 186 dB $L_{E,p,24hr}$ fleeing animal).

The modelled scenario was chosen to provide the greatest geographical spread of noise sources that would lead to the greatest impact range contours. In a modelling scenario where piles are installed close to each other, there would be an expansion of the single location contour in all directions, but by less overall than the spread seen in Figure 4-1.

For the results in the following section only impact areas rather than linear ranges are provided as results; impact ranges have not been presented due to there being multiple starting points for receptors (a linear impact range, such as those discussed in section 3.3, requires a single start point, which is not possible with multiple pile locations). Fields denoted with a dash “-” show where there is no in-combination effect when piling occurs at the two locations simultaneously. This is generally where the ranges are small enough that the distant sites do not produce an influencing additional exposure, such as with the typically small HF cetacean-weighted impact ranges.

Specific circumstances would lead to the combined range being less than the two separated ranges combined: this is commonly where the two modelling locations are close, or individual ranges are very large. In other cases, the combined ranges may be greater than the two separated ranges in summation: this is often where the individual ranges are large but there is little overlap between the two when not in combination.

4.2.1 Concurrent piling at the NW and SE corners

4.2.1.1 Monopile foundations

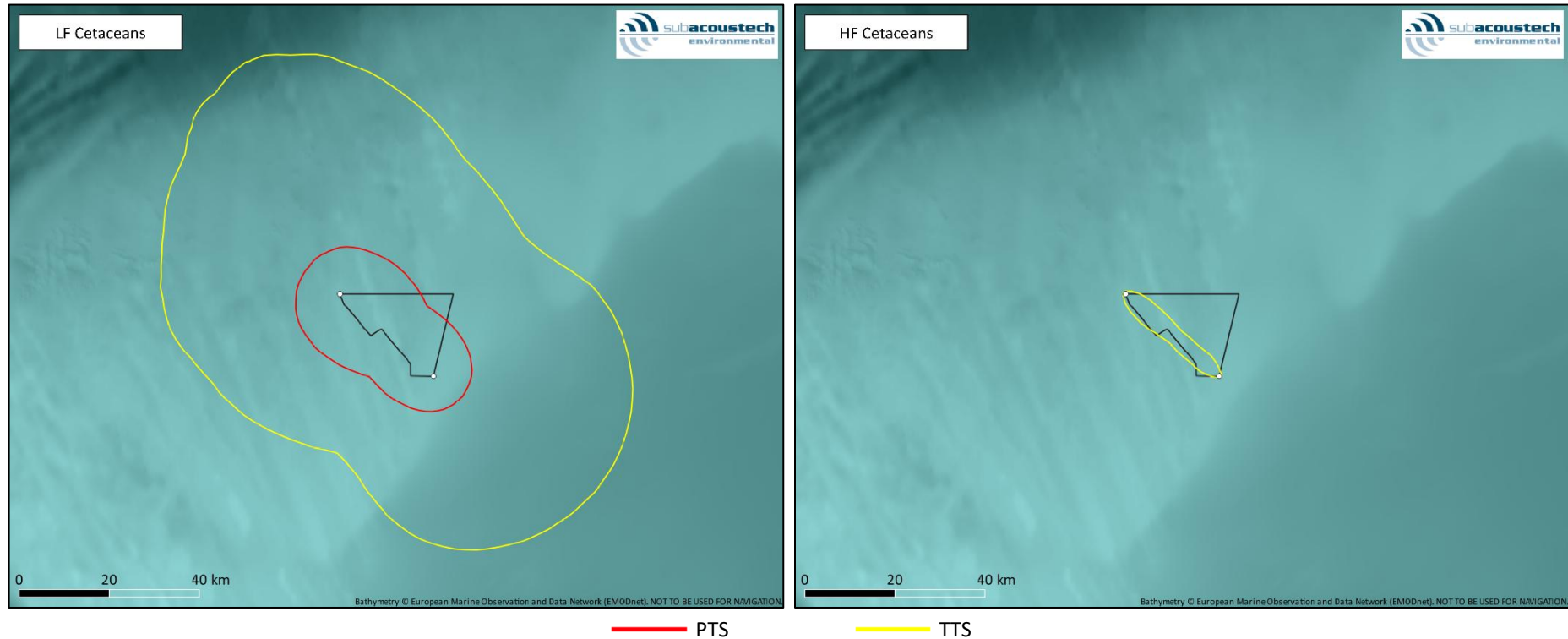


Figure 4-2 Contour plots showing the in-combination impacts of concurrent installation of monopile foundations at the NW and SE corners of the Dogger Bank D site for LF and HF cetaceans using the impulsive Southall et al. (2019) criteria assuming a fleeing animal.

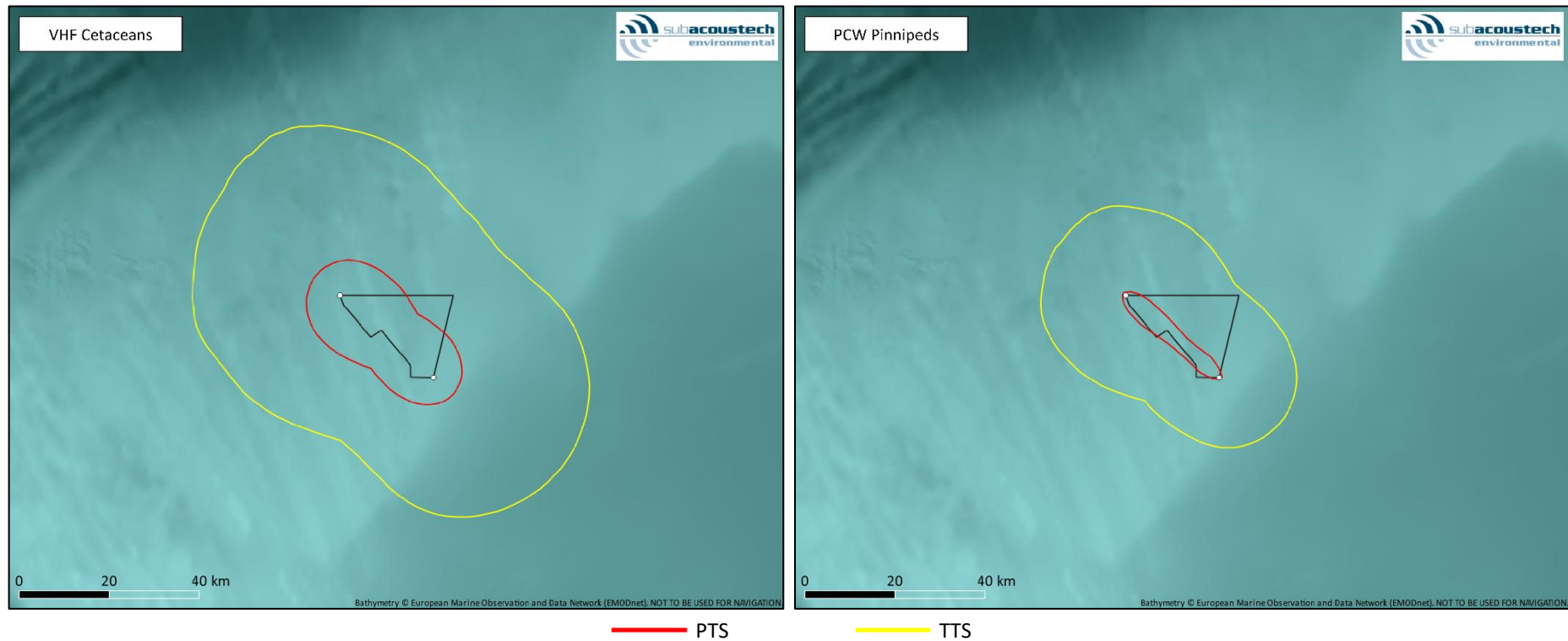


Figure 4-3 Contour plots showing the in-combination impacts of concurrent installation of monopile foundations at the NW and SE corners of the Dogger Bank D site for VHF cetaceans and PCW pinnipeds using the impulsive Southall et al. (2019) criteria assuming a fleeing animal.

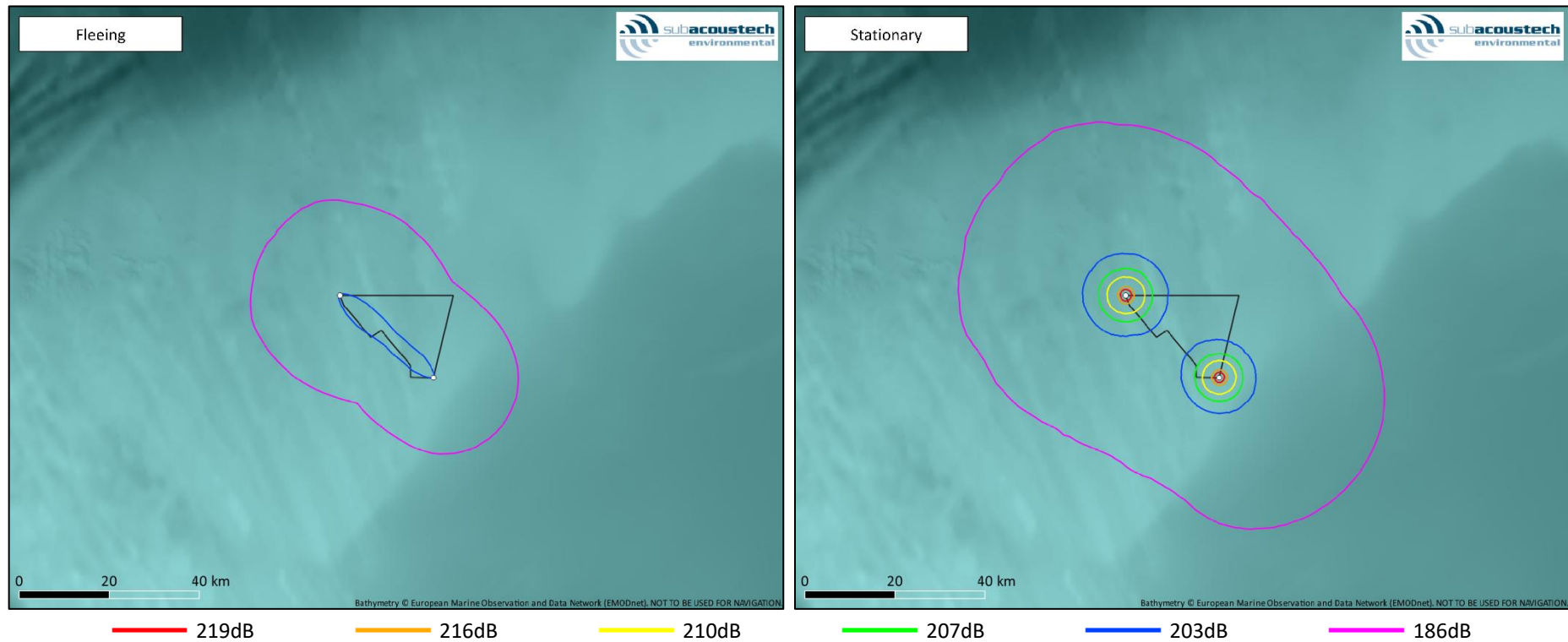


Figure 4-4 Contour plots showing the in-combination impacts of concurrent installation of monopile foundations at the NW and SE corners of the Dogger Bank D site for fish using the pile driving Popper et al. (2014) criteria assuming both fleeing and stationary animals.

Table 4-30 Summary of the impact areas for the installation of monopile foundations at the NW and SE corners of the Dogger Bank D site for marine mammals using the impulsive Southall et al. (2019) criteria assuming a fleeing animal.

Monopile foundations (Southall et al., 2019) $L_{E,p,24h,wtd}$		NW corner	SE corner	In-combination area
PTS (Impulsive)	LF (183dB)	200km ²	130km ²	900km ²
	HF (185dB)	< 0.1km ²	< 0.1km ²	-
	VHF (155dB)	120km ²	80km ²	600km ²
	PCW (185dB)	1km ²	0.51km ²	110km ²
TTS (Impulsive)	LF (168dB)	4,200km ²	3,500km ²	7,600km ²
	HF (170dB)	0.67km ²	0.4km ²	110km ²
	VHF (140dB)	2,700km ²	2,300km ²	5,100km ²
	PCW (170dB)	820km ²	570km ²	2,000km ²

Table 4-31 Summary of the impact areas for the installation of monopile foundations at the NW and SE corners of the Dogger Bank D site for fish using the pile driving Popper et al. (2014) criteria assuming both fleeing and stationary animals.

Monopile foundations (Popper et al., 2014) $L_{E,p,24h}$		NW corner	SE corner	In-combination area
Fleeing (1.5 m/s)	219dB	< 0.1km ²	< 0.1km ²	-
	216dB	< 0.1km ²	< 0.1km ²	-
	210dB	< 0.1km ²	< 0.1km ²	-
	207dB	< 0.1km ²	< 0.1km ²	-
	203dB	0.26km ²	0.14km ²	110km ²
	186dB	920km ²	680km ²	2,200km ²
Stationary (0 m/s)	219dB	4.3km ²	3.7km ²	9.1km ²
	216dB	10km ²	8.5km ²	20km ²
	210dB	51km ²	41km ²	97km ²
	207dB	110km ²	84km ²	200km ²
	203dB	260km ²	200km ²	490km ²
	186dB	3,600km ²	3,100km ²	5,800km ²

5 Other noise sources

Although impact piling is expected to be the greatest overall noise source during offshore construction and development (Bailey *et al.*, 2014), several other anthropogenic noise sources may be present. Each of these has been considered, and relevant biological noise criteria presented, in this section.

Table 5-1 provides a summary of the various noise producing sources, aside from impact piling, that are expected to be present during the construction and operation of Dogger Bank D.

Table 5-1: Summary of the possible noise making activities at Dogger Bank D other than impact piling.

Activity	Description
Drilling	There is the potential for WTG foundations to be installed using drilling depending on seabed type, or if a pile refuses during impact piling operations.
Suction bucket installation	An alternative method for fixing the WTG foundations to the seabed. Underwater suction pumps are the primary source of noise.
Gravity base installation	An alternative method for fixing the WTG foundations to the seabed. It is assumed that installing the gravity base itself will only cause minimal noise, however associated works to prepare the ground for the gravity base should still be considered. These could include dredging and rock placement, which have been modelled.
Vibropiling	There is the potential for a vibratory hammer to be used to install piles.
Cable laying / trenching	Noise from the cable laying vessel and other associated noise, such as plough trenching, during the offshore cable installation.
Rock placement	May be required on site for installation of offshore cables (cable crossings and cable protection) and scour protection around foundation structures.
Vessel noise	Jack-up barges for piling substructure and WTG installation. Other large and medium sized vessels to carry out other construction tasks and anchor handling. Other small vessels for crew transport and maintenance on site.
Operational WTGs	Noise transmitted through the water from operational WTGs. The project design envelope has made predictions for turbine parameters which could be available for Dogger Bank D and has allowed for power outputs of between 14 and 27MW.
UXO clearance	There is a possibility that Unexploded Ordnance (UXO) may exist within the Dogger Bank D array area, which would need to be cleared before construction can begin.

The majority of these activities are covered in section 5.1, with operational WTG noise and UXO clearance assessed in sections 5.2 and 5.3 respectively.

The NPL Good Practice Guide 133 for underwater noise measurements (Robinson *et al.*, 2014) indicates that under certain circumstances, a simple modelling approach may be considered appropriate. Such an approach has been used for these noise sources, which are variously either quiet compared to impact piling (e.g., drilling), or where detailed modelling would imply unjustified accuracy (e.g., for small charges such as those used in low-order detonations). The high-level overview of modelling that has been presented here is considered sufficient and there would be little benefit in using a more detailed modelling approach at this stage due to their relatively low impacts. The limitations of this approach are noted, including the lack of frequency and bathymetric dependence.

5.1 Noise making activities

For the purposes of identifying the greatest effects from noise, approximate subsea noise levels have been predicted using a simple modelling approach based on measurement data from Subacoustech Environmental's own underwater noise measurement database scaled to relevant parameters for Dogger Bank D and to the

specific noise sources to be used. The calculation of underwater noise transmission loss for these non-impulsive sources is based on empirical analysis of the noise measurements taken along transects around these sources by Subacoustech Environmental. The predictions use the following principle fitted to the measured data, where R is the range from the source, N is the transmission loss coefficient, and α is the absorption loss coefficient:

$$Received\ level = Source\ level\ (SL) - N \log_{10} R - \alpha R$$

Predicted source levels and propagation calculations for the construction activities are presented in Table 5-2 along with a summary of the number of datasets used in each case. As previously, all criteria use the same assumptions as presented in section 3.2, and ranges smaller than 0.05km (single pulse) and 0.1km (cumulative) have not been presented. It should be reiterated that this modelling approach does not take bathymetry or any other environmental conditions into account, and as such can be applied to any location at, or surrounding, Dogger Bank D.

Table 5-2: Summary of the estimated unweighted source levels and transmission losses for the different considered noise sources.

Source	Estimated L_p source level	Transmission loss parameters	Comments
Cable laying	171dB re 1 μ Pa @ 1m	$N: 13, \alpha: 0$ (no absorption)	Based on 11 datasets from a pipe laying vessel measuring 300m in length; this is considered a worst-case noise source for cable laying operations.
Dredging (backhoe)	165dB re 1 μ Pa @ 1m	$N: 19, \alpha: 0.0009$	Based on three datasets from backhoe dredgers.
Dredging (suction)	186dB re 1 μ Pa @ 1m	$N: 19, \alpha: 0.0009$	Based on five datasets from suction and cutter suction dredgers.
Drilling	169dB re 1 μ Pa @ 1m	$N: 16, \alpha: 0.0006$	Based on six datasets from various drilling operations covering ground investigations and pile installation. A 200kW drill has been assumed for modelling.
Rock placement	172dB re 1 μ Pa @ 1m	$N: 12, \alpha: 0.0005$	Based on four datasets from rock placement vessel <i>Rollingstone</i> .
Suction bucket installation	192dB re 1 μ Pa @ 1m	$N: 19, \alpha: 0.0009$	Based on a review by Koschinski and Lüdemann (2019).
Trenching	172dB re 1 μ Pa @ 1m	$N: 13, \alpha: 0.0004$	Based on three datasets of measurements from trenching vessels more than 100m in length.
Vessel noise (large)	168dB re 1 μ Pa @ 1m	$N: 12, \alpha: 0.0021$	Based on five datasets of large vessels including container ships, FPSOs and other vessels more than 100m in length. Vessel speed assumed as 10 knots.
Vessel noise (medium)	161dB re 1 μ Pa @ 1m	$N: 12, \alpha: 0.0021$	Based on three datasets of moderate sized vessels less than 100m in length. Vessel speed assumed as 10 knots.
Vibropiling	183dB re 1 μ Pa @ 1m	$N: 15, \alpha: 0.0002$	Based on four datasets from vibropiling installation of sheet piles and tubular piles.

All values of N and α are empirically derived and will be linked to the size and shape of the machinery, the transect on which the measurements were taken and the local environment at the time.

For $L_{E,p,t}$ calculations in this section, the duration the noise is present also needs to be considered, with all sources assumed to operate constantly for 24 hours to give a worst-case assessment of the noise. Due to the low noise level of the sources, both fleeing and stationary animals have been included for all $L_{E,p,t}$ criteria.

To account for the weightings required for modelling using the Southall *et al.* (2019) criteria (see section 2.3.1), reductions have been applied to the source levels of the various noise sources. Figure 5-1 shows the representative noise measurements used to calculate these reductions, which have been adjusted based on the source levels given in Table 5-2. Details of the reductions in source level for each of the marine mammal weightings are given in Table 5-3.

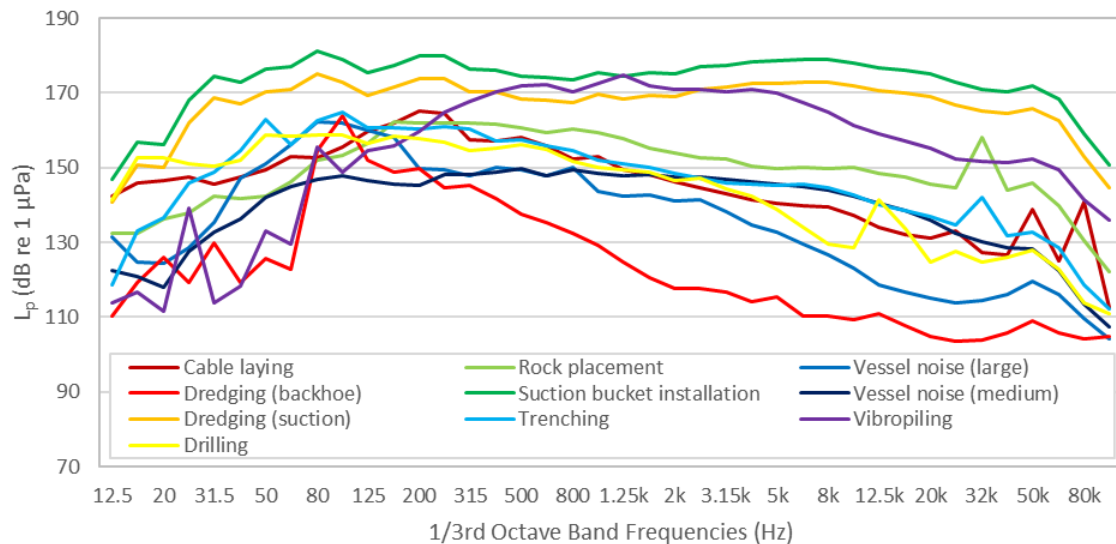


Figure 5-1: Summary of the 1/3rd octave frequency bands to which Southall *et al.* (2019) weightings have been applied.

Table 5-3: Reductions in source level for the different construction noise sources considered when the Southall *et al.* (2019) weightings are applied.

Source	Reduction in L_p source level from the unweighted level (Southall <i>et al.</i> , 2019)			
	LF	HF	VHF	PCW
Cable laying	3.6dB re 1µPa	22.9dB re 1µPa	23.9dB re 1µPa	13.2dB re 1µPa
Dredging (backhoe)	6.3dB re 1µPa	46.7dB re 1µPa	48.7dB re 1µPa	23.1dB re 1µPa
Dredging (suction)	2.5dB re 1µPa	7.9dB re 1µPa	9.6dB re 1µPa	4.2dB re 1µPa
Drilling	4dB re 1µPa	25.8dB re 1µPa	48.7dB re 1µPa	13.2dB re 1µPa
Rock placement	1.6dB re 1µPa	11.9dB re 1µPa	12.5dB re 1µPa	8.2dB re 1µPa
Suction bucket installation	2.5dB re 1µPa	7.9dB re 1µPa	9.6dB re 1µPa	4.2dB re 1µPa
Trenching	4.1dB re 1µPa	23dB re 1µPa	25dB re 1µPa	13.7dB re 1µPa
Vessel noise	5.5dB re 1µPa	34.4dB re 1µPa	38.6dB re 1µPa	17.4dB re 1µPa
Vibropiling	2.4dB re 1µPa	16dB re 1µPa	20.8dB re 1µPa	4.4dB re 1µPa

Given the modelled impact ranges, almost any marine mammal would have to be closer than 100m from the continuous source at the start of the activity to acquire the necessary exposure to induce PTS as per Southall *et al.* (2019), with the possible exception of suction dredging, rock placement and suction bucket installation for stationary receptors. The exposure calculation assumes the same receptor swim speeds as the impact piling modelling in section 4. As explained in section 3.3, this would only mean that the receptor reaches the ‘onset’

stage at these ranges, which is the minimum exposure that could potentially lead to the start of an effect and may only be marginal. In most hearing groups, the noise levels are low enough that there is minimal risk.

For fish, there is a minimal risk of any injury or TTS with reference to the L_p guidance for continuous noise sources in Popper *et al.* (2014).

All sources presented here produce much quieter levels than those predicted for impact piling in section 4.

*Table 5-4: Summary of the impact ranges for the different noise sources related to construction using the non-impulsive criteria from Southall *et al.* (2019) for marine mammals assuming a fleeing receptor.*

Southall <i>et al.</i> (2019) $L_{E,p,24h,wtd}$	PTS (non-impulsive)				TTS (non-impulsive)			
	LF (199dB)	HF (198dB)	VHF (173dB)	PCW (201dB)	LF (179dB)	HF (178dB)	VHF (153dB)	PCW (181dB)
Cable laying	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	0.11km	< 0.1km
Dredging (backhoe)	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km
Dredging (suction)	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	0.23km	< 0.1km
Drilling	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km
Rock placement	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	0.99km	< 0.1km
Suction bucket installation	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	3.2km	< 0.1km
Trenching	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km
Vessel noise (large)	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km
Vessel noise (medium)	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km
Vibropiling	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km

*Table 5-5: Summary of the impact ranges for the different noise sources related to construction using the non-impulsive criteria from Southall *et al.* (2019) for marine mammals assuming a stationary receptor.*

Southall <i>et al.</i> (2019) $L_{E,p,24h,wtd}$	PTS (non-impulsive)				TTS (non-impulsive)			
	LF (199dB)	HF (198dB)	VHF (173dB)	PCW (201dB)	LF (179dB)	HF (178dB)	VHF (153dB)	PCW (181dB)
Cable laying	< 0.1km	< 0.1km	< 0.1km	< 0.1km	0.81km	< 0.1km	< 0.1km	< 0.1km
Dredging (backhoe)	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km
Dredging (suction)	< 0.1km	< 0.1km	0.4km	< 0.1km	0.46km	0.28km	3.3km	0.3km
Drilling	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km	< 0.1km
Rock placeme nt	< 0.1km	< 0.1km	0.53km	< 0.1km	1.3km	0.23km	9.9km	0.27km
Suction bucket installati on	0.12km	0.14km	2.2km	< 0.1km	1.2km	1.4km	11km	0.95km
Trenchin g	< 0.1km	< 0.1km	< 0.1km	< 0.1km	0.83km	< 0.1km	< 0.1km	0.12km

Southall <i>et al.</i> (2019) $L_{E,p,24h,wtd}$	PTS (non-impulsive)				TTS (non-impulsive)			
	LF (199dB)	HF (198dB)	VHF (173dB)	PCW (201dB)	LF (179dB)	HF (178dB)	VHF (153dB)	PCW (181dB)
Vessel noise (large)	< 0.1km	< 0.1km	< 0.1km	< 0.1km	0.48km	< 0.1km	< 0.1km	< 0.1km
Vessel noise (medium)	< 0.1km	< 0.1km	< 0.1km	< 0.1km	0.13km	< 0.1km	< 0.1km	< 0.1km
Vibropiling	< 0.1km	< 0.1km	0.11km	< 0.1km	< 0.1km	0.11km	1.6km	0.37km

Ranges for a stationary animal are theoretical only and are expected to be over-conservative as the assumption is for the animal to remain stationary in respect to the noise source, when, in all cases other than drilling, and suction bucket installation the source of the noise moves.

Table 5-6: Summary of the impact ranges for the different noise sources related to construction using the continuous noise criteria from Popper *et al.* (2014) for fish (swim bladder involved in hearing).

Popper <i>et al.</i> (2014) L_p	Recoverable injury 170dB re 1μPa (48 hours)	TTS 158dB re 1μPa (12 hours)
Cable laying	< 0.05km	< 0.05km
Dredging (backhoe)	< 0.05km	< 0.05km
Dredging (suction)	< 0.05km	< 0.05km
Drilling	< 0.05km	< 0.05km
Rock placement	< 0.05km	< 0.05km
Suction bucket installation	< 0.05km	0.06km
Trenching	< 0.05km	< 0.05km
Vessel noise (large)	< 0.05km	< 0.05km
Vessel noise (medium)	< 0.05km	< 0.05km
Vibropiling	< 0.05km	< 0.05km

5.2 Operational WTG noise

The main source of underwater noise from operational WTGs will be mechanically generated vibration from the rotating machinery in the WTGs, which is transmitted into the sea through the structure of the WTG tower and foundations (Nedwell *et al.*, 2003; Tougaard *et al.*, 2020). Noise levels generated above the water surface are low enough that no significant airborne noise will pass from the air to the water.

Tougaard *et al.* (2020) published a study investigating underwater noise data from 17 operational WTGs in Europe and the United States, from 0.2MW to 6.15MW nominal power output. The paper identified the nominal power output and wind speed as the two primary driving factors for underwater noise generation. Although the datasets were acquired under different conditions, the authors devised a formula based on the published data for the operational wind farms, allowing a broadband noise level to be estimated based on the application of wind speed, turbine size (by nominal power output) and distance from the turbine:

$$L_{eq} = C + \alpha \log_{10} \left(\frac{\text{distance}}{100m} \right) + \beta \log_{10} \left(\frac{\text{wind speed}}{10m/s} \right) + \gamma \log_{10} \left(\frac{\text{turbine size}}{1MW} \right)$$

where C is a fixed constant, and the coefficients α , β , and γ are derived from empirical data for the 17 datasets. This enables the calculation to extrapolate to greater turbine power outputs such as those to be proposed at Dogger Bank D.

Indicative power outputs have been used to calculate the impacts for this study. For Dogger Bank D, WTGs with power outputs from 14 to 27MW are being considered.

The maximum turbine sizes considered at Dogger Bank D are much larger than those used for the equation above, so caution must be used when considering the results presented in this section; no empirical data is available for large wind turbines close to the specifications proposed here. It is recognised that the data used in the development for the calculation above was derived from turbines much smaller than those proposed for installation at Dogger Bank D. Research from Bellmann *et al.* (2023) using more up to date operational noise data from larger turbines currently installed (up to 8MW) found that the predictions above are likely to overestimate the noise produced from the turbines, giving an extra margin of safety for the estimations.

Figure 5-2 presents a level against range plot for the range of WTG sizes proposed at Dogger Bank D using the Tougaard *et al.* (2020) equation, assuming an average 6m/s wind speed.

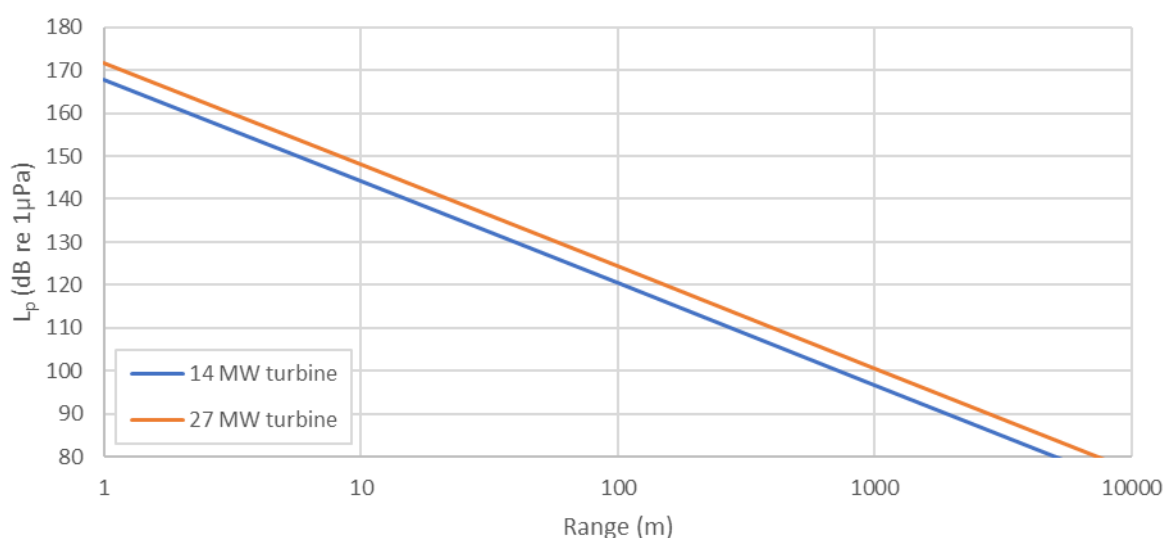


Figure 5-2 Predicted unweighted L_p from operational WTGs using the calculation from Tougaard *et al.* (2020).

Using this data, a summary of the predicted impact ranges for operational WTGs using fixed foundations has been produced, shown in Table 5-7 and Table 5-8. All operational WTG modelling uses the same assumptions as presented in the previous sections. Ranges smaller than 0.05km (L_p) and 0.1km ($L_{E,p,24h,wtd}$) have not been presented. The operational WTG source is considered non-impulsive or continuous. For $L_{E,p,t}$ calculations, a worst-case stationary animal has been used and it is assumed that the operational WTG noise is present 24 hours a day.

Table 5-7: Summary of the fixed-foundation operational WTG noise impact ranges using the non-impulsive noise criteria from Southall *et al.* (2019) for marine mammals.

Southall <i>et al.</i> (2019) $L_{E,p,24h,wtd}$		Operational WTG (14MW)	Operational WTG (27MW)
PTS (non-impulsive)	LF (199dB)	< 0.1km	< 0.1km
	HF (198dB)	< 0.1km	< 0.1km
	VHF (173dB)	< 0.1km	< 0.1km

Southall <i>et al.</i> (2019) $L_{E,p,24h,wtd}$	Operational WTG (14MW)	Operational WTG (27MW)
PCW (201dB)	< 0.1km	< 0.1km
TTS (non-impulsive)	LF (179dB)	< 0.1km
	HF (178dB)	< 0.1km
	VHF (153dB)	< 0.1km
	PCW (181dB)	< 0.1km

Table 5-8: Summary of the fixed-foundation operational WTG noise impact ranges using the continuous noise criteria from Popper *et al.* (2014) for fish (swim bladder involved in hearing).

Popper <i>et al.</i> (2014) L_p	Operational WTG (14MW)	Operational WTG (27MW)
Recoverable injury 170dB (48 hours)	< 0.05km	< 0.05km
TTS 158dB (12 hours)	< 0.05km	< 0.05km

These results show that noise from operational WTGs poses minimal injury risk to marine fauna.

Stöber and Thomsen (2021) produced a similar study of operational WTG datasets and raises the potential for behavioural disturbance caused by larger wind turbines. While prospective WTG sizes are increasing, Stöber and Thomsen (2021) conclude that these might only have limited impacts related to behavioural responses in marine mammals and fish, although there is considerable uncertainty in criteria available to assess these. Based on the highly precautionary NOAA Level B behavioural threshold (120dB re 1 μ Pa L_p , see NOAA, 2005) that the study utilises, it is estimated that the larger WTGs may only achieve this at ranges of approximately 150m. As the distance between the turbines at Dogger Bank D will likely be much greater than this, any array effect from the turbines is not expected. Bellmann *et al.* (2023) takes this further and shows that the predictions of underwater noise during the operational phase in Stöber and Thomsen (2021) represent significant over-estimations of the actual levels seen on site.

5.3 UXO clearance

It is possible that UXO devices with a range of charge weights (or quantity of contained explosive) are present within the Dogger Bank D array area. These would need to be cleared before any construction can begin. When modelling potential noise from UXO clearance, a variety of explosive types need to be considered, with the potential that many have been subject to degradation and burying over time. Two otherwise identical explosive devices are likely to produce different blasts in the case where one has spent an extended period on the seabed or sits in a different topographical situation. A selection of explosive sizes has been considered based on what might be present, and in each case, it has been assumed that the maximum explosive charge in each device is present and either detonates with the clearance (high-order) or a clearance method such as deflagration (low-order) can be used. In accordance with the Marine Environment: Unexploded Ordnance Clearance Joint Position Statement³, a low order technique is intended to be the primary method of UXO clearance, with high order clearance only to occur in exceptional circumstances.

³ <https://www.gov.uk/government/publications/marine-environment-unexploded-ordnance-clearance-joint-position-statement> 21st January 2025

5.3.1 Estimation of underwater noise level

5.3.1.1 High-order clearance

The noise produced by the detonation of explosives is affected by several different elements, only one of which can easily be factored into a calculation: the charge weight. In this case the charge weight is based on the equivalent weight of TNT. Many other elements relating to its situation (e.g., its design, composition, age, position, orientation, whether it is covered by sediment) and exactly how they will affect the sound produced by detonation are usually unknown and cannot be directly considered in this type of assessment. This leads to a high degree of uncertainty in the estimation of the source noise level. A worst-case estimation has therefore been used for calculations, assuming the UXO to be detonated is not buried, degraded or subject to any other significant attenuation from its 'as-new' condition. It assumes that a 'high-order' clearance technique is used, using an external 'donor charge' initiator to detonate the explosive material in the UXO, producing a blast wave equivalent to full detonation of the device.

The consequence of this is that the noise levels produced, particularly by the larger explosives under consideration, are likely to be over-estimated as some degree of degradation would be expected.

The maximum equivalent charge weight for the potential UXO devices that could be present within the Dogger Bank D array area has been estimated as 907kg based on a Dogger Bank C pre-construction UXO hazard assessment (more detail in **Volume 2, Appendix 12.4 UXO Assessment**). This has been modelled alongside a range of smaller devices, at charge weights of 25, 55, 120, 240, 525, and 698kg, which have been chosen to give a good spread of what has been identified at similar sites in the North Sea. In each case, an additional donor weight of 0.5kg has been included to initiate detonation.

Estimation of the source noise level for each charge weight has been carried out in accordance with the methodology of Soloway and Dahl (2014), which follows Arons (1954) and the Marine Technical Directorate Ltd. (MTD) (1996).

5.3.1.2 Low-order clearance

Other techniques are being considered to reduce the impact of noise impacts from high order UXO clearance, caused by detonation of the main charge of the UXO. Deflagration is such an alternative technique, intended to result in a 'low order' burn of the explosive material in a UXO, which destroys, but does not detonate, the internal explosive.

Where the technique proceeds as intended, it is still not without noise impact. The process requires an initial shaped explosive donor charge, typically less than 250g, to breach the casing and ignite the internal high explosive (HE) material without full detonation. The shaped charge and burn will both produce noise, although it will be significantly less than the high order detonation of the much larger UXO. It may not destroy all of the HE, necessitating further deflagration events or collection of the remnants. The deflagration may produce an unintentional high-order event.

For calculation of the scenario of total destruction of the HE material using deflagration, it is anticipated that the initial shaped charge is the greatest source of noise (Cheong *et al.*, 2020). The shaped charge is treated as a bulk charge with NEQ (net explosive quantity) determined according to the size of UXO on which it is placed. A prediction of this impact is based on a charge weight of 250g. The worst-case scenario would of course be a high order detonation with maximum pressures from complete detonation of the UXO, and this has been calculated separately for comparison.

5.3.2 Estimation of underwater noise propagation

For this assessment, the attenuation of the noise from UXO detonation has been accounted for in calculations using geometric spreading and a sound absorption coefficient, primarily using the methodologies cited in Soloway and Dahl (2014), which establishes a trend based on measured data in open water. These are, for $L_{p,pk}$:

$$L_{p,pk} = 52.4 \times 10^6 \left(\frac{R}{W^{1/3}} \right)^{-1.13}$$

and for $L_{E,p}$:

$$L_{E,p} = 6.14 \times \log_{10} \left(W^{1/3} \left(\frac{R}{W^{1/3}} \right)^{-2.12} \right) + 219$$

where W is the equivalent charge weight for TNT in kg and R is the range from the source.

These equations give a relatively simple calculation which can be used to give an indication of the range of effect. The equation does not consider variable bathymetry or seabed type, and thus calculation results will be the same regardless of where it is used. An attenuation correction can be added to the Soloway and Dahl (2014) equations for the absorption over long ranges (i.e., of the order of thousands of metres), based on measurements of high intensity noise propagation taken in the North Sea and Irish Sea. This uses standard frequency-based absorption coefficients for the seawater conditions expected in the region.

Despite this attenuation correction, the resulting noise levels still need to be considered carefully. For example, $L_{p,pk}$ noise levels over larger distances are difficult to predict accurately (von Benda-Beckmann *et al.*, 2015). Soloway and Dahl (2014) only verify results from the equation above for small charges at ranges of less than 1km, although the results are similar to the measurements presented by von Benda-Beckmann *et al.* (2015). At longer ranges, greater confidence is expected with the $L_{E,p}$ calculations.

A further limitation in the Soloway and Dahl (2014) equations are that variations in noise levels at different depths are not considered. Where animals are swimming near the surface, the acoustics can cause the noise level, and hence the exposure, to be lower (MTD, 1996). The risk to animals near the surface may therefore be lower than indicated by the impact ranges and therefore the results presented can be considered conservative in respect of the impact at different depths.

Additionally, an impulsive wave tends to be smoothed (i.e., the pulse becomes longer) over distance (Cudahy and Parvin, 2001), meaning the injurious potential of a wave at greater range can be even lower than just a reduction in the absolute noise level. An assessment in respect of SEL is considered preferential at long range as it considers the overall energy, and the degree of smoothing of the peak with increasing distance is less critical.

The selection of assessment criteria must also be considered in light of this. As discussed in section 2.2.1, the smoothing of the pulse at range means that a pulse may be considered non-impulsive at distance, suggesting that, at greater ranges, it may be more appropriate to use the non-impulsive criteria. This consideration may begin at 3.5km (Hastie *et al.*, 2019).

A summary of the unweighted UXO clearance source levels, calculated using the equations above, are given in Table 5-9.

Table 5-9: Summary of the $L_{p,pk}$ and $L_{E,p}$ source levels used for UXO clearance modelling.

Charge weight	$L_{p,pk}$ source level	$L_{E,p}$ source level
Low-order (0.25kg)	269.8dB re 1µPa @ 1m	215.2dB re 1µPa ² s @ 1m
25kg (+ donor)	284.9dB re 1µPa @ 1m	228.0dB re 1µPa ² s @ 1m
55kg (+ donor)	287.5dB re 1µPa @ 1m	230.1dB re 1µPa ² s @ 1m
120kg (+ donor)	290.0dB re 1µPa @ 1m	232.3dB re 1µPa ² s @ 1m

Charge weight	$L_{p,pk}$ source level	$L_{E,p}$ source level
240kg (+ donor)	292.3dB re 1µPa @ 1m	234.2dB re 1µPa ² s @ 1m
525kg (+ donor)	294.8dB re 1µPa @ 1m	236.4dB re 1µPa ² s @ 1m
698kg (+ donor)	295.7dB re 1µPa @ 1m	237.1dB re 1µPa ² s @ 1m
907kg (+ donor)	296.6dB re 1µPa @ 1m	237.9dB re 1µPa ² s @ 1m

5.3.3 Impact ranges

Table 5-10 to Table 5-13 present the impact ranges for UXO detonation, considering various charge weights and impact criteria. It should be noted that Popper *et al.* (2014) gives specific impact criteria for explosions (Table 2-5). A UXO detonation source is defined as a single pulse, as such the $L_{E,p}$ criteria from Southall *et al.* (2019) have been given as single pulse values in the following tables and fleeing animal assumptions do not apply. As with the previous sections, ranges smaller than 50 m have not been presented.

Although the impact ranges in Table 5-10 to Table 5-13 are large, the duration the noise is present must also be considered. For the detonation of a UXO, each explosion is a single noise event, compared to the multiple pulse nature and longer durations of impact piling.

Table 5-10 Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive $L_{p,pk}$ noise criteria from Southall *et al.* (2019) for marine mammals.

Southall <i>et al.</i> (2019) $L_{p,pk}$	PTS (impulsive)				TTS (impulsive)			
	LF 219dB	HF 230dB	VHF 202dB	PCW 218dB	LF 213dB	HF 224dB	VHF 196dB	PCW 212dB
Low order (0.25kg)	0.17km	0.06km	0.99km	0.19km	0.32km	0.1km	1.8km	0.36km
25kg + donor	0.82km	0.26km	4.6km	0.91km	1.5km	0.49km	8.5km	1.6km
55kg + donor	1.0km	0.34km	6.0km	1.1km	1.9km	0.64km	11km	2.1km
120kg + donor	1.3km	0.45km	7.8km	1.5km	2.5km	0.83km	14km	2.8km
240kg + donor	1.7km	0.56km	9.8km	1.9km	3.2km	1km	18km	3.5km
525kg + donor	2.2km	0.73km	12km	2.5km	4.1km	1.3km	23km	4.6km
698kg + donor	2.4km	0.81km	13km	2.7km	4.5km	1.4km	25km	5.0km
907kg + donor	2.7km	0.88km	15km	3.0km	4.9km	1.6km	28km	5.5km

Table 5-11 Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive $L_{E,p}$ (single pulse) noise criteria from Southall *et al.* (2019) for marine mammals.

Southall <i>et al.</i> (2019) $L_{E,p}$ (single pulse)	PTS (impulsive)				TTS (impulsive)			
	LF 183dB	HF 185dB	VHF 155dB	PCW 185dB	LF 168dB	HF 170dB	VHF 140dB	PCW 170dB
Low order (0.25kg)	0.23km	<0.05km	0.08km	<0.05km	3.2km	<0.05km	0.75km	0.57km
25kg + donor	2.2km	<0.05km	0.57km	0.39km	29km	0.15km	2.4km	5.2km
55kg + donor	3.2km	<0.05km	0.74km	0.57km	41km	0.21km	2.8km	7.5km
120kg + donor	4.7km	<0.05km	0.95km	0.83km	57km	0.3km	3.2km	10km
240kg + donor	6.5km	<0.05km	1.1km	1.1km	76km	0.39km	3.5km	14km
525kg + donor	9.5km	0.05km	1.4km	1.6km	100km	0.53km	4.0km	19km
698kg + donor	10km	0.06km	1.5km	1.9km	110km	0.59km	4.1km	22km
907kg + donor	12km	0.07km	1.6km	2.2km	120km	0.65km	4.3km	24km

Table 5-12 Summary of the PTS and TTS impact ranges for UXO detonation using the non-impulsive $L_{E,p}$ (single pulse) noise criteria from Southall *et al.* (2019) for marine mammals.

Southall <i>et al.</i> (2019) $L_{E,p}$ (single pulse)	PTS (non-impulsive)				TTS (non-impulsive)			
	LF 199dB	HF 198dB	VHF 173dB	PCW 201dB	LF 179dB	HF 178dB	VHF 153dB	PCW 181dB
Low order (0.25kg)	<0.05km	<0.05km	<0.05km	<0.05km	0.46km	<0.05km	0.11km	0.08km

Southall <i>et al.</i> (2019) $L_{E,p}$ (single pulse)	PTS (non-impulsive)				TTS (non-impulsive)			
	LF 199dB	HF 198dB	VHF 173dB	PCW 201dB	LF 179dB	HF 178dB	VHF 153dB	PCW 181dB
25kg + donor	0.13km	<0.05km	<0.05km	<0.05km	4.4km	<0.05km	0.73km	0.79km
55kg + donor	0.19km	<0.05km	<0.05km	<0.05km	6.4km	0.06km	0.94km	1.1km
120kg + donor	0.28km	<0.05km	0.07km	<0.05km	9.4km	0.08km	1.1km	1.6km
240kg + donor	0.39km	<0.05km	0.1km	0.07km	13km	0.11km	1.4km	2.3km
525kg + donor	0.57km	<0.05km	0.13km	0.1km	18km	0.16km	1.7km	3.3km
698kg + donor	0.66km	<0.05km	0.15km	0.11km	21km	0.18km	1.8km	3.8km
907kg + donor	0.75km	<0.05km	0.17km	0.13km	24km	0.2km	1.9km	4.3km

Table 5-13 Summary of the impact ranges for UXO detonation using the explosions $L_{p,pk}$ noise criteria from Popper *et al.* (2014) for species of fish.

Popper <i>et al.</i> (2014) $L_{p,pk}$	Mortality and potential mortal injury	
	234dB	229dB
Low order (0.25kg)	< 0.05km	0.06km
25kg + donor	0.17km	0.29km
55kg + donor	0.23km	0.38km
120kg + donor	0.3km	0.49km
240kg + donor	0.37km	0.62km
525kg + donor	0.49km	0.81km
698kg + donor	0.53km	0.89km
907kg + donor	0.58km	0.97km

5.3.4 Summary

The maximum PTS ranges calculated for UXO clearance is 15km for the VHF cetacean category when considering the $L_{p,pk}$ criteria for the largest high-order clearance. For $L_{E,p}$ criteria, the largest PTS range is calculated for LF cetaceans with a predicted impact range of 12km using the impulsive noise criteria. As explained earlier, this assumes no degradation of the UXO and no smoothing of the pulse over distance, which is very precautionary. Although an assumption of non-pulse could underestimate the potential impact (Martin *et al.*, 2020) (the equivalent range based on LF cetacean non-pulse criteria is 750m), it is likely that the long-range smoothing of the pulse peak would reduce its potential harm and the maximum 'impulsive' range for all species is very precautionary.

6 Summary and conclusions

This report presents the findings of an assessment of potential underwater noise (and its effects) during the construction and operation of the proposed Dogger Bank D offshore wind farm, located in the North Sea, within English waters.

The level of underwater noise from the installation of turbine foundations during construction using impact piling has been estimated using the semi-empirical underwater noise model INSPIRE. The modelling considers a wide variety of input parameters including bathymetry, hammer blow energy, strike rate, and receptor fleeing speed.

Four modelling locations were chosen to give spatial variation across the site as well as accounting for changes in water depth. Two scenarios were considered across the modelling locations:

- A monopile foundation scenario considering an 18m diameter pile installed using a maximum hammer energy of 8,000kJ and up to 2 piles installed per vessel per day, and
- A multi-leg jacket pile foundation scenario considering 5m diameter piles installed using a maximum hammer energy of 5,000kJ and up to 4 piles installed per vessel per day.

The modelling results were analysed in terms of relevant noise metrics and criteria to assess the effects of the impact piling on marine mammals (Southall *et al.*, 2019) and fish (Popper *et al.*, 2014), which have been used to inform biological assessments.

For marine mammals, maximum PTS ranges were predicted for LF cetaceans, with ranges of up to 9.5km predicted based on the monopile foundation scenario with impulsive criteria. Using the non-impulsive criteria (Appendix A), this reduces to less than 100m, although as Matei *et al.* (2024) indicates that there is still low confidence in the distance at which piling noise could be considered non-impulsive, this does suggest that a presumption of full impulsivity out to 9.5km is highly precautionary.

For fish, the largest recoverable injury ranges (203dB $L_{E,p,24h}$) were predicted to be 12km for a stationary receptor, reducing to 350m for a fleeing receptor.

Noise sources other than piling have been considered using a high-level, simple modelling approach, including drilling, alternative foundation options, cable and scour protection, vessel movement, and operational WTG noise. The predicted noise levels for these construction noises are well below those predicted for impact piling noise. The risk of any potentially injurious effects to fish or marine mammals from these sources are expected to be minimal as the noise emissions from these are close to, or below, the appropriate injury criteria, even when very close to the source of the noise.

UXO clearance has also been considered across the Dogger Bank D site, and for the potential UXO clearance noise, there is a risk of PTS up to 15km from the largest UXO device considered (907kg + donor charge), using the unweighted $L_{p,pk}$ criteria for VHF cetaceans. However, this is likely to be highly precautionary as the impact range is based on a worst-case criterion and calculation methodology that does not account for any smoothing of the pulse over long ranges, which would reduce the pulse peak and other characteristics of the sound that cause injury.

The outputs of this modelling have been used to inform assessments of the impacts of underwater noise on marine mammals and fish at Dogger Bank D in their respective reports.

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Appendix A Additional modelling results

Following the impulsive Southall *et al.* (2019) modelled impact piling ranges presented in Section 4, the modelling results for the non-impulsive criteria are presented below. The predicted ranges here fall well below the impulsive criteria presented in the main report.

A.1 Single location modelling

Table A 1: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall *et al.* (2019) non-impulsive criteria covering the monopile foundation modelling for two sequentially installed piles at the NE corner modelling location.

Southall <i>et al.</i> (2019) $L_{E,p,24h,wtd}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	HF (198dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (173dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	PCW (201dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
TTS (Non-impulsive)	LF (179dB)	650km ²	16km	12km	14km
	HF (178dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (153dB)	240km ²	9.3km	7.8km	8.8km
	PCW (181dB)	23km ²	2.9km	2.5km	2.7km

Table A 2: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall *et al.* (2019) non-impulsive criteria covering the jacket pile foundation modelling for two sequentially installed piles at the NE corner modelling location.

Southall <i>et al.</i> (2019) $L_{E,p,24h,wtd}$		Jacket pile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	HF (198dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (173dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	PCW (201dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
TTS (Non-impulsive)	LF (179dB)	460km ²	13km	9.8km	12km
	HF (178dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (153dB)	180km ²	8.0km	6.7km	7.5km
	PCW (181dB)	13km ²	2.2km	1.9km	2.1km

Table A 3: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the monopile foundation modelling for two sequentially installed piles at the NW corner modelling location.

Southall et al. (2019) $L_{E,p,24h,wtd}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	HF (198dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (173dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	PCW (201dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
TTS (Non-impulsive)	LF (179dB)	600km ²	17km	11km	14km
	HF (178dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (153dB)	220km ²	9.5km	7.2km	8.4km
	PCW (181dB)	16km ²	2.5km	2.1km	2.3km

Table A 4: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the jacket pile foundation modelling for two sequentially installed piles at the NW corner modelling location.

Southall et al. (2019) $L_{E,p,24h,wtd}$		Jacket pile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	HF (198dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (173dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	PCW (201dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
TTS (Non-impulsive)	LF (179dB)	< 0.1km ²	0.25km	0.13km	0.16km
	HF (178dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (153dB)	160km ²	8.2km	6.1km	7.2km
	PCW (181dB)	9.2km ²	1.9km	1.5km	1.7km

Table A 5: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the monopile foundation modelling for two sequentially installed piles at the SE corner modelling location.

Southall et al. (2019) $L_{E,p,24h,wtd}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	HF (198dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (173dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	PCW (201dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
TTS (Non-impulsive)	LF (179dB)	430km ²	15km	9.2km	12km
	HF (178dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (153dB)	150km ²	8km	6.1km	7km
	PCW (181dB)	8.4km ²	1.7km	1.5km	1.6km

Table A 6: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the jacket pile foundation modelling for two sequentially installed piles at the SE corner modelling location.

Southall et al. (2019) $L_{E,p,24h,wtd}$		Jacket pile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	HF (198dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (173dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	PCW (201dB)	< 0.1km ²	< 0.1km	< 0.1k	< 0.1km
TTS (Non-impulsive)	LF (179dB)	< 0.1km ²	0.18km	< 0.1km	0.12km
	HF (178dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (153dB)	110km ²	6.7km	5.1km	5.8km
	PCW (181dB)	4.2km ²	1.2km	1.1km	1.2km

Table A 7: Summary of the weighted $L_{E,p,t}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria covering the monopile foundation modelling for two sequentially installed piles at the Centre (OSP) modelling location.

Southall et al. (2019) $L_{E,p,24h,wtd}$		Monopile foundation			
		Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	HF (198dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (173dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	PCW (201dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
TTS (Non-impulsive)	LF (179dB)	560km ²	16km	11km	13km
	HF (178dB)	< 0.1km ²	< 0.1km	< 0.1km	< 0.1km
	VHF (153dB)	220km ²	9.6km	7.5km	8.3km
	PCW (181dB)	21km ²	2.9km	2.3km	2.6km

A.2 Multiple location modelling

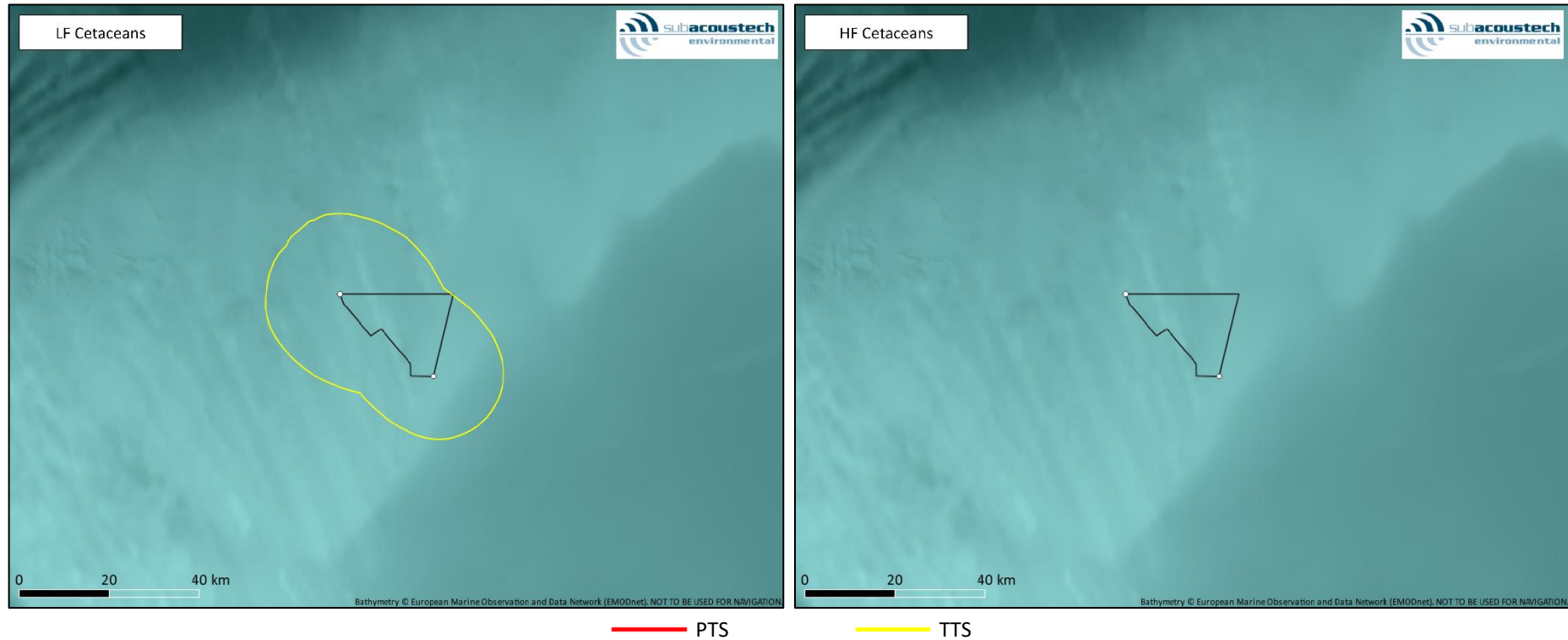


Figure A 1: Contour plots showing the in-combination impacts of concurrent installation of monopile foundations at the NW and SE corners of the Dogger Bank D site for LF and HF cetaceans using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal.

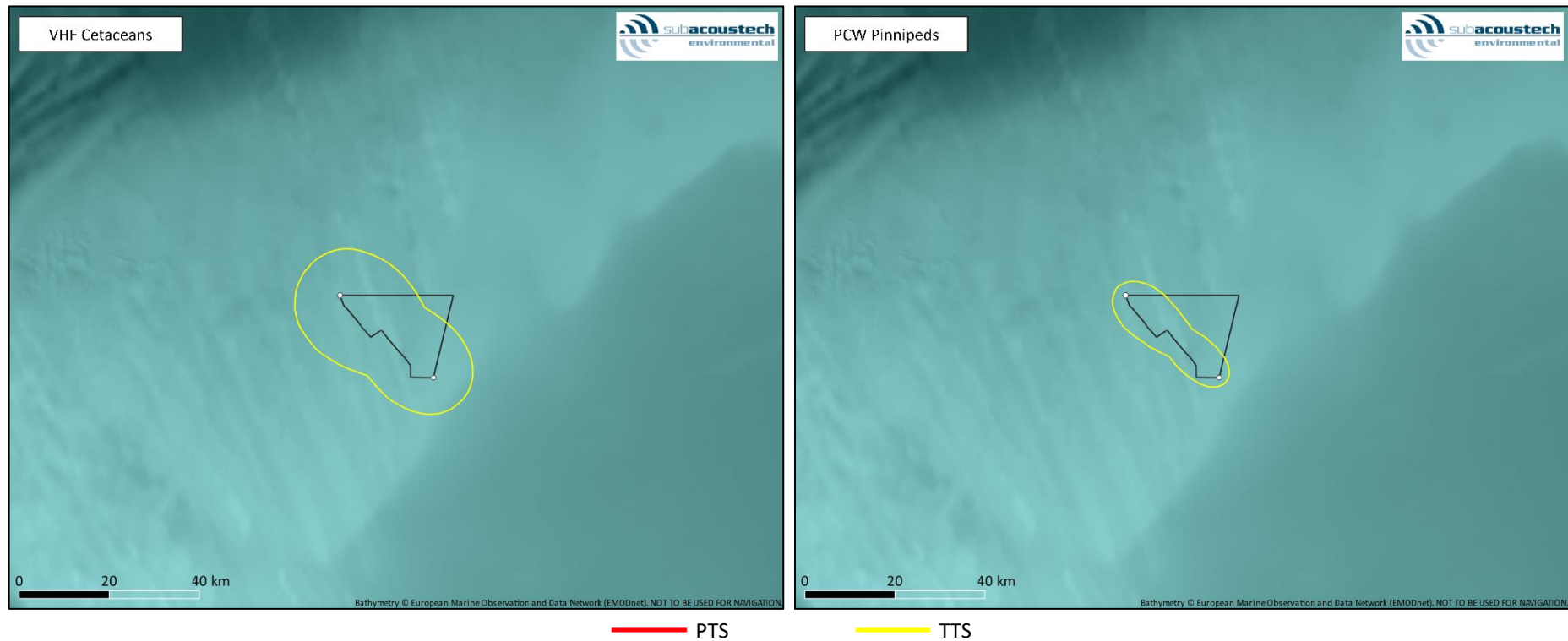


Figure A 2: Contour plots showing the in-combination impacts of concurrent installation of monopile foundations at the NW and SE corners of the Dogger Bank D site for VHF cetaceans and PCW pinnipeds using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal.

Table A 8: Summary of the impact areas for the installation of monopile foundations at the NW and SE corners of the Dogger Bank D site for marine mammals using the non-impulsive Southall *et al.* (2019) criteria assuming a fleeing animal.

Monopile foundations (Southall <i>et al.</i> , 2019) $L_{E,p,24h,wtd}$		NW corner	SE corner	In-combination area
PTS (Non-impulsive)	LF (199dB)	< 0.1km ²	< 0.1km ²	-
	HF (198dB)	< 0.1km ²	< 0.1km ²	-
	VHF (173dB)	< 0.1km ²	< 0.1km ²	-
	PCW (201dB)	< 0.1km ²	< 0.1km ²	-
TTS (Non-impulsive)	LF (179dB)	600km ²	430km ²	1,700km ²
	HF (178dB)	< 0.1km ²	< 0.1km ²	-
	VHF (153dB)	220km ²	150km ²	890km ²
	PCW (181dB)	16km ²	8.4km ²	280km ²

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