Muir Mhòr Offshore Wind Farm

Environmental Impact Assessment Report

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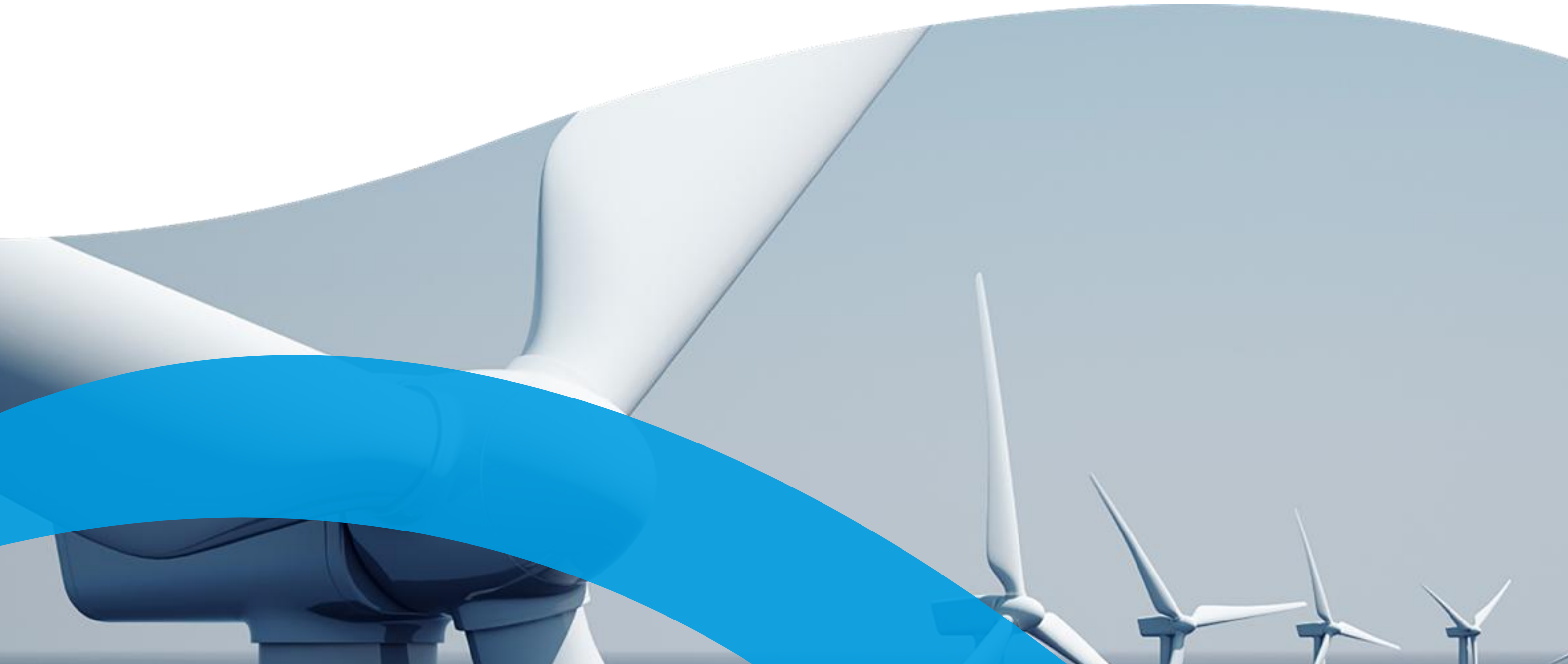

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Muir Mhòr Offshore Wind Farm: Underwater noise assessment

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Executive Summary

Subacoustech Environmental Ltd., on behalf of GoBe Consultants Ltd., has undertaken a study to assess the potential underwater noise caused by the Proposed Development and the effects on local marine fauna during its construction and operation.

Modelling of the noise from impact piling for the Offshore Electrical Platform (OEP) and anchor piles for floating turbines was undertaken at three representative locations. The loudest levels of underwater noise and the greatest impact ranges for key species were predicted for the OEP pile foundation scenario, due to the large pile diameter and high blow energies required to drive the pile.

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, maximum Permanent Threshold Shift (PTS) impact ranges were predicted for animals in the Low-Frequency (LF) cetacean category, with ranges out to 51 km. For fish, the largest recoverable injury ranges were predicted to be 22 km assuming a stationary receptor, reducing to 1.1 km when considering a fleeing receptor.

Noise sources other than piling, including cable laying, dredging, drilling, rock placement, trenching and vessel movements, and operational Wind Turbine Generator (WTG) noise, were all predicted to have PTS ranges of under 1 km, well below those predicted for impact piling noise. Noise from Unexploded Ordnance (UXO) clearance showed a risk of PTS out to 14 km from the largest device considered (750 kg + donor charge). However, this is likely to be highly precautionary due to the necessary assumptions made for the modelling.

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 works associated with the Proposed Development.

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.

List of contents

Glossary

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 second symbol identifying the specific reference value (e.g., re 1 µPa).
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)	Onset of a permanent total or partial loss of 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. $L_{E,p}$ 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 1 µPa for water and 20 µPa 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 of temporary reduction of hearing acuity because of exposure to sound over time. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory cells. The duration of TTS varies depending on the nature of the stimulus.
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.

Units

dB	Decibel (sound pressure)
GW	Gigawatt (power)
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^2s	Pascal squared seconds (acoustic energy)
µPa	Micropascal (pressure)

Acronyms

ADD	Acoustic Deterrent Device
BGS	British Geological Survey
EIAR	Environmental Impact Assessment Report
EMODnet	European Marine Observation and Data Network
FPSO	Floating Production Storage and Offloading (vessel type)
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
OEP	Offshore Electrical Platform
PCW	Phocid Carnivores in Water
PPV	Peak Particle Velocity
PTS	Permanent Threshold Shift
RMS	Root Mean Square
SE	Sound Exposure
SEL	Sound Exposure Level
SNH	Scottish Natural Heritage
SPL	Sound Pressure Level
TNT	Trinitrotoluene (explosive)
TTS	Temporary Threshold Shift
UXO	Unexploded Ordnance
VHF	Very High-Frequency Cetaceans
WTG	Wind Turbine Generator

1 Introduction

Muir Mhòr Offshore Wind Farm Limited (the Developer) is proposing to develop Muir Mhòr Offshore Wind Farm (OWF) (hereafter referred to as the Project). The Project is made up of both offshore and onshore components. The offshore infrastructure of the Project seaward of Mean High-Water Springs (MHWS) is hereafter referred to as 'the Proposed Development'. The Proposed Development Array Area is located approximately 63 km east of Peterhead on the east coast of Scotland, covering an area of approximately 200 km^2. The Project is anticipated to have a capacity of approximately 1 Gigawatt (GW) comprising floating offshore wind technology.

The location of the array area boundary is shown in Figure 1-1.

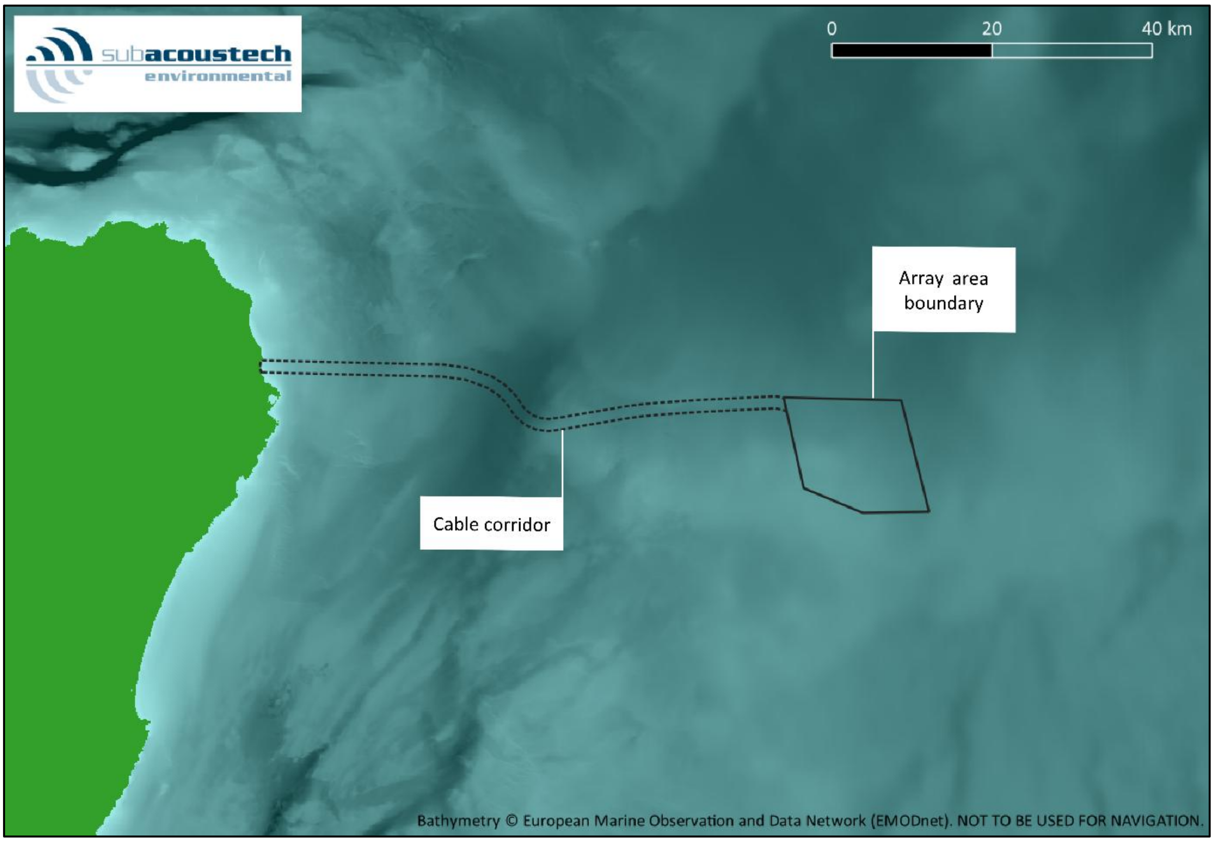

Figure 1-1 Overview map showing the Proposed Development array area boundary, cable corridor, the surrounding bathymetry and coastline.

As part of the Environmental Impact Assessment Report (EIAR) process, Subacoustech Environmental Ltd. has undertaken detailed modelling and analysis to predict the effect of underwater noise on marine mammals and fish. This report presents a detailed assessment of the potential underwater noise during the construction and operation of the Proposed Development 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 the Proposed Development, including cable laying, dredging, drilling, rock placement, vessel movements, operational WTG noise, and unexploded ordnance (UXO) clearance (Section 5); and
- Summary and conclusions (Section 6).

Further modelling results are presented in Annex A.

2 Underwater noise concepts

2.1 Underwater noise

Sound travels much faster in water (approximately 1,500 m/s) than in air (340 m/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 20 micropascals (µPa) is used for sound in air since that is the lower threshold of human hearing. One Pascal (Pa) is equal to the pressure exerted by one Newton over one square metre, one micropascal (µPa) equals one millionth of this.

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 1 µPa is typically used as the reference unit (P_{ref}).

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.

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

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^{2}s).

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

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

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 10 dB higher than the L_p; for a sound of 100 seconds duration the $L_{E,p,100s}$ will be 20 dB 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 $L_{E,p,t}$ is the sound exposure level of one impulse and X is the total number of impulses or strikes. Unless otherwise defined, all $L_{E,p,t}$ noise levels in this report are references to 1 µPa^{2}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.

Objective categorisation of noise sources 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 impulsive noise will become less injurious if it becomes less impulsive.

Active research is currently underway to define 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 3.5 km from the source. Using these findings, Southall (2021) suggests that noise should be considered non-impulsive when there is no longer energy content above 10 kHz. However, research remains in progress, with work ongoing in an attempt to determine numerical values of other pulse characteristics, such as for kurtosis, that can aid categorisation of a pulse as either impulsive or non-impulsive.

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 ($L_{E,p,t}$)

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, is 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 (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.

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 in the vicinity of the Proposed Development.

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;
- NOAA (2005) behavioural disturbance criteria (Level B) for marine mammals; and
- 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. The 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 and Moray Firth.

It should be noted that despite Southall *et al*. (2019) referring to peak SPL as $\mathrm{SPL_{peak}}$, 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)	7 Hz to 35 kHz	Baleen whales
High-frequency cetaceans (HF)	150 Hz to 160 kHz	Dolphins, toothed whales, beaked whales, bottlenose whales (including bottlenose dolphin)
Very high-frequency cetaceans (VHF)	275 Hz to 160 kHz	True porpoises (including harbour porpoise)
Phocid carnivores in water (PCW)	50 Hz to 86 kHz	True seals (including harbour seals)

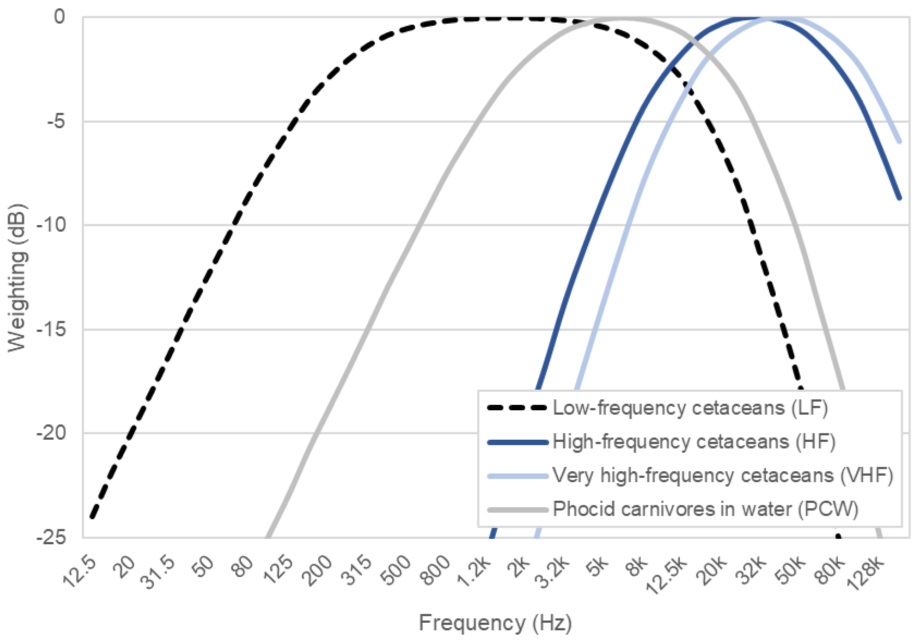

Figure 2-1 Auditory weighting functions for LF, HF, VHF, and PCW (from Southall et al., 2019).

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 relevant. Both impulsive and non-impulsive criteria have been presented in this study.

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. For this study, the following flee speeds have been used for marine mammals:

- 2.1 m/s for low-frequency cetaceans (LF) (Scottish Natural Heritage; SNH, 2016);
- 1.52 m/s for high-frequency cetaceans (HF) (Bailey and Thompson, 2006);

- 1.4 m/s for very high-frequency cetaceans (VHF) (SNH, 2016); and
- 1.8 m/s for phocid carnivores in water (PCW) (SNH, 2016).

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. The fleeing animal model and the assumptions related to it are discussed in more detail in Section 3.3.

Within each of the impulsive and non-impulsive noise criteria set out by Southall *et al.* (2019), different impact thresholds are presented depending on the potential of different levels of auditory injury at different noise levels of that sound. Auditory injury is grouped into the following two types:

- Permanent Threshold Shift (PTS) – unrecoverable (but incremental) hearing damage; and
- Temporary Threshold Shift (TTS) – a temporary reduction in hearing sensitivity.

It should be noted that the greatest calculated impact range is usually associated with TTS. However, the effects from PTS present permanent (but only incremental, not total) impairment, and thus, PTS is usually quoted as the most important impact threshold.

In summary, when using Southall *et al*. (2019) assessment criteria to calculate impacts, three variables are considered:

- The marine mammal receptors within the area;
- The nature of the sound (and subsequently, the appropriate metrics); and
- The type of auditory injury.

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

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

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

Table 2-3 $L_{E,p,24h,wtd}$ criteria for PTS and TTS in marine mammals (Southall et al., 2019).

Southall *et al.* (2019)	**$L_{E,p,24h,wtd}$ (dB re 1 µPa²s)**			
	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

Limited data is available for behavioural disturbance on species of marine mammal. To take this into account, the NOAA (2005) Level B (behavioural disturbance) harassment criterion for impulsive noise on marine mammals has been included to cover disturbance effects. This criterion is 160 dB unweighted L_p (RMS).

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. While previous studies have applied broad criteria based on limited studies of fish that are not present in UK waters (McCauley *et al*. 2000), or measurement data not intended to be used as criteria (Hawkins *et al*., 2014), Popper *et al*. (2014) provides a summary of the latest research and guidelines for fish (and other marine fauna) exposure to sound and uses categories for fish that are representative of the species present around the 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 1.5 m/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). Despite this, including only a stationary animal model as a worst-case scenario is likely to greatly overestimate the potential risk to fish species. 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, but as a worst case the stationary modelling results for fish should be considered in the first instance.

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	> 219 dB $L_{E,p,24h}$ > 213 dB $L_{p,pk}$	> 216 dB $L_{E,p,24h}$ > 213 dB $L_{p,pk}$	>> 186 dB $L_{E,p,24h}$	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder not involved in hearing	210 dB $L_{E,p,24h}$ > 207 dB $L_{p,pk}$	203 dB $L_{E,p,24h}$ > 207 dB $L_{p,pk}$	> 186 dB $L_{E,p,24h}$	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder involved in hearing	207 dB $L_{E,p,24h}$ > 207 dB $L_{p,pk}$	203 dB $L_{E,p,24h}$ > 207 dB $L_{p,pk}$	186 dB $L_{E,p,24h}$	(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate
Sea turtles	> 210 dB $L_{E,p,24h}$ > 207 dB $L_{p,pk}$	(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	> 210 dB $L_{E,p,24h}$ > 207 dB $L_{p,pk}$	(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 – 234 dB $L_{p,pk}$	(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 – 234 dB $L_{p,pk}$	(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 – 234 dB $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low
Sea turtles	229 – 234 dB $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low
Eggs and larvae	> 13 mm/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 *et al.* (2014) criteria for shipping and continuous					
Receptor	**Mortality and potential mortal injury**	**Impairment**			**Behaviour**
		Recoverable injury	**TTS**	**Masking**	
Fish: no swim bladder	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder not involved in hearing	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder involved in hearing	(N) Low (I) Low (F) Low	170 dB $L_{p,48h}$	158 dB $L_{p,12h}$	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
Sea turtles	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) High (I) Moderate (F) Low
Eggs and larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) Moderate (I) Moderate (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 300 Hz tones, whereas Spiga *et al.* (2016) describes behavioural changes in the same species at $L_{E,p}$ (single pulse) 153.47 dB re 1 µPa. These inconsistencies make it difficult to generate accurate thresholds for the onset of any impact for invertebrate species. A notable exception is the cephalopods group, in which several studies, mainly by Solé *et al.* (2019, 2018, 2013) and André *et al.* (2011) show a consistent threshold for auditory damage on various species of cephalopod at 157 dB re 1 µPa. 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 confidently generate impact thresholds which would be satisfactory to regulators. While it is acknowledged that evidence of noise impacts to marine invertebrates does exist, there is still limited potential for utilisation of the data available in underwater noise assessments for any key species in the vicinity of the Project. Therefore, the focus of this assessment will focus on fish as per the guidance in Popper *et al.* (2014).

3 Modelling methodology

To estimate the underwater noise levels likely to arise during the construction and operation of the Proposed Development, 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 underwater noise model. 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 acoustically shallow (i.e., less than 100 m), 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 the Proposed Development; 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.

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 current version of INSPIRE (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 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.

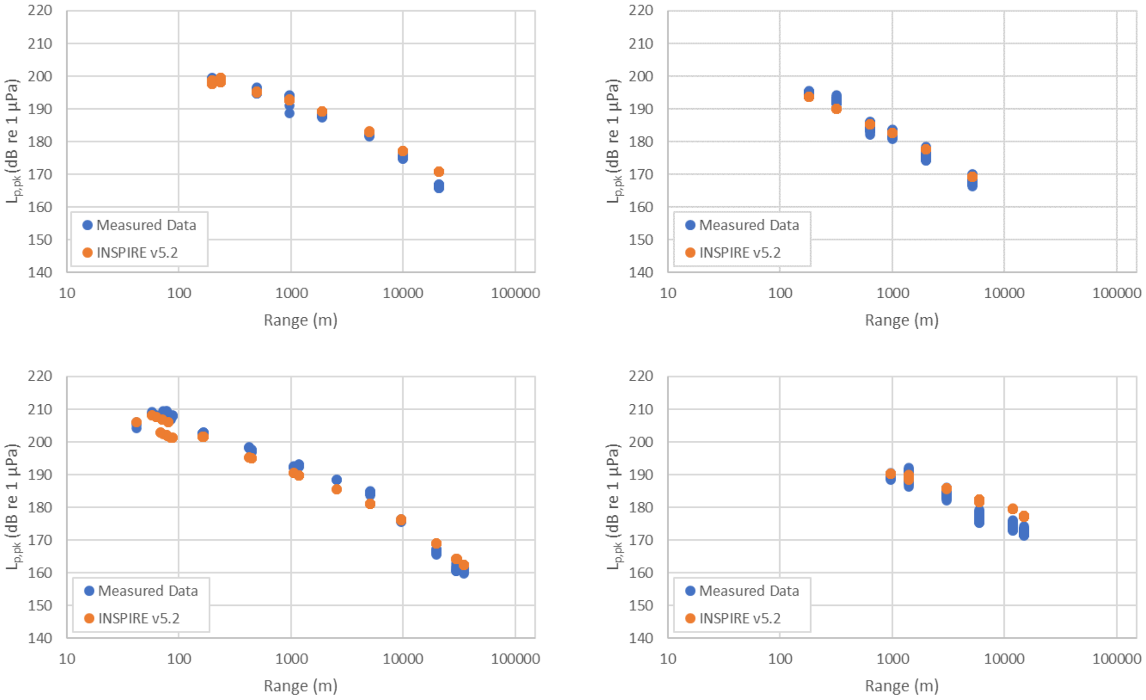

Figure 3-1 Comparison between example measured $L_{p,pk}$ impact piling data (blue points) and modelled data using INSPIRE version 5.2 (orange points)[1].

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

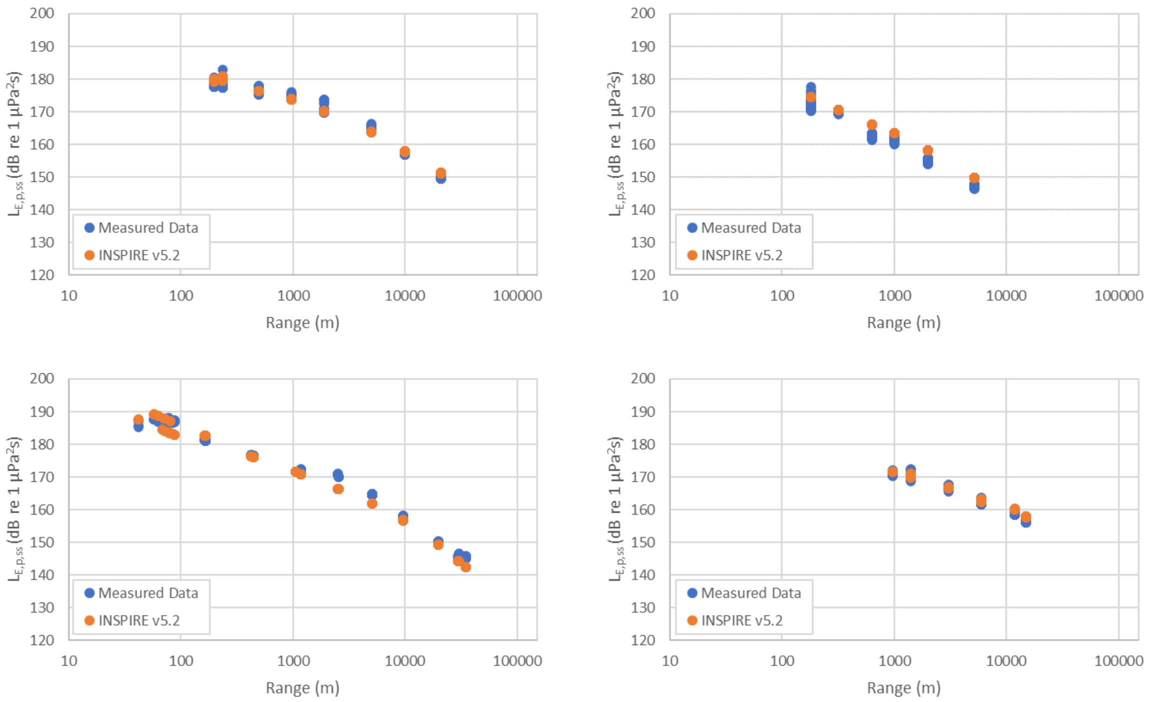

Figure 3-2 Comparison between example measured $L_{E,p,ss}$ impact piling data (blue points) and modelled data using INSPIRE version 5.2 (orange points)[2].

3.2 Modelling parameters

3.2.1 Modelling locations

Modelling for foundation impact piling, covering piled anchors for the floating WTGs and fixed foundations for the OEP, has been undertaken at three representative locations covering the extents of the array area boundary.

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

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

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

Modelling locations	Latitude	Longitude	Water depth
North East (NE) corner (Piled anchors)	57.4762° N	0.4738° W	97.1 m
South West (SW) corner (Piled anchors)	57.3819° N	0.6831° W	61.8 m
Centre location (OEP piles)	57.4187° N	0.5698° W	73.9 m

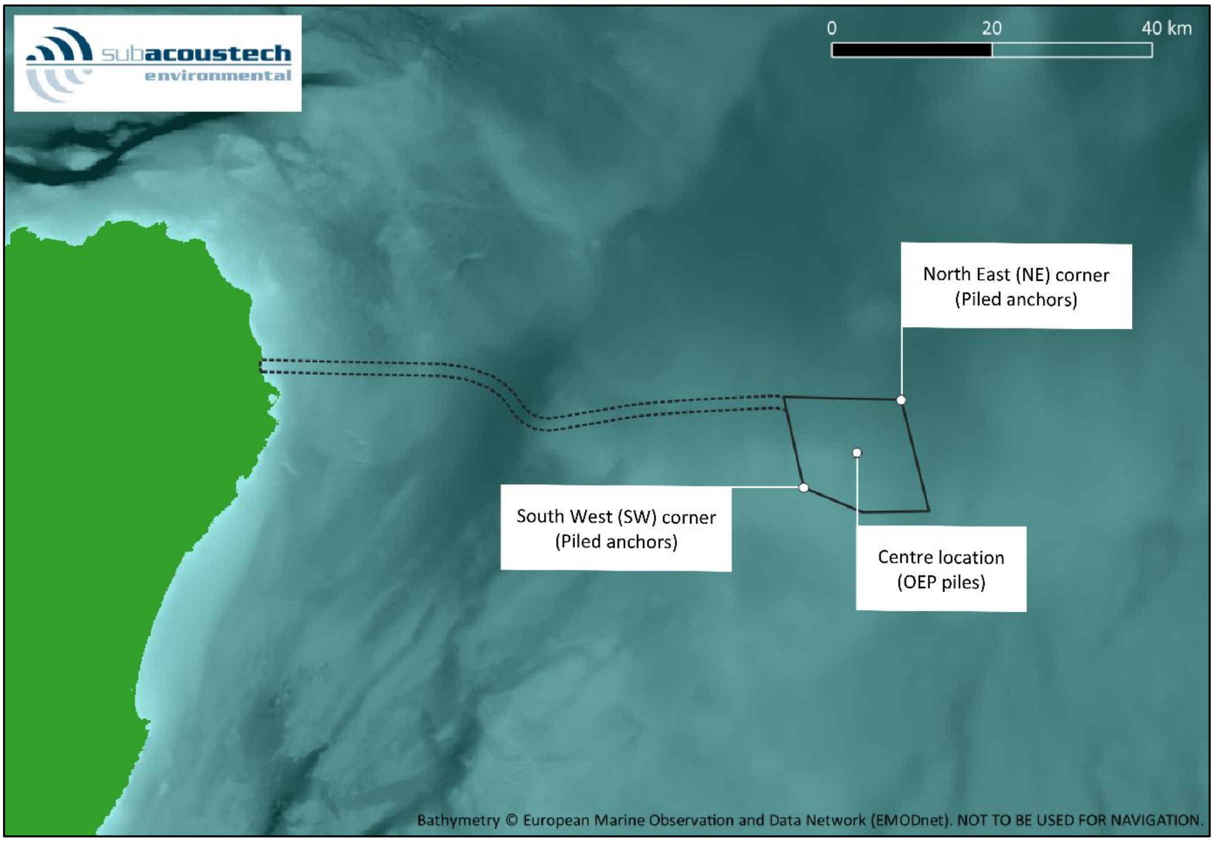

Figure 3-3 Approximate positions of the modelling locations at the Proposed Development.

3.2.2 Impact piling parameters

Two foundation designs have been considered for this study: piled anchors for the floating WTGs and fixed pin piles for the OEP.

- A piled anchor scenario for floating WTGs, installing 4.0 m diameter piles with a maximum blow energy of 2,400 kJ; and
- An OEP foundation scenario, installing 5.0 m[3] diameter pile with a maximum blow energy of 3,200 kJ.

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[3] *A 5 m OEP pile diameter was applied for modelling, to cover the maximum conservative scenario when the project was considering both HVAC and HVDC technology. Subsequently, the Developer determined HVAC technology as the preferred alternative, and the realistic scenario for OEP pile diameter changed to 4 m. Any difference in potential effects from 5 m and 4 m pile diameter is expected to be negligible, or marginally lower. The original conservative scenario of 5 m pile diameter has therefore been retained here.*

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 to Table 3-3.

In a 24-hour period, it is expected that up to ten piled anchors, or six OEP pile foundations can be installed sequentially from the same piling vessel. This has been taken into consideration for the modelling. Due to the worst-case nature of this, “more likely” scenarios of five sequentially installed piled anchors and three sequentially installed OEP piles have also been included separately.

There is also the possibility that two piling vessels could be operational simultaneously across the Proposed Development. These scenarios have also been modelled and are considered in Section 4.2. Where multiple sequential piles are modelled, no break has been assumed between each one, as a worst-case scenario.

A portion of the piling for each of the piled anchors will take place subsea, with the piling hammer submerged. It has been assumed that the piled anchors measure 70 m in length and the OEP piles measure 110 m, and in each case, once fully installed, 10 m of the pile will protrude from the seabed. This has been included in the modelling, as the radiating area for noise reduces as the pile is driven further, affecting its noise output.

Table 3-2 Summary of the soft start and ramp up scenario used for the piled anchor modelling.

Piled anchors	**15% (360 kJ)**	**40% (960 kJ)**	**60% (1,440 kJ)**	**80% (1,920 kJ)**	**100% (2,400 kJ)**
No of strikes	200	350	350	350	2,100
Duration	20 mins	10 mins	10 mins	10 mins	60 mins
Strike rate (bl/min)	10	35	35	35	53
3,350 strikes over 1 hour, 50 minutes per pile **33,500 strikes over 18 hours, 20 minutes for ten piles (worst case)** **16,750 strikes over 9 hours, 10 minutes for five piles (more likely)**					

Table 3-3 Summary of the soft start and ramp up scenario used for the OEP pile foundation modelling.

OEP piles	**15% (480 kJ)**	**40% (1,280 kJ)**	**60% (1,920 kJ)**	**80% (2,560 kJ)**	**100% (3,200 kJ)**
No of strikes	200	350	350	350	5,250
Duration	20 mins	10 mins	10 mins	10 mins	150 mins
Strike rate (bl/min)	10	35	35	35	35
6,500 strikes over 3 hour, 20 minutes per pile **39,000 strikes over 20 hours for six piles (worst case)** **19,500 strikes over 10 hours for three piles (more likely)**					

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 (< 100 m) 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 single-point 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 are all in excess of 50 m.

Table 3-4 Summary of the unweighted source levels used for modelling

Source levels	Modelling location	$L_{p,pk}$ @ 1 m	$L_{E,p,ss}$ @ 1 m
Piled anchor (4.0 m diameter pile / 2,400 kJ maximum energy)	NE corner	241.2 dB re 1 µPa @ 1 m	221.9 dB re 1 µPa^{2}s @ 1 m
	SW corner	241.2 dB re 1 µPa @ 1 m	221.9 dB re 1 µPa^{2}s @ 1 m
OEP pile (5.0 m diameter pile / 3,200 kJ maximum energy)	Centre	242.0 dB re 1 µPa @ 1 m	22.9 dB re 1 µPa^{2}s @ 1 m

There will be a variation in the piled anchors' apparent source levels as the length of the pile in the water reduces during driving. The maximum levels are shown in the table above.

3.2.4 Predicted noise levels at 750 m 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 750 m 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 750 m 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. Due to the aforementioned deep water across the array area, there are minimal differences in the noise levels at different locations at this range.

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	$L_{p,pk}$ @ 750 m	$L_{E,p,ss}$ @ 750 m
Piled anchor (4.0 m diameter pile / 2,400 kJ maximum energy)	NE corner	201.8 dB re 1 µPa	182.5 dB re 1 µPa^{2}s
	SW corner	201.7 dB re 1 µPa	182.4 dB re 1 µPa^{2}s
OEP pile (5.0 m diameter pile / 3,200 kJ maximum energy)	Centre	202.5 dB re 1 µPa	183.4 dB re 1 µPa^{2}s

3.2.5 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 the array area is generally made up of various combinations of sand, mud and gravel.

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 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 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 1.5 m/s, it is 9 m 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 in Figure 3-4 and Figure 3-5 show the difference in the received $L_{E,p,t}$ from a stationary receptor and a fleeing receptor travelling at a constant speed of 1.5 m/s, using the piled anchor 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 3-4, 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 piled anchor is 360 kJ (15% of maximum energy), fleeing at a rate of 1.5 m/s, a receptor has the potential to move 1.8 km from the noise source. After the full installation of one hour 50 minutes, the receptor has the potential to be almost 10 km from the noise source.

Figure 3-5 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 1 m, the first strike results in a received level of 213.5 dB re 1 µPa^{2}s. If the receptor were to remain stationary throughout the piling operation, it would receive a cumulative level of 256.5 dB re 1 µPa^{2}s, whereas when fleeing at 1.5 m/s over the same scenario, a cumulative received level of just 214.5 dB re 1 µPa^{2}s is achieved.

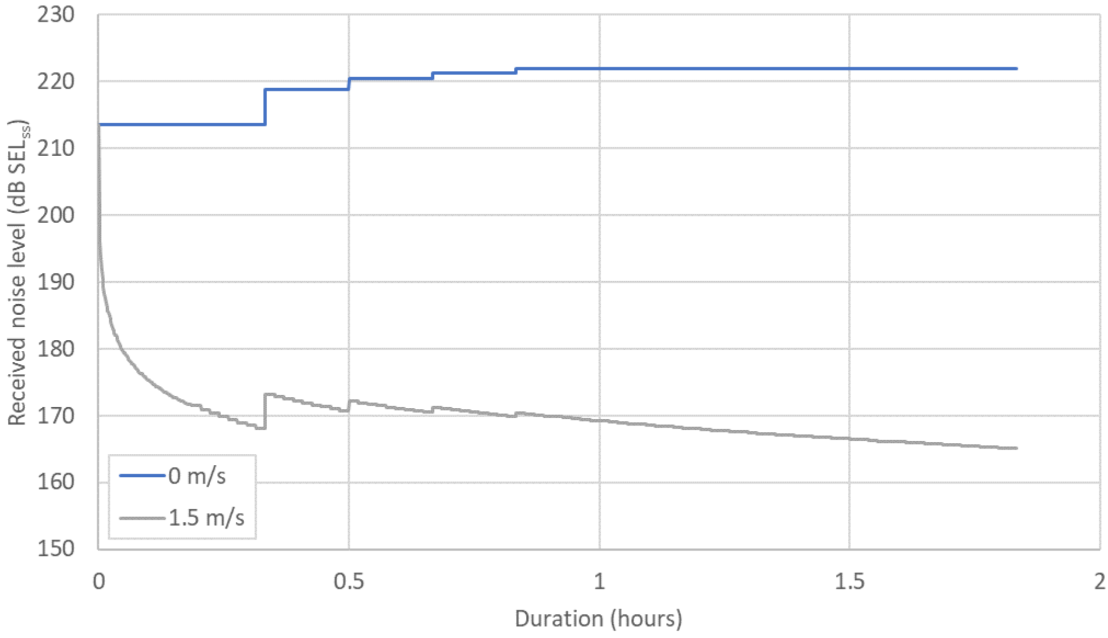

Figure 3-4 Received single strike noise levels ($L_{E,p,ss}$) for receptors during the piled anchor installation at the NE corner modelling location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source.

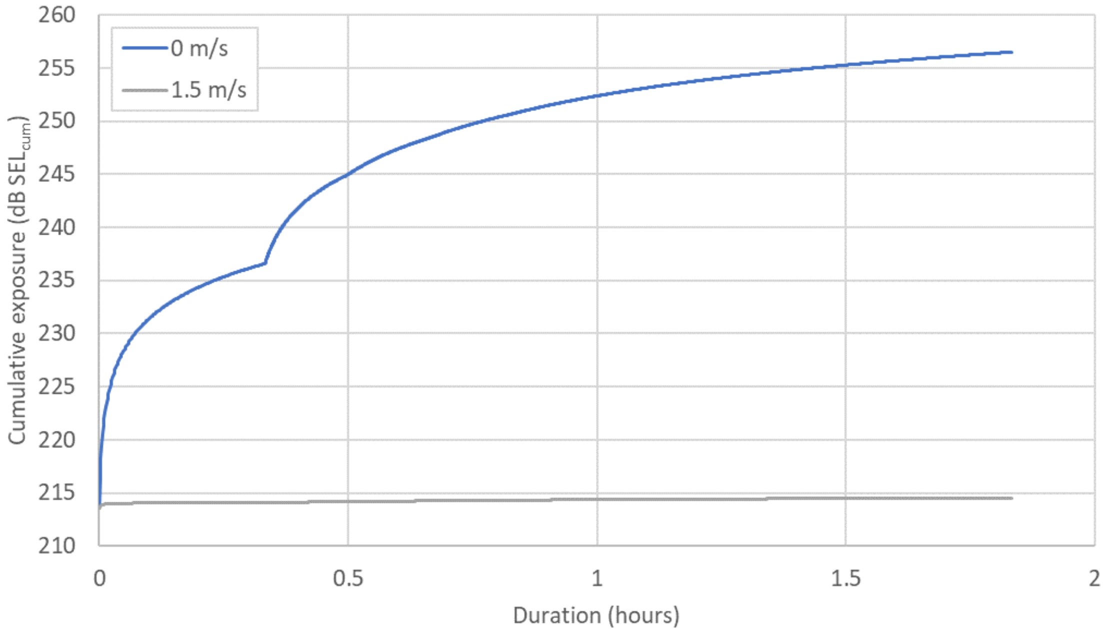

Figure 3-5 Cumulative received noise level ($L_{E,p,t}$) for receptors during pile anchor installation at the NE corner modelling location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source.

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 3-6.

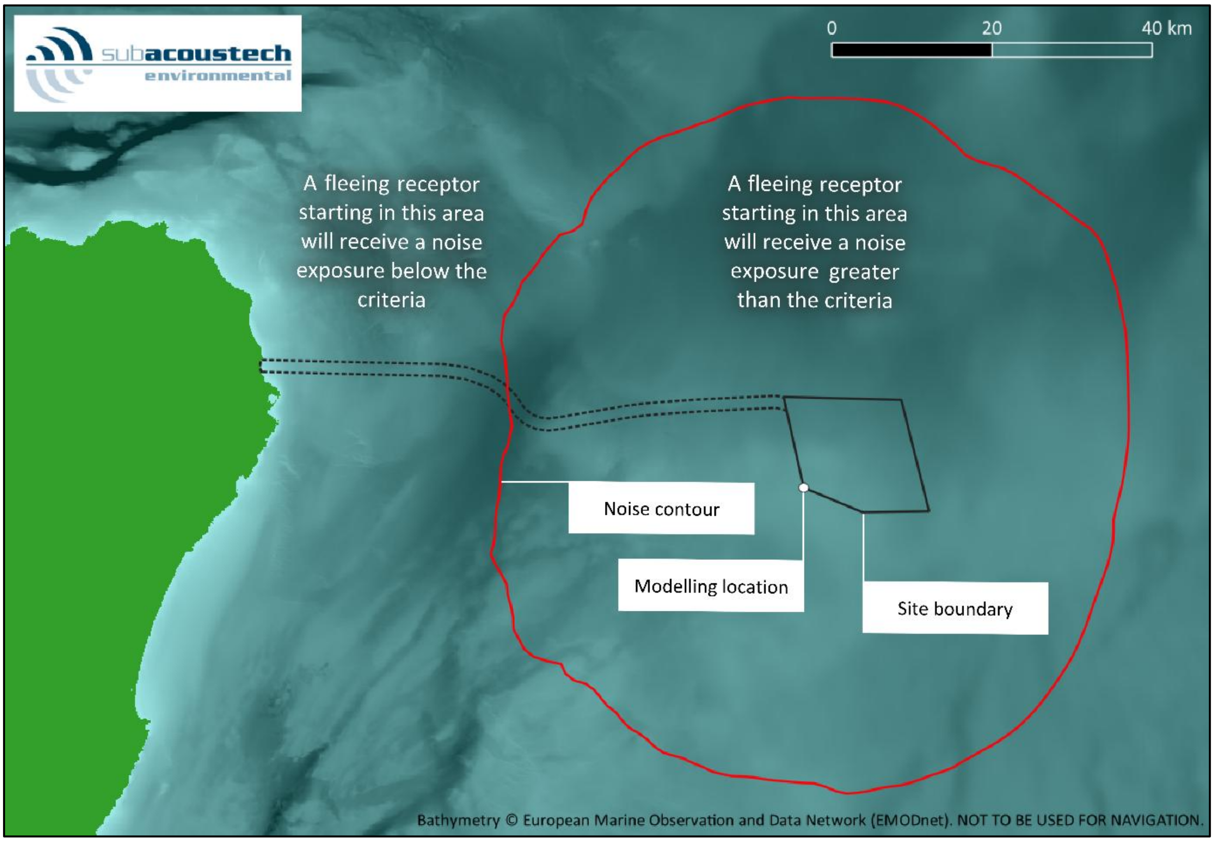

Figure 3-6 Example plot showing a fleeing animal $L_{E,p,t}$ criteria contour and the areas where the cumulative noise exposure will exceed an impact criteria.

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 effects 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 1.5 m/s, it would travel 1.8 km before piling begins. If a calculated cumulative $L_{E,p,t}$ impact range was below 1.8 km, 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 overall 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 subsequent 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, an increase in impact ranges will occur.

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-predicting 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 elements for acoustic modelling, described below. 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, in the locations likely to lead to maximum underwater noise transmission. 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 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 (i.e., there is a small under-estimate of noise attenuation with distance built in).

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 equally sensitive to sound at all frequencies, which is not the case. The thresholds calculated for PTS and TTS are the 'onset' to these effects, 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 for piling noise following the parameters detailed in Section 3.2, covering the Southall *et al*. (2019) and NOAA (2005) 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 contains a list of the impact range results tables included in Section 4.1. The largest modelled ranges are predicted for the worst case OEP pile foundation scenario due to the larger pile size and blow energies used for installation. Modelling covering concurrent piling at multiple locations is covered in Section 4.2.

Throughout this report, any predicted ranges smaller than 50 m and areas less than 0.01 km^2 for single strike criteria and ranges smaller than 100 m and areas less than 0.1 km^2 for cumulative criteria have not been presented precisely. 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. < 100 m).

For the $L_{p,pk}$ modelling results, no distinction is made between a Worst Case and More Likely as it is identical for this metric.

The modelling results for the Southall *et al*. (2019) non-impulsive criteria are presented in Annex 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 (p25)	NE corner (4.1.1) -- Piled anchors	Southall *et al.* (2019)	$L_{p,pk}$ (Impulsive)
Table 4-3 (p25)			$L_{E,p,24h,wtd}$ (Impulsive) Worst case (10 piles)
Table 4-4 (p25)			$L_{E,p,24h,wtd}$ (Impulsive) More likely (5 piles)
Table 4-5 (p26)		NOAA (2005)	L_p (Level B)
Table 4-6 (p26)		Popper *et al.* (2014)	$L_{p,pk}$ (Pile driving)
Table 4-7 (p26)			$L_{E,p,24h}$ (Pile driving) Worst case (10 piles)
Table 4-8 (p27)			$L_{E,p,24h}$ (Pile driving) More likely (5 piles)
Table 4-9 (p27)	SW corner (4.1.2) -- Piled anchors	Southall *et al.* (2019)	$L_{p,pk}$ (Impulsive)
Table 4-10 (p27)			$L_{E,p,24h,wtd}$ (Impulsive) Worst case (10 piles)
Table 4-11 (p28)			$L_{E,p,24h,wtd}$ (Impulsive) More likely (5 piles)
Table 4-12 (p28)		NOAA (2005)	L_p (Level B)
Table 4-13 (p28)		Popper *et al.* (2014)	$L_{p,pk}$ (Pile driving)
Table 4-14 (p28)			$L_{E,p,24h}$ (Pile driving) Worst case (10 piles)
Table 4-15 (p29)			$L_{E,p,24h}$ (Pile driving) More likely (5 piles)
Table 4-16 (p29)	Centre (4.1.3) -- OEP piles	Southall *et al.* (2019)	$L_{p,pk}$ (Impulsive)
Table 4-17 (p29)			$L_{E,p,24h,wtd}$ (Impulsive) Worst case (6 piles)
Table 4-18 (p30)			$L_{E,p,24h,wtd}$ (Impulsive) More likely (3 piles)
Table 4-19 (p30)		NOAA (2005)	L_p (Level B)
Table 4-20 (p30)		Popper *et al.* (2014)	$L_{p,pk}$ (Pile driving)
Table 4-21 (p30)			$L_{E,p,24h}$ (Pile driving) Worst case (6 piles)
Table 4-22 (p31)			$L_{E,p,24h}$ (Pile driving) More likely (3 piles)

4.1 Single location modelling

Table 4-2 to Table 4-22 present the modelling results for the single location scenarios, covering piled anchor and OEP pile foundation scenarios. For these scenarios, the largest marine mammal impact ranges are predicted for the worst case OEP pile foundation scenario, due to the larger pile size and higher blow energies in this scenario. Maximum PTS ranges are predicted for LF cetaceans out to 51 km. For fish, the largest recoverable injury ranges

(203 dB $L_{E,p,24h}$) are predicted out to 22 km when considering a stationary receptor, reducing to 1.1 km when a fleeing receptor is assumed.

It is worth noting that there are only small increases in $L_{E,p,24h}$ impact range between the more likely scenarios (5 sequential piles) and the worst case scenarios (10 sequential piles) for fleeing animals, as any additional piling occurs once a receptor has moved to a distance where noise levels are much lower than they are close to the source (as discussed in Section 3.3). This means that the additional accumulative noise to the total exposure is relatively low in comparison with the exposure already received.

4.1.1 NE corner

Table 4-2 Summary of the $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the piled anchor modelling at the NE corner modelling location.

Southall *et al.* (2019) $L_{p,pk}$		NE corner, piled anchor			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.2 km^2	620 m	620 m	620 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.03 km^2	100 m	100 m	100 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	8.5 km^2	1.6 km	1.6 km	1.6 km
	PCW (212 dB)	0.05 km^2	120 m	120 m	120 m

Table 4-3 Summary of the $L_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the worst case piled anchor modelling at the NE corner modelling location assuming a fleeing animal.

Southall *et al.* (2019) $L_{E,p,24h,wtd}$		NE corner, piled anchor (worst case, 10 piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	4,000 km^2	44 km	29 km	36 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	800 km^2	18 km	14 km	16 km
	PCW (185 dB)	2.7 km^2	1.1 km	750 m	920 m
TTS (Impulsive)	LF (168 dB)	44,000 km^2	161 km	71 km	117 km
	HF (170 dB)	0.8 km^2	580 m	430 m	510 m
	VHF (140 dB)	20,000 km^2	104 km	62 km	80 km
	PCW (170 dB)	8,200 km^2	65 km	41 km	51 km

Table 4-4 Summary of the $L_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the more likely piled anchor modelling at the NE corner modelling location assuming a fleeing animal.

Southall *et al.* (2019) $L_{E,p,24h,wtd}$		NE corner, piled anchor (more likely, 5 piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	3,800 km^2	41 km	29 km	35 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	740 km^2	17 km	14 km	15 km
	PCW (185 dB)	2.2 km^2	950 m	700 m	840 m
TTS	LF (168 dB)	43,000 km^2	156 km	71 km	115 km

Southall *et al.* (2019) **$L_{E,p,24h,wtd}$**		**NE corner, piled anchor (more likely, 5 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
(Impulsive)	HF (170 dB)	0.7 km^2	530 m	430 m	480 m
	VHF (140 dB)	18,000 km^2	96 km	62 km	76 km
	PCW (170 dB)	7,400 km^2	59 km	40 km	48 km

Table 4-5 Summary of the L_p impact ranges for marine mammals using the NOAA (2005) Level B criteria for the piled anchor modelling at the NE corner modelling location.

NOAA (2005) **L_p**		**NE corner, piled anchor**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	5,000 km^2	43 km	36 km	40 km

Table 4-6 Summary of the $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the worst case piled anchor modelling at the NE corner modelling location.

Popper *et al.* (2014) **$L_{p,pk}$**		**NE corner, piled anchor**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	0.03 km^2	100 m	100 m	100 m
	207 dB	0.24 km^2	280 m	280 m	280 m

Table 4-7 Summary of the $L_{E,p,24h}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the worst case piled anchor modelling at the NE corner modelling location assuming both a fleeing and stationary animal.

Popper *et al.* (2014) **$L_{E,p,24h}$**		**NE corner, piled anchor (worst case, 10 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 m/s)	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	100 m	< 100 m	< 100 m
	186 dB	7,200 km^2	59 km	39 km	48 km
Stationary (0 m/s)	219 dB	8.1 km^2	1.6 km	1.6 km	1.6 km
	216 dB	21 km^2	2.6 km	2.6 km	2.6 km
	210 dB	130 km^2	6.5 km	6.4 km	6.5 km
	207 dB	310 km^2	10 km	9.8 km	9.9 km
	203 dB	880 km^2	17 km	16 km	17 km
	186 dB	21,000 km^2	97 km	69 km	82 km

Table 4-8 Summary of the $L_{E,p,24h}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the more likely piled anchor modelling at the NE corner modelling location assuming both a fleeing and stationary animal.

Popper *et al.* (2014) $L_{E,p,24h}$		**NE corner, piled anchor (more likely, 5 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 m/s)	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	100 m	< 100 m	< 100 m
	186 dB	6,500 km^2	54 km	38 km	45 km
Stationary (0 m/s)	219 dB	3.2 km^2	1.0 km	1.0 km	1.0 km
	216 dB	8.1 km^2	1.6 km	1.6 km	1.6 km
	210 dB	53 km^2	4.1 km	4.1 km	4.1 km
	207 dB	130 km^2	6.5 km	6.4 km	6.5 km
	203 dB	400 km^2	12 km	11 km	11 km
	186 dB	14,000 km^2	75 km	58 km	66 km

4.1.2 SW corner

Table 4-9 Summary of the $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the piled anchor modelling at the SW corner modelling location.

Southall *et al.* (2019) $L_{p,pk}$		**SW corner, piled anchor**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.2 km^2	620 m	620 m	620 m
	PCW (218 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.03 km^2	100 m	100 m	100 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	8.1 km^2	1.6 km	1.6 km	1.6 km
	PCW (212 dB)	0.05 km^2	120 m	120 m	120 m

Table 4-10 Summary of the $L_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the worst case piled anchor modelling at the SW corner modelling location assuming a fleeing animal.

Southall *et al.* (2019) $L_{E,p,24h,wtd}$		**SW corner, piled anchor (worst case, 10 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	3,300 km^2	39 km	28 km	32 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	650 km^2	16 km	13 km	14 km
	PCW (185 dB)	1.0 km^2	700 m	480 m	570 m
TTS (Impulsive)	LF (168 dB)	39,000 km^2	154 km	60 km	109 km
	HF (170 dB)	0.3 km^2	350 m	250 m	300 m
	VHF (140 dB)	17,000 km^2	96 km	53 km	74 km
	PCW (170 dB)	6,900 km^2	58 km	38 km	47 km

Table 4-11 Summary of the $L_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the more likely piled anchor modelling at the SW corner modelling location assuming a fleeing animal.

Southall *et al.* (2019) $L_{E,p,24h,wtd}$		**SW corner, piled anchor (more likely, 5 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	3,100 km^2	37 km	28 km	31 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	600 km^2	15 km	13 km	14 km
	PCW (185 dB)	0.8 km^2	600 m	450 m	520 m
TTS (Impulsive)	LF (168 dB)	37,000 km^2	149 km	60 km	107 km
	HF (170 dB)	0.3 km^2	300 m	250 m	280 m
	VHF (140 dB)	16,000 km^2	88 km	53 km	71 km
	PCW (170 dB)	6,300 km^2	54 km	38 km	45 km

Table 4-12 Summary of the L_p impact ranges for marine mammals using the NOAA (2005) Level B criteria for the piled anchor modelling at the SW corner modelling location.

NOAA (2005) L_p		**SW corner, piled anchor**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	4,400 km^2	41 km	35 km	37 km

Table 4-13 Summary of the $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the worst case piled anchor modelling at the SW corner modelling location.

Popper *et al.* (2014) $L_{p,pk}$		**SW corner, piled anchor**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	0.03 km^2	100 m	100 m	100 m
	207 dB	0.23 km^2	270 m	270 m	270 m

Table 4-14 Summary of the $L_{E,p,24h}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the worst case piled anchor modelling at the SW corner modelling location assuming both a fleeing and stationary animal.

Popper *et al.* (2014) $L_{E,p,24h}$		**SW corner, piled anchor (worst case, 10 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 m/s)	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	6,000 km^2	53 km	37 km	44 km
Stationary (0 m/s)	219 dB	7.9 km^2	1.6 km	1.6 km	1.6 km
	216 dB	20 km^2	2.5 km	2.5 km	2.5 km
	210 dB	120 km^2	6.2 km	6.1 km	6.1 km
	207 dB	270 km^2	9.4 km	9.2 km	9.3 km
	203 dB	760 km^2	16 km	15 km	16 km
	186 dB	18,000 km^2	89 km	66 km	76 km

Table 4-15 Summary of the $L_{E,p,24h}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the more likely piled anchor modelling at the SW corner modelling location assuming both a fleeing and stationary animal.

Popper *et al.* (2014) **$L_{E,p,24h}$**		**SW corner, piled anchor (more likely, 5 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 m/s)	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	5,500 km^2	49 km	26 km	42 km
Stationary (0 m/s)	219 dB	3.1 km^2	1.0 km	980 m	990 m
	216 dB	7.9 km^2	1.6 km	1.6 km	1.6 km
	210 dB	49 km^2	4.0 km	4.0 km	4.0 km
	207 dB	120 km^2	6.2 km	6.1 km	6.1 km
	203 dB	350 km^2	11 km	10 km	11 km
	186 dB	12,000 km^2	71 km	56 km	62 km

4.1.3 Centre

Table 4-16 Summary of the $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the OEP pile foundation modelling at the central modelling location.

Southall *et al.* (2019) **$L_{p,pk}$**		**Centre, OEP piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.6 km^2	700 m	700 m	700 m
	PCW (218 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.04 km^2	120 m	120 m	120 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	11 km^2	1.8 km	1.8 km	1.8 km
	PCW (212 dB)	0.06 km^2	140 m	140 m	140 m

Table 4-17 Summary of the $L_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the worst case OEP pile foundation modelling at the central modelling location assuming a fleeing animal.

Southall *et al.* (2019) **$L_{E,p,24h,wtd}$**		**Centre, OEP piles (worst case, 6 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	5,200 km^2	51 km	33 km	40 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	1,100 km^2	22 km	17 km	19 km
	PCW (185 dB)	9.0 km^2	2.0 km	1.4 km	1.7 km
TTS (Impulsive)	LF (168 dB)	48,000 km^2	172 km	66 km	120 km
	HF (170 dB)	4.6 km^2	1.4 km	1.0 km	1.2 km
	VHF (140 dB)	23,000 km^2	113 km	61 km	84 km
	PCW (170 dB)	9,300 km^2	70 km	44 km	54 km

Table 4-18 Summary of the $L_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the more likely OEP pile foundation modelling at the central modelling location assuming a fleeing animal.

Southall *et al.* (2019) **$L_{E,p,24h,wtd}$**		**Centre, OEP piles (more likely, 3 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	4,900 km^2	48 km	33 km	40 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	1,100 km^2	21 km	16 km	18 km
	PCW (185 dB)	8.1 km^2	1.8 km	1.4 km	1.6 km
TTS (Impulsive)	LF (168 dB)	47,000 km^2	167 km	66 km	120 km
	HF (170 dB)	4.3 km^2	1.3 km	1.0 km	1.2 km
	VHF (140 dB)	21,000 km^2	106 km	61 km	81 km
	PCW (170 dB)	8,500 km^2	64 km	43 km	52 km

Table 4-19 Summary of the L_p impact ranges for marine mammals using the NOAA (2005) Level B criteria for the OEP pile foundation modelling at the central modelling location.

NOAA (2005) **L_p**		**Centre, OEP piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	5,500 km^2	47 km	38 km	42 km

Table 4-20 Summary of the $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the worst case OEP pile foundation modelling at the central modelling location.

Popper *et al.* (2014) **$L_{p,pk}$**		**Centre, OEP piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	0.04 km^2	120 m	120 m	120 m
	207 dB	0.31 km^2	310 m	310 m	310 m

Table 4-21 Summary of the $L_{E,p,24h}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the worst case OEP pile foundation modelling at the central modelling location assuming both a fleeing and stationary animal.

Popper *et al.* (2014) **$L_{E,p,24h}$**		**Centre, OEP piles (worst case, 6 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 m/s)	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	2.7 km^2	1.1 km	730 m	920 km
	186 dB	9,200 km^2	69 km	44 km	54 km
Stationary (0 m/s)	219 dB	16 km^2	2.3 km	2.2 km	2.3 km
	216 dB	39 km^2	3.6 km	3.5 km	3.6 km
	210 dB	220 km^2	8.6 km	8.3 km	8.5 km
	207 dB	500 km^2	13 km	12 km	13 km
	203 dB	1,300 km^2	22 km	20 km	21 km
	186 dB	25,000 km^2	110 km	72 km	90 km

Table 4-22 Summary of the $L_{E,p,24h}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the more likely OEP pile foundation modelling at the central modelling location assuming both a fleeing and stationary animal.

Popper *et al.* (2014) $L_{E,p,24h}$		**Centre, OEP piles (more likely, 3 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean Range**
Fleeing (1.5 m/s)	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	2.3 km^2	1.0 km	700 m	860 m
	186 dB	8,400 km^2	63 km	43 km	51 km
Stationary (0 m/s)	219 dB	6.6 km^2	1.5 km	1.4 km	1.5 km
	216 dB	16 km^2	2.3 km	2.2 km	2.3 km
	210 dB	95 km^2	5.6 km	5.5 km	5.5 km
	207 dB	22 km^2	8.6 km	8.3 km	8.5 km
	203 dB	650 km^2	15 km	14 km	14 km
	186 dB	17,000 km^2	86 km	64 km	74 km

4.2 Multiple location modelling

Modelling has been carried out to investigate the potential impacts of multiple piling vessels installing foundations and anchors simultaneously at separated locations. Two scenarios have been considered:

- Anchor piles installed simultaneously over two locations:
  - More likely piled anchor scenario at the NE corner (5 piles installed sequentially)
  - More likely piled anchor scenario at the SW corner (5 piles installed sequentially)

  Total 10 piles installed.
- OEP piles and anchor piles installed simultaneously over two locations:
  - More likely OEP pile scenario at the Centre location (3 piles installed sequentially)
  - More likely piled anchor scenario at the NE corner – the worst case of the two piled anchor locations (5 piles installed sequentially)

  Total 8 piles installed.

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 resulting in higher cumulative exposures. Figure 4-1 shows the TTS contour for fish from Popper *et al*. (2014) (186 dB $L_{E,p,24h}$) 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.

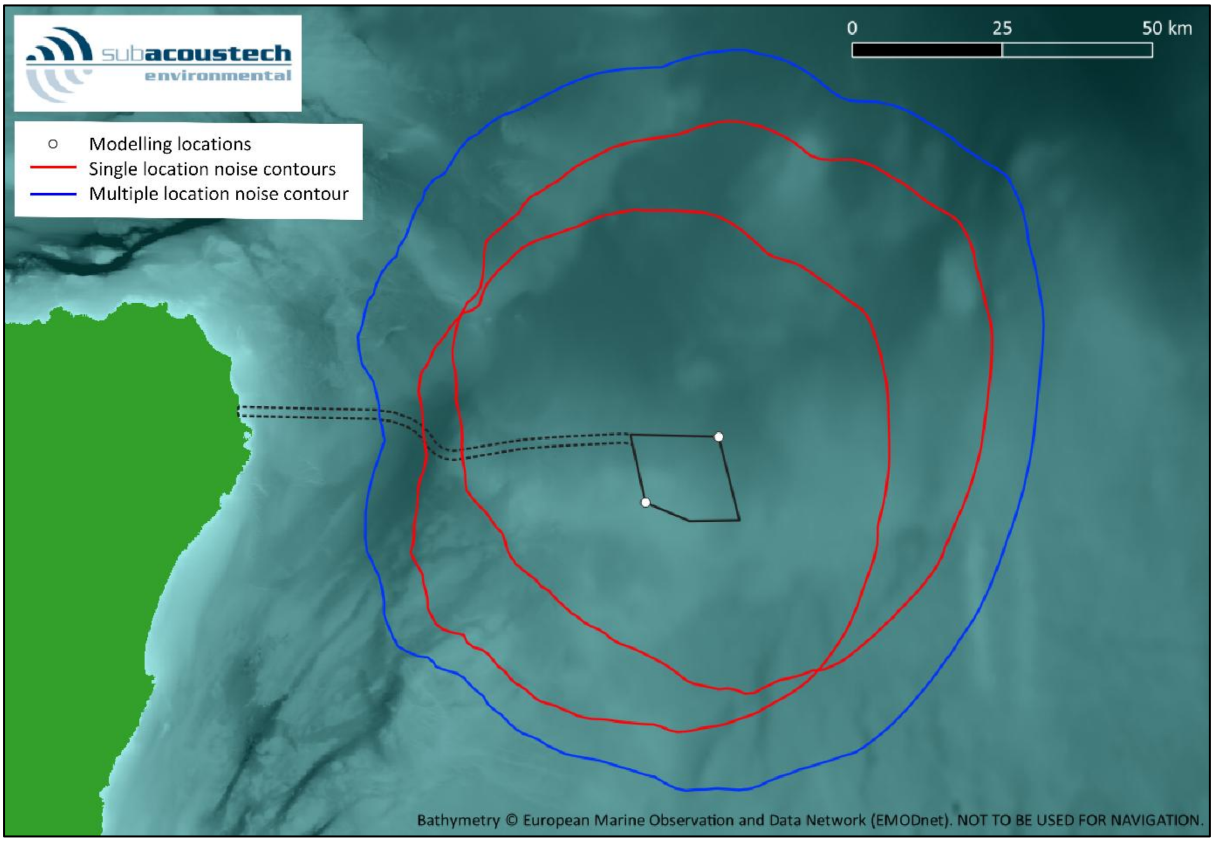

Figure 4-1 Example contour plot showing the interaction between two noise sources occurring simultaneously (TTS in fish, 186 dB $L_{E,p,24h}$, fleeing animal).

The scenarios modelled were chosen to provide the greatest geographical spread of noise sources inside the Muir Mhòr array area 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 even greater expansion of the single location contour in all directions, but by less overall than the spread seen in Figure 4-1.

The following pages present contour plots for the multiple location piling scenarios alongside tables showing the increases in the combined impact areas. Only areas 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. Contours that are too small to be seen clearly at the scale of the figures are not included.

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 Sequential piling of piled anchors over two locations

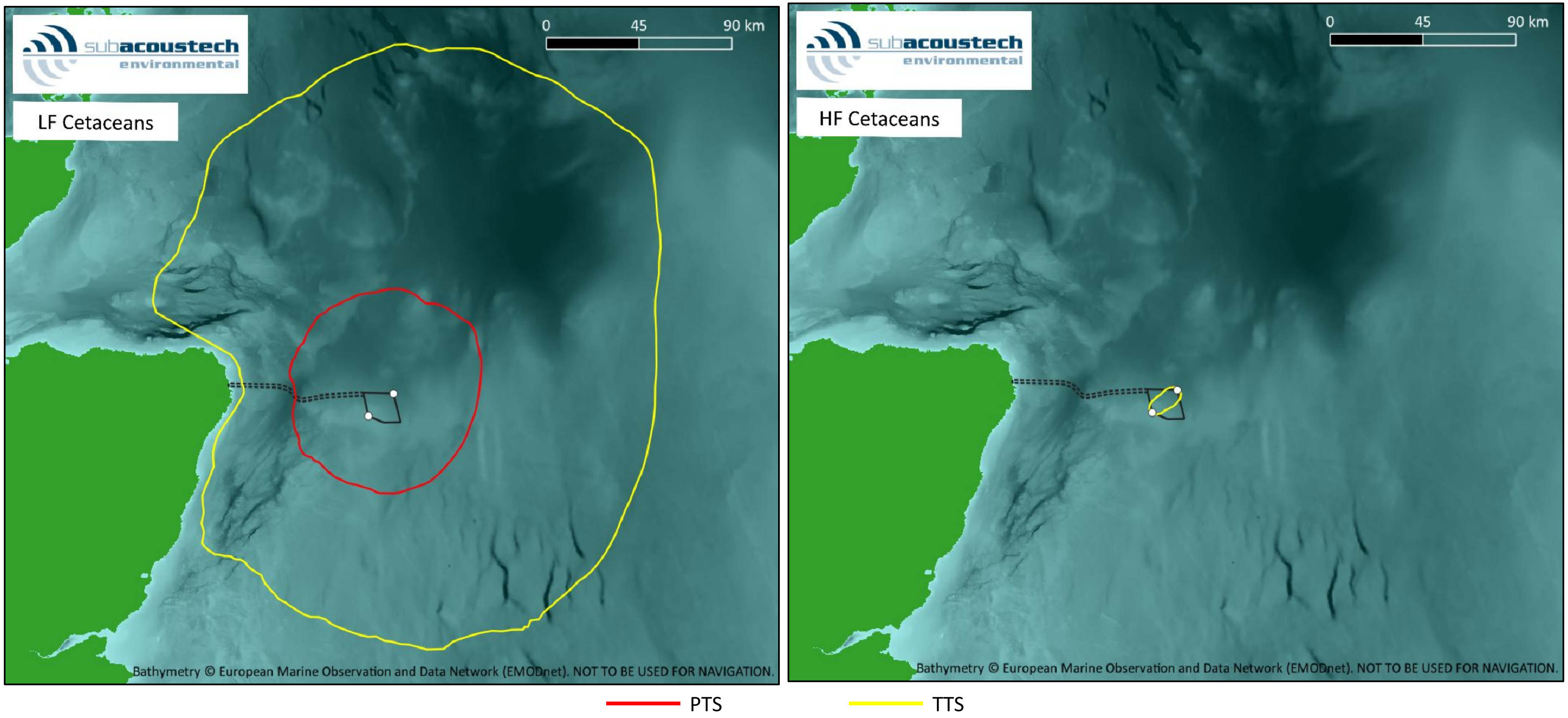

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Figure 4-2 Contour plots showing the in-combination impacts of concurrent installation of piled anchors at the NE and SW corner modelling locations for LF and HF cetaceans using the impulsive Southall et al. (2019) criteria assuming a fleeing animal.

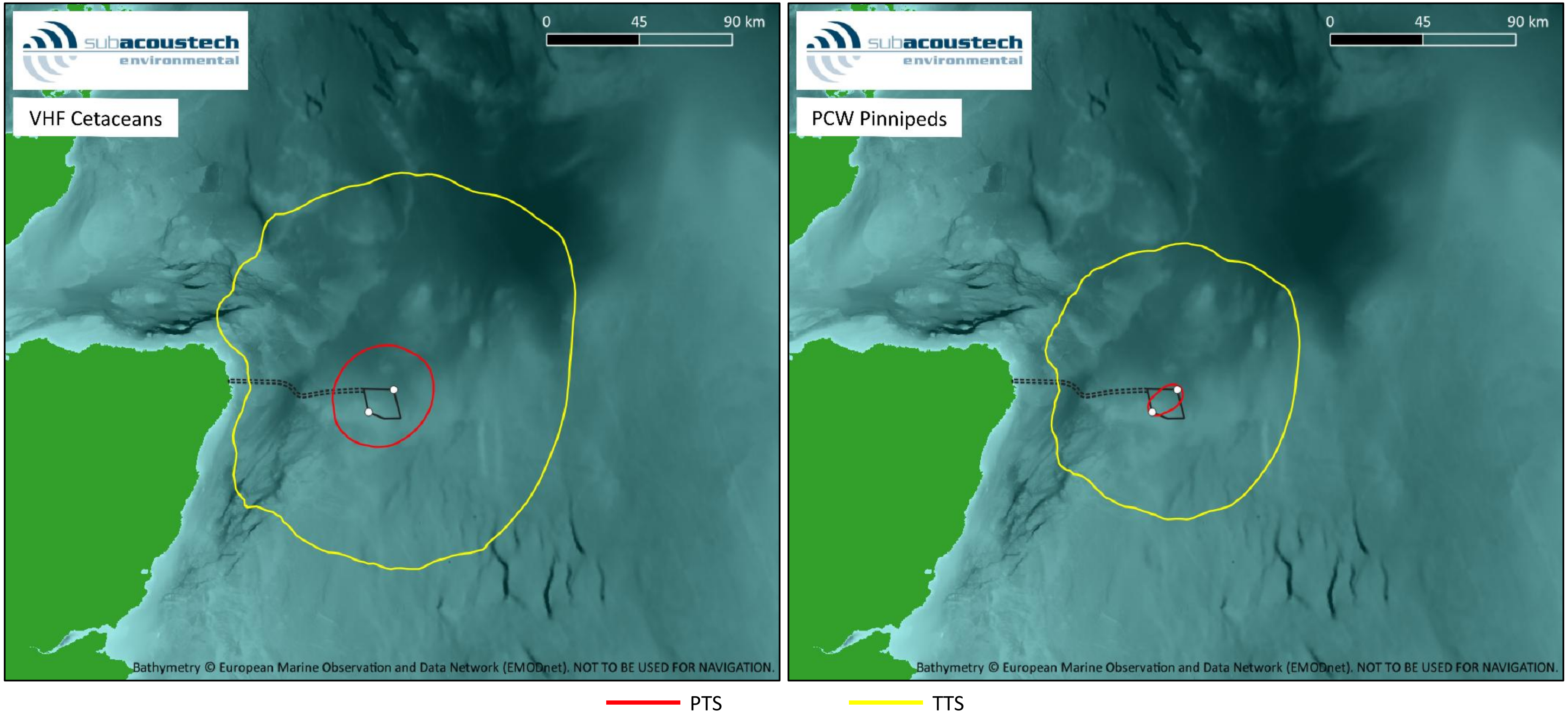

Figure 4-3 Contour plots showing the in-combination impacts of concurrent installation of piled anchors at the NE and SW corner modelling locations for VHF cetaceans and PCW pinnipeds using the impulsive Southall et al. (2019) criteria assuming a fleeing animal.

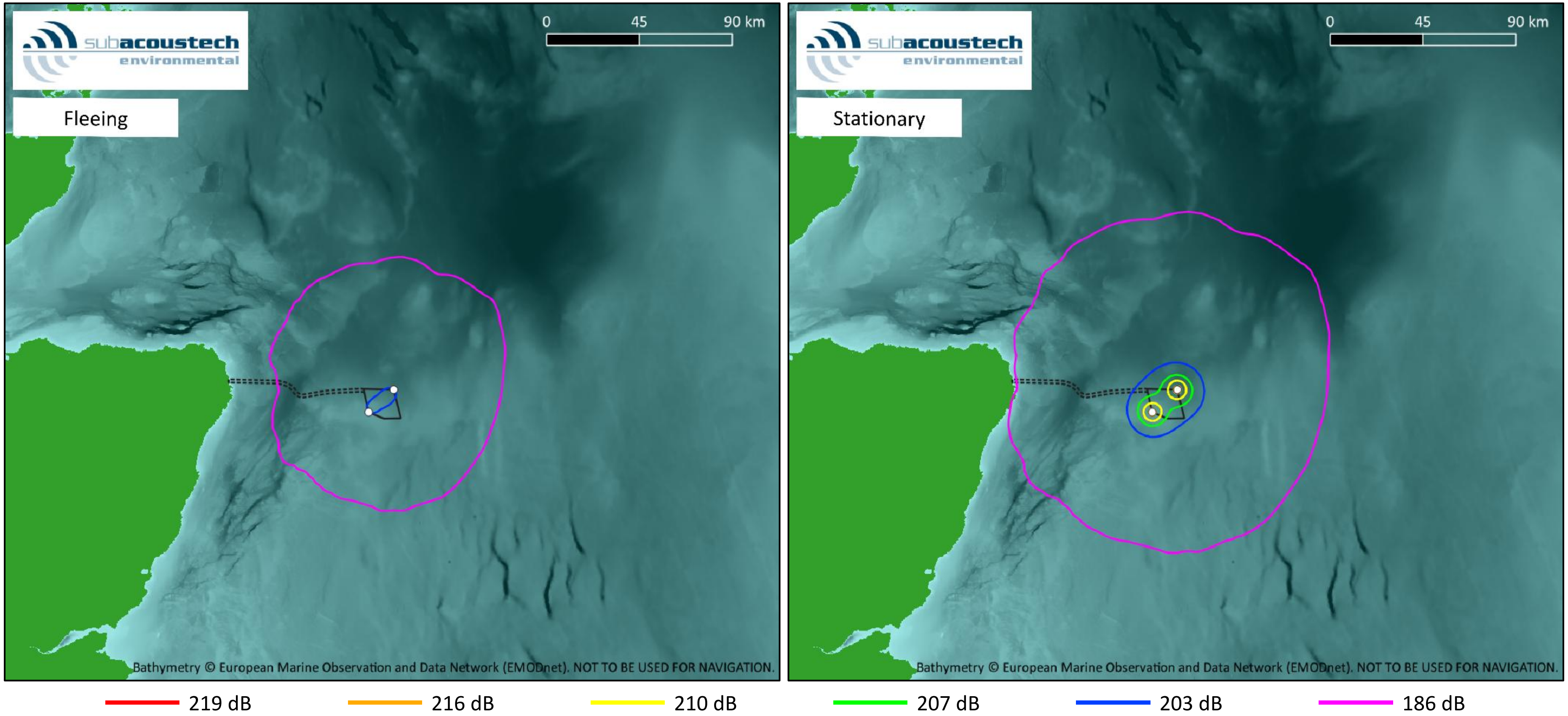

Figure 4-4 Contour plots showing the in-combination impacts of concurrent installation of piled anchors at the NE and SW corner modelling locations for fish using the pile driving Popper et al. (2014) criteria assuming both fleeing and stationary animals.

Table 4-23 Summary of the impact areas for the installation of piled anchors at the NE and SW corner modelling locations for marine mammals using the impulsive Southall et al. (2019) criteria assuming a fleeing animal.

Piled anchors (Southall *et al.*, 2019) $L_{E,p,24h,wtd}$		**NE corner**	**SW corner**	**In-combination area**
PTS (Impulsive)	LF (183 dB)	3,800 km^2	3,100 km^2	7,200 km^2
	HF (185 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (155 dB)	740 km^2	600 km^2	1,900 km^2
	PCW (185 dB)	2.2 km^2	0.8 km^2	170 km^2
TTS (Impulsive)	LF (168 dB)	43,000 km^2	37,000 km^2	55,000 km^2
	HF (170 dB)	0.7 km^2	0.3 km^2	120 km^2
	VHF (140 dB)	740 km^2	16,000 km^2	26,000 km^2
	PCW (170 dB)	7,400 km^2	6,300 km^2	13,000 km^2

Table 4-24 Summary of the impact areas for the installation of piled anchors at the NE and SW corner modelling locations for fish using the pile driving Popper et al. (2014) criteria assuming both fleeing and stationary animals.

Piled anchors (Popper *et al.*, 2014) $L_{E,p,24h}$		**NE corner**	**SW corner**	**In-combination area**
Fleeing (1.5 m/s)	219 dB	< 0.1 km^2	< 0.1 km^2	-
	216 dB	< 0.1 km^2	< 0.1 km^2	-
	210 dB	< 0.1 km^2	< 0.1 km^2	-
	207 dB	< 0.1 km^2	< 0.1 km^2	-
	203 dB	< 0.1 km^2	< 0.1 km^2	100 km^2
	186 dB	7,200 km^2	5,500 km^2	11,000 km^2
Stationary (0 m/s)	219 dB	8.1 km^2	3.1 km^2	7 km^2
	216 dB	21 km^2	7.9 km^2	18 km^2
	210 dB	130 km^2	49 km^2	120 km^2
	207 dB	310 km^2	120 km^2	370 km^2
	203 dB	880 km^2	350 km^2	980 km^2
	186 dB	21,000 km^2	12,000 km^2	20,000 km^2

4.2.2 Sequential piling of OEP piles and piled anchors over two locations

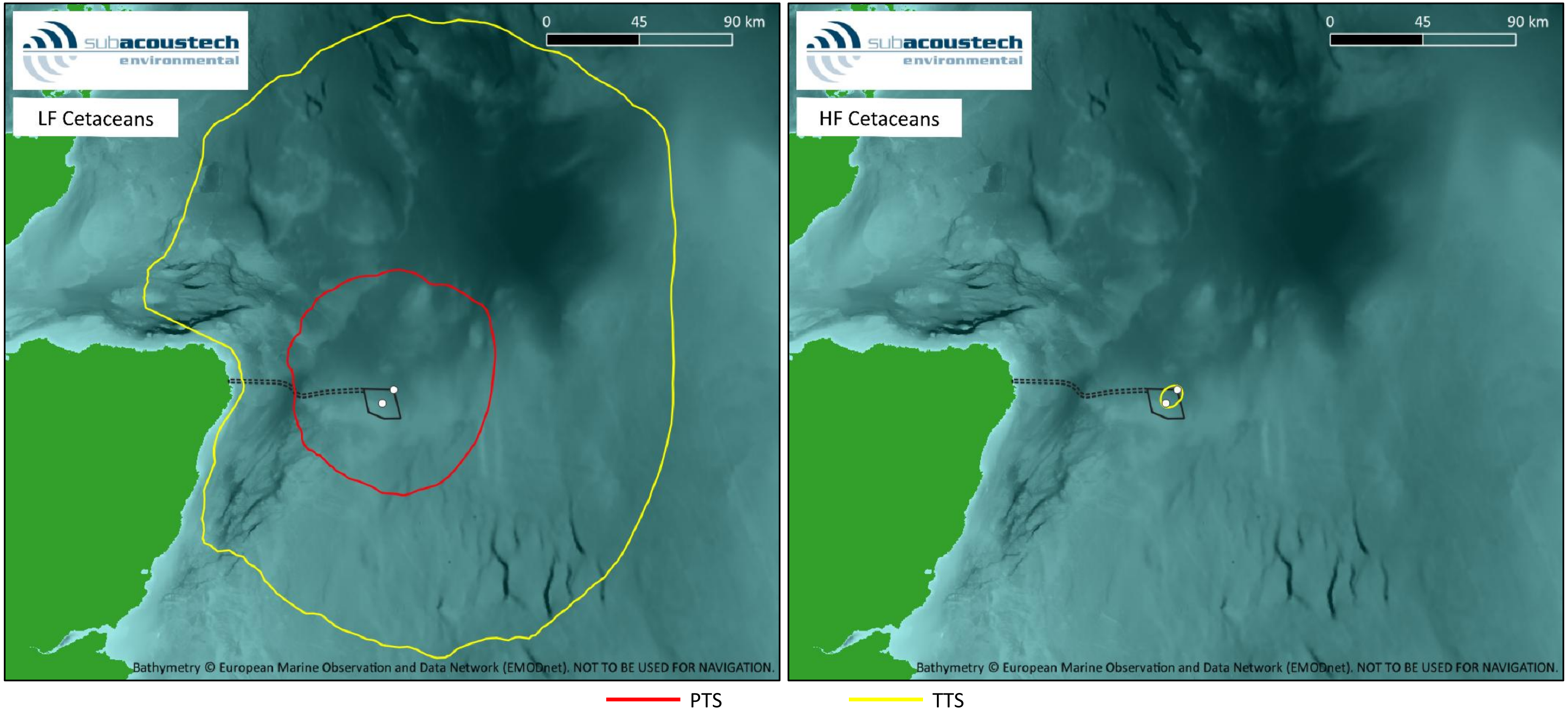

Figure 4-5 Contour plots showing the in-combination impacts of concurrent installation of piled anchors at the NE corner modelling location and OEP piles at the Centre modelling location for LF and HF cetaceans using the impulsive Southall et al. (2019) criteria assuming a fleeing animal.

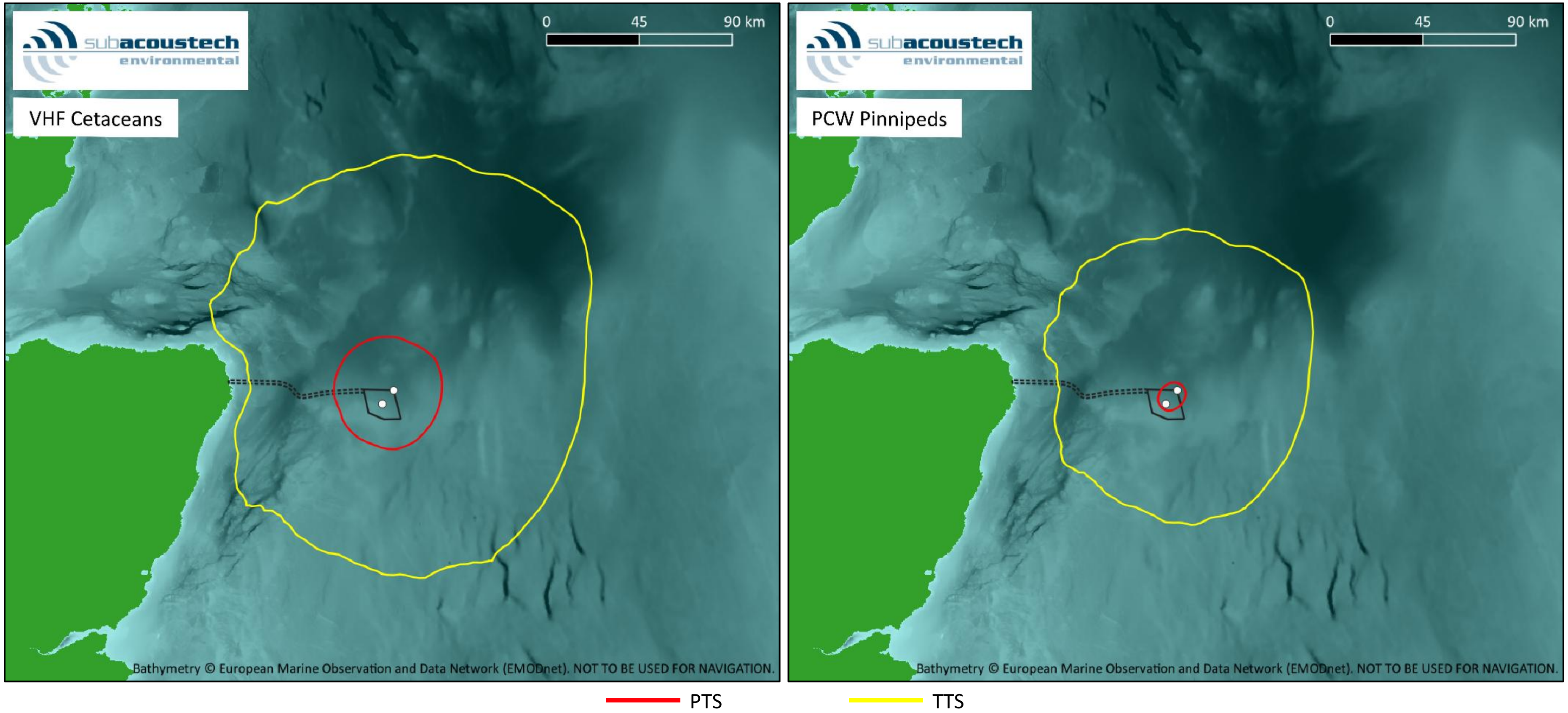

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Figure 4-6 Contour plots showing the in-combination impacts of concurrent installation of piled anchors at the NE corner modelling location and OEP piles at the Centre modelling location for VHF cetaceans and PCW pinnipeds using the impulsive Southall et al. (2019) criteria assuming a fleeing animal.

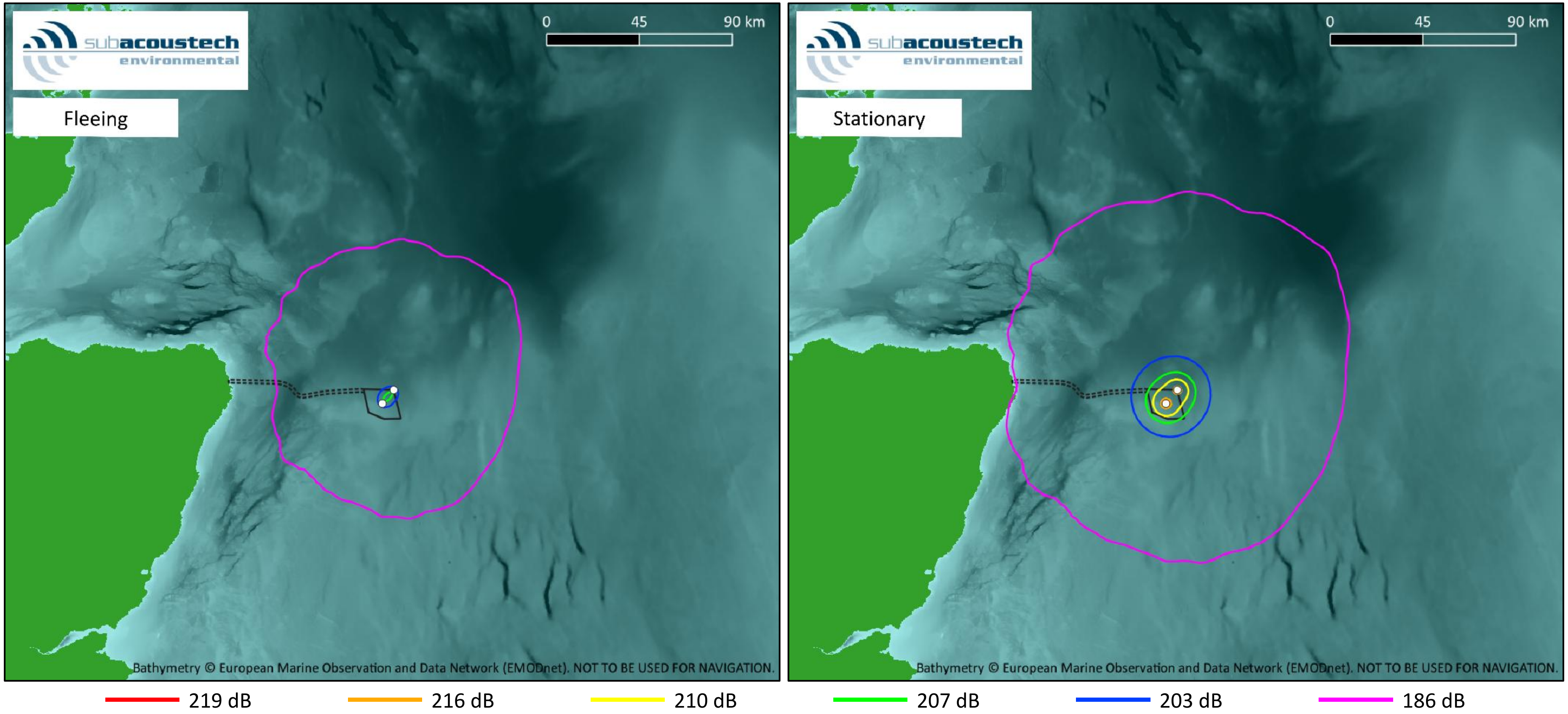

Figure 4-7 Contour plots showing the in-combination impacts of concurrent installation of piled anchors at the NE corner modelling location and OEP piles at the Centre modelling location for fish using the pile driving Popper et al. (2014) criteria assuming both fleeing and stationary animals.

Table 4-25 Summary of the impact areas for the installation of piled anchors at the NE corner modelling location and OEP piles at the Centre modelling location for marine mammals using the impulsive Southall et al. (2019) criteria assuming a fleeing animal.

OEP pile + piled anchors (Southall *et al.*, 2019) $L_{E,p,24h,wtd}$		**NE corner**	**Centre location**	**In-combination area**
PTS (Impulsive)	LF (183 dB)	3,800 km^2	4,900 km^2	8,500 km^2
	HF (185 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (155 dB)	740 km^2	1,100 km^2	2,200 km^2
	PCW (185 dB)	2.2 km^2	8.1 km^2	140 km^2
TTS (Impulsive)	LF (168 dB)	43,000 km^2	47,000 km^2	60,000 km^2
	HF (170 dB)	0.7 km^2	4.3 km^2	85 km^2
	VHF (140 dB)	740 km^2	21,000 km^2	29,000 km^2
	PCW (170 dB)	7,400 km^2	8,500 km^2	14,000 km^2

Table 4-26 Summary of the impact areas for the installation of piled anchors at the NE corner modelling location and OEP piles at the Centre modelling location for fish using the pile driving Popper et al. (2014) criteria assuming both fleeing and stationary animals.

OEP pile + piled anchors (Popper *et al.*, 2014) $L_{E,p,24h}$		**NE corner**	**Centre location**	**In-combination area**
Fleeing (1.5 m/s)	219 dB	< 0.1 km^2	< 0.1 km^2	-
	216 dB	< 0.1 km^2	< 0.1 km^2	-
	210 dB	< 0.1 km^2	< 0.1 km^2	-
	207 dB	< 0.1 km^2	< 0.1 km^2	15 km^2
	203 dB	< 0.1 km^2	2.3 km^2	75 km^2
	186 dB	7,200 km^2	8,400 km^2	13,000 km^2
Stationary (0 m/s)	219 dB	8.1 km^2	6.6 km^2	10 km^2
	216 dB	21 km^2	16 km^2	29 km^2
	210 dB	130 km^2	95 km^2	210 km^2
	207 dB	310 km^2	22 km^2	450 km^2
	203 dB	880 km^2	650 km^2	1,200 km^2
	186 dB	21,000 km^2	17,000 km^2	24,000 km^2

5 Other noise sources

Although impact piling is expected to be the greatest overall noise source during offshore construction (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 of the Proposed Development.

Table 5-1 Summary of the possible noise making activities at the Proposed Development other than impact piling.

Activity	Description
Cable laying	Noise from the cable laying vessel and other associated noise during the offshore cable installation.
Drilling	There is the potential for piles to be installed using drilling depending on seabed type of if a pile refuses during impact piling operations.
Rock placement	May be required on site for installation of offshore cables (cable crossings and cable protection) and scour protection around foundation structures.
Trenching	Plough trenching may be required during installation of the offshore cables.
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. Turbine parameters were not specified for the Proposed Development at the time of writing, and as such, a typical power output of up to 20 MW has been assumed for modelling.
UXO clearance	There is a possibility that UXO may exist within the array area boundaries, which would need to be cleared before construction can begin.

Most 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.

Decommissioning is considered to utilise the same or less noisy equipment than during the construction phase, and as such has not been considered further.

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., cable laying and dredging), or where detailed modelling would imply unjustified accuracy (e.g., where data is limited, such as with UXO clearance). 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. 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 the Proposed Development 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 (in metres), N is the transmission loss coefficient, and α is the absorption loss coefficient:

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

The measured noise level and its transmission loss are affected not only by the environment, but also the size of the overall source, the location of the actual source within the structure (e.g. the position of an engine on a vessel) and its orientation.

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 2.3, and ranges smaller than 50 m (single pulse) and 100 m (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, the Proposed Development.

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	171 dB re 1 µPa @ 1 m	N: 13, α: 0 (no absorption)	Based on 11 datasets from a pipe laying vessel measuring 300 m in length; this is considered a worst-case noise source for cable laying operations.
Dredging (backhoe)	165 dB re 1 µPa @ 1 m	N: 19, α: 0.0009	Based on three datasets from backhoe dredgers.
Dredging (suction)	186 dB re 1 µPa @ 1 m	N: 19, α: 0.0009	Based on five datasets from suction and cutter suction dredgers.
Drilling	169 dB re 1 µPa @ 1 m	N: 16, α: 0.0006	Based on six datasets from various drilling operations covering ground investigations and pile installation. A 200 kW drill has been assumed for modelling.
Rock placement	172 dB re 1 µPa @ 1 m	N: 12, α: 0.0005	Based on four datasets from rock placement vessel *Rollingstone*.
Trenching	172 dB re 1 µPa @ 1 m	N: 13, α: 0.0004	Based on three datasets of measurements from trenching vessels more than 100 m in length.
Vessel noise (large)	168 dB re 1 µPa @ 1 m	N: 12, α: 0.0021	Based on five datasets of large vessels including container ships, FPSOs and other vessels more than 100 m in length. Vessel speed assumed as 10 knots.
Vessel noise (medium)	161 dB re 1 µPa @ 1 m	N: 12, α: 0.0021	Based on three datasets of moderate sized vessels less than 100 m in length. Vessel speed assumed as 10 knots.

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.

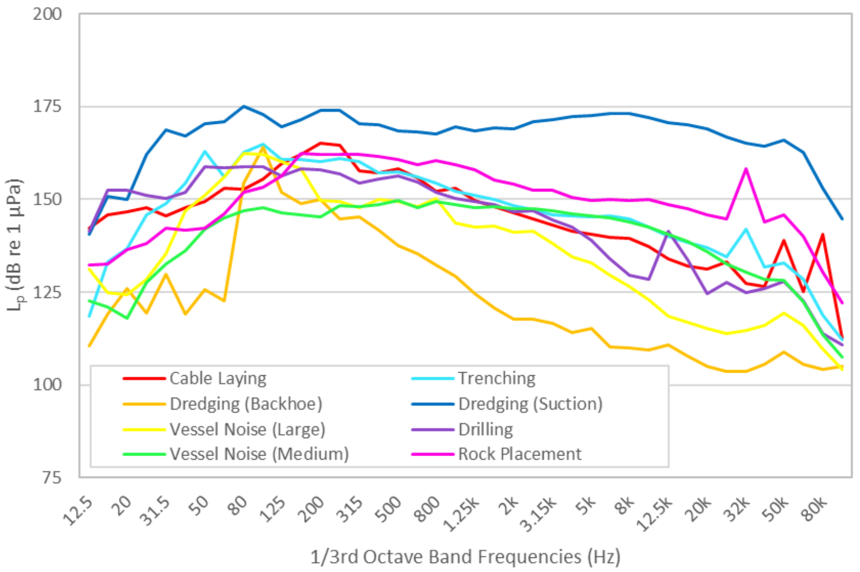

Figure 5-1 Summary of the 1/3rd octave frequency bands to which Southall et al. (2019) weightings have been applied.

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 *et al*., 2019)			
	LF	HF	VHF	PCW
Cable laying	3.6 dB re 1 µPa	22.9 dB re 1 µPa	23.9 dB re 1 µPa	13.2 dB re 1 µPa
Dredging	2.5 dB re 1 µPa	7.9 dB re 1 µPa	9.6 dB re 1 µPa	4.2 dB re 1 µPa
Drilling	4.0 dB re 1 µPa	25.8 dB re 1 µPa	48.7 dB re 1 µPa	13.2 dB re 1 µPa
Rock placement	1.6 dB re 1 µPa	11.9 dB re 1 µPa	12.5 dB re 1 µPa	8.2 dB re 1 µPa
Trenching	4.1 dB re 1 µPa	23.0 dB re 1 µPa	25.0 dB re 1 µPa	13.7 dB re 1 µPa
Vessel noise	5.5 dB re 1 µPa	34.4 dB re 1 µPa	38.6 dB re 1 µPa	17.4 dB re 1 µPa

Table 5-4 to Table 5-6 summarise the predicted impact ranges for these noise sources. All the sources in this Section are considered non-impulsive or continuous. As with the previous results, ranges smaller than 50 m (single pulse) and 100 m (cumulative) have not been presented.

Given the modelled impact ranges, almost any marine mammal would have to be closer than 100 m 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 rock placement. 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 *et al.* (2019) $L_{E,p,24h,wtd}$	PTS (non-impulsive)				TTS (non-impulsive)			
	LF (199 dB)	HF (198 dB)	VHF (173 dB)	PCW (201 dB)	LF (179 dB)	HF (178 dB)	VHF (153 dB)	PCW (181 dB)
Cable laying	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Dredging (backhoe)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Dredging (suction)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	250 m	< 100 m
Drilling	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Rock placement	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	1.2 km	< 100 m
Trenching	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Vessel noise (large)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Vessel noise (medium)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m

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 *et al.* (2019) $L_{E,p,24h,wtd}$	PTS (non-impulsive)				TTS (non-impulsive)			
	LF (199 dB)	HF (198 dB)	VHF (173 dB)	PCW (201 dB)	LF (179 dB)	HF (178 dB)	VHF (153 dB)	PCW (181 dB)
Cable laying	< 100 m	< 100 m	< 100 m	< 100 m	810 m	< 100 m	2.3 km	110 m
Dredging (backhoe)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Dredging (suction)	< 100 m	< 100 m	570 m	< 100 m	640 m	390 m	4.3 km	420 m
Drilling	< 100 m	< 100 m	< 100 m	< 100 m	160 m	< 100 m	200 m	< 100 m
Rock placement	< 100 m	< 100 m	900 m	< 100 m	2.1 km	410 m	13 km	460 m
Trenching	< 100 m	< 100 m	< 100 m	< 100 m	830 m	< 100 m	1.9 km	120 m
Vessel noise (large)	< 100 m	< 100 m	< 100 m	< 100 m	480 m	< 100 m	140 m	< 100 m
Vessel noise (medium)	< 100 m	< 100 m	< 100 m	< 100 m	130 m	< 100 m	< 100 m	< 100 m

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, 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 *et al.* (2014) L_p	Recoverable injury 170 dB re 1 µPa (48 hours)	TTS 158 dB re 1 µPa (12 hours)
Cable laying	< 50 m	< 50 m
Dredging (backhoe)	< 50 m	< 50 m
Dredging (suction)	< 50 m	< 50 m
Drilling	< 50 m	< 50 m
Rock placement	< 50 m	< 50 m
Trenching	< 50 m	< 50 m
Vessel noise (large)	< 50 m	< 50 m
Vessel noise (medium)	< 50 m	< 50 m

5.2 Operational WTG noise

The noise source for most operational WTGs is the radiating area of the foundation in the water. For a fixed-bottom monopile foundation, this is the surface area of the cylindrical pile in the water column, other fixed foundations such as jacket or tripod foundations are more complex. The complexities of the acoustics in large structures such as these make it difficult to predict their effect on the noise output (Tougaard *et al*., 2020). The radiating area source for a floating WTG is limited to the weighted and buoyant section that rests beneath the sea surface, a significantly smaller area than a fixed WTG. With a much smaller submerged radiating area, the noise is expected to be lower, with a reasonable assumption of equivalent sound generation within the WTG and transmission through the tower.

Little empirical data exists for the operational noise produced by floating WTGs. For example, Tougaard *et al*. (2020) and the study by Stöber and Thomsen (2021) did not consider any floating designs. Measurements taken by Jasco Applied Science (Martin *et al*., 2011) of the HYWIND demonstrator, west of Stavanger, Norway, showed broadband noise levels of the order of 120 dB re 1 µPa (L_p) over an approximate 10-week period in June to August 2011, at a range of 150 m from the WTG. However, much of this was found to be influenced by ambient noise from existing shipping sources and none of the components of noise relating to WTG operation appeared to exceed 110 dB re 1 µPa (L_p) at the monitoring location. It is worth noting that this is dominated by noise at low frequency (< 100 Hz), which is below the auditory sensitivity for most marine mammals, and they differ minimally from background noise over the long term at all measured frequencies up to 16 kHz (1/3rd octave band). It is therefore likely that even if the noise measurement at the position near the WTG was influenced by operational WTG noise, ambient noise levels will typically reach this level naturally; the WTG at this study was 2.3 MW (82.4 m rotor diameter). While some other monitoring data for floating wind farm projects do exist (Molinero, 2020), comparing potential noise levels to worst-case examples such as those from HYWIND are considered best practice for this study as they are the largest available.

Using the Tougaard *et al*. (2020) calculator for noise from operational WTGs, an uplift of approximately 13 dB would need to be applied to the sound output from a 2.3 MW WTG to the approximate turbine sizes of up to 20 MW). This would suggest an upper limit of 133 dB re 1 µPa (L_p) at 150 m for floating turbines at the Proposed Development.

Using this extrapolated level and the Popper *et al*. (2014) criteria for continuous noise, the TTS threshold of 158 dB (L_p) would require an individual to be closer than 20 m for 12 hours continuously. For a source near the surface in water depths of the order of 100 m, this would be very low risk. As studies have shown that fish populations have increased in the vicinity of offshore wind farms (Stenberg *et al*., 2015), there appears to be minimal risk to fish from operational WTGs.

To compare this to the relevant marine mammal impact thresholds in Southall *et al*. (2019), at a range of 100 m from the floating WTG for an hour, a receptor would receive an unweighted 173 dB ($L_{E,p,1h}$). With weighting considered, this is still well below potentially injurious or TTS thresholds for any Southall *et al*. (2019) criteria. Therefore, for noise from operational floating WTGs, TTS risk is small. Importantly, this assumes a stationary animal model with an individual remaining within 100 m from a WTG for much more than a 1-hour period. This is a highly unlikely scenario: when the animal is able to move, the risk of direct harm from the noise is minimal.

5.2.1 Cable noise

As well as relatively low noise levels from the operational machinery in a variety of conditions, measurements taken by Jasco (2011) for Statoil in Norway identified what appeared to be a "snapping" noise that was thought to be related to tension release in the mooring system, although this has not been verified. It is understood that the mooring cables are designed to be permanently in tension such that no line should ever go into slack, even in extreme conditions, partly to avoid the risk of entanglement of marine mammals (Statoil, 2015). If the cables are the source of the noise, this will be caused by the specific circumstances at the HYWIND 1 project: that is, the depth of water, length of cables in use, current and current fluctuations. The findings at HYWIND 1 were isolated, and it does not necessarily follow that this will occur at the Proposed Development but does not rule out the potential for it either. Unless there was further evidence that other floating WTG moorings, or some other noise source associated with the WTGs, is shown to create this snap then it may be an anomaly or potentially even an artifact of the monitoring system (although the latter is unlikely).

According to Jasco (2011), up to 23 of these snaps were identified per day. Over the two months of monitoring undertaken by Jasco, less than 10 snaps exceeding 160 dB re 1 µPa (L_p) at the measurement position, 150 m from the WTG, were identified on most days.

As the source of noise is unclear, its distance from the monitor cannot be ascertained and thus a prediction of the noise closer to the source is not possible for estimation of PTS in terms of $L_{p,pk}$. Subsequent analysis of the HYWIND 1 data by Xodus (2015) for the HYWIND Scotland Pilot Park Project predicted a potential $L_{E,p,24h}$ of up to 157 dB re 1 µPa^{2}s caused by snapping chains from six WTGs; the equivalent for ten would be approximately 160 dB re 1 µPa^{2}s. This prediction makes a series of worst-case assumptions (e.g., all WTGs producing the maximum number of snaps in a day, equivalent noise levels from multiple locations affecting a receptor to the same degree) and this level is below any PTS or injury criteria to marine mammals or fish.

There are no reliable noise thresholds that would be recommended to identify disturbance for rare/intermittent impulses of this type. As any snapping occurs at an average rate of less than one snap per hour, disturbance leading to avoidance behaviour is considered unlikely.

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 array area boundary and offshore Export Cable Corridor (ECC). 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 alternatively a clearance method such as deflagration (low-order) can be used.

5.3.1 Estimation of underwater noise levels

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 array area boundary has been estimated as 750 kg. This has been modelled alongside a range of smaller devices, at charge weights of 25, 55, 120, 240, 525, 698 kg. In each case, an additional donor weight of 0.5 kg 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 effect 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 low-order technique proceeds as intended, it is still not without noise impact. The process requires an initial shaped explosive donor charge, typically less than 250 g, 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 250 g. The worst-case scenario would of course be a high order detonation with maximum sound 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 1 km, 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 3.5 km (Hastie *et al*., 2019).

A summary of the unweighted UXO clearance source levels, calculated using the equations above, are given in Table 5-7.

Table 5-7 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 (0.25 kg)	269.8 dB re 1 μPa @ 1 m	215.2 dB re 1 μPa^2s @ 1 m
25 kg (+ donor)	284.9 dB re 1 μPa @ 1 m	228.0 dB re 1 μPa^2s @ 1 m
55 kg (+ donor)	287.5 dB re 1 μPa @ 1 m	230.1 dB re 1 μPa^2s @ 1 m
120 kg (+ donor)	290.0 dB re 1 μPa @ 1 m	232.3 dB re 1 μPa^2s @ 1 m
240 kg (+ donor)	292.3 dB re 1 μPa @ 1 m	234.2 dB re 1 μPa^2s @ 1 m
525 kg (+ donor)	294.8 dB re 1 μPa @ 1 m	236.4 dB re 1 μPa^2s @ 1 m
698 kg (+ donor)	295.7 dB re 1 μPa @ 1 m	237.1 dB re 1 μPa^2s @ 1 m
750 kg (+ donor)	296.0 dB re 1 μPa @ 1 m	237.3 dB re 1 μPa^2s @ 1 m

5.3.3 Impact ranges

Table 5-8 to Table 5-11 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 5-8 to Table 5-11 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 5-8 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 *et al*. (2019) $L_{p,pk}$	PTS (impulsive)				TTS (impulsive)			
	LF 219 dB	HF 230 dB	VHF 202 dB	PCW 218 dB	LF 213 dB	HF 224 dB	VHF 196 dB	PCW 212 dB
Low order (0.25 kg)	170 m	60 m	990 m	190 m	320 m	100 m	1.8 km	360 m
25 kg + donor	820 m	260 m	4.6 km	910 m	1.5 km	490 m	8.5 km	1.6 km
55 kg + donor	1.0 km	340 m	6.0 km	1.1 km	1.9 km	640 m	11 km	2.1 km
120 kg + donor	1.3 km	450 m	7.8 km	1.5 km	2.5 km	830 m	14 km	2.8 km
240 kg + donor	1.7 km	560 m	9.8 km	1.9 km	3.2 km	1.0 km	18 km	3.5 km
525 kg + donor	2.2 km	730 m	12 km	2.5 km	4.1 km	1.3 km	23 km	4.6 km
698 kg + donor	2.4 km	810 m	13 km	2.7 km	4.5 km	1.4 km	25 km	5.0 km
750 kg + donor	2.5 km	830 m	14 km	2.8 km	4.6 km	1.5 km	26 km	5.1 km

Table 5-9 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 *et al*. (2019) $L_{E,p}$ (single pulse)	PTS (impulsive)				TTS (impulsive)			
	LF 183 dB	HF 185 dB	VHF 155 dB	PCW 185 dB	LF 168 dB	HF 170 dB	VHF 140 dB	PCW 170 dB
Low order (0.25 kg)	230 m	< 50 m	80 m	< 50 m	3.2 km	< 50 m	750 m	570 m
25 kg + donor	2.2 km	< 50 m	570 m	390 m	29 km	150 m	2.4 km	5.2 km
55 kg + donor	3.2 km	< 50 m	740 m	570 m	41 km	210 m	2.8 km	7.5 km
120 kg + donor	4.7 km	< 50 m	950 m	830 m	57 km	300 m	3.2 km	10 km
240 kg + donor	6.5 km	< 50 m	1.1 km	1.1 km	76 km	390 m	3.5 km	14 km
525 kg + donor	9.5 km	50 m	1.4 km	1.6 km	100 km	530 m	4.0 km	19 km
698 kg + donor	10 km	60 m	1.5 km	1.9 km	110 km	590 m	4.1 km	22 km
750 kg + donor	11 km	60 m	1.5 km	2.0 km	110 km	600 m	4.2 km	22 km

Table 5-10 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 *et al.* (2019) $L_{E,p}$ (single pulse)	PTS (non-impulsive)				TTS (non-impulsive)			
	LF 199 dB	HF 198 dB	VHF 173 dB	PCW 201 dB	LF 179 dB	HF 178 dB	VHF 153 dB	PCW 181 dB
Low order (0.25 kg)	< 50 m	< 50 m	< 50 m	< 50 m	460 m	< 50 m	110 m	80 m
25 kg + donor	130 m	< 50 m	< 50 m	< 50 m	4.4 km	< 50 m	730 m	790 m
55 kg + donor	190 m	< 50 m	< 50 m	< 50 m	6.4 km	60 m	940 m	1.1 km
120 kg + donor	280 m	< 50 m	70 m	< 50 m	9.4 km	80 m	1.1 km	1.6 km
240 kg + donor	390 m	< 50 m	100 m	70 m	13 km	110 m	1.4 km	2.3 km
525 kg + donor	570 m	< 50 m	130 m	100 m	18 km	160 m	1.7 km	3.3 km
698 kg + donor	660 m	< 50 m	150 m	110 m	21 km	180 m	1.8 km	3.8 km
750 kg + donor	680 m	< 50 m	160 m	120 m	22 km	190 m	1.8 km	4.0 km

Table 5-11 Summary of the impact ranges for UXO detonation using the explosions $L_{p,pk}$ noise criteria from Popper et al. (2019) for species of fish.

Popper *et al.* (2014) $L_{p,pk}$	Mortality and potential mortal injury	
	234 dB	229 dB
Low order (0.25 kg)	< 50 m	60 m
25 kg + donor	170 m	290 m
55 kg + donor	230 m	380 m
120 kg + donor	300 m	490 m
240 kg + donor	370 m	620 m
525 kg + donor	490 m	810 m
698 kg + donor	530 m	890 m
750 kg + donor	550 m	910 m

5.3.4 Summary

The maximum PTS ranges calculated for UXO clearance is 14 km 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 11 km 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 680 m), 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

Subacoustech Environmental has undertaken a study on behalf of GoBe Consultants to assess the potential underwater noise and its effects during the construction and operation of the Proposed Development..

The level of underwater noise from the installation of piled anchors and OEP piles during construction 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.

Three representative modelling locations were chosen to give spatial variation across the site as well as accounting for changes in water depth. The following foundation scenarios were considered across the modelling locations:

- Piled anchors considering 4 m diameter piles installed using a maximum hammer energy of 2,400 kJ and either 10 piles (worst case) or 5 piles (more likely case) installed per vessel per day; and
- OEP pile foundations considering 5 m diameter piles installed using a maximum hammer energy of 3,200 kJ and either 6 piles (worst case) or 3 piles (more likely case) installed per vessel per day.

The loudest levels of noise and the greatest impact ranges were predicted for the worst case OEP pile foundation scenarios due to the larger piles and blow energies.

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; NOAA, 2005) 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 51 km based on the worst case OEP pile scenario. For fish, the largest recoverable injury ranges (203 dB $L_{E,p,24h}$) were predicted to be 22 km for a stationary receptor, reducing to 1.1 km for a fleeing receptor. Further modelling involving multiple piling vessels operating concurrently were also considered, covering scenarios for simultaneous piling at both the NE and SW corners of the array area boundary.

Noise sources other than piling have been considered using a high-level, simple modelling approach, including cable laying, dredging, drilling, rock placement, vessel movement, and operational WTG noise. The predicted noise levels for these construction activities are well below those predicted for impact piling noise, with maximum PTS ranges of less than 1 km. 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 at the Proposed Development, and for the potential UXO clearance noise, there is a risk of PTS up to 14 km from the largest UXO device considered (750 kg + donor charge), using the $L_{p,pk}$ 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, or degradation of the devices with time, 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 from the Proposed Development on marine mammals (EIAR Volume 3, Chapter 12) and fish (Volume 3, Chapter 10).

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Annex 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 from impact piling noise at the Proposed Development are presented below. The predicted ranges here fall well below the results based on impulsive criteria presented in the main report.

A.1 Single location modelling

Table A 1 Summary of the $L_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the worst case piled anchor modelling at the NE corner modelling location assuming a fleeing animal.

Southall *et al.* (2019) $L_{E,p,24h,wtd}$		**NE corner, piled anchor (worst case, 10 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	11,000 km^2	78 km	48 km	60 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	1,500 km^2	25 km	19 km	22 km
	PCW (181 dB)	170 km^2	8.3 km	6.3 km	7.3 km

Table A 2 Summary of the $L_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the more likely piled anchor modelling at the NE corner modelling location assuming a fleeing animal.

Southall *et al.* (2019) $L_{E,p,24h,wtd}$		**NE corner, piled anchor (more likely, 5 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	11,000 km^2	74 km	48 km	58 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	1,400 km^2	23 km	19 km	21 km
	PCW (181 dB)	150 km^2	7.6 km	6.2 km	7.0 km

Table A 3 Summary of the $L_{E,p,24h,wtd}$ *impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the worst case piled anchor modelling at the SW corner modelling location assuming a fleeing animal.*

Southall *et al.* (2019) $L_{E,p,24h,wtd}$		**SW corner, piled anchor (worst case, 10 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	9,600 km^2	70 km	44 km	55 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	1,200 km^2	23 km	18 km	20 km
	PCW (181 dB)	120 km^2	7.0 km	5.6 km	6.2 km

Table A 4 Summary of the $L_{E,p,24h,wtd}$ *impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the more likely piled anchor modelling at the SW corner modelling location assuming a fleeing animal.*

Southall *et al.* (2019) $L_{E,p,24h,wtd}$		**SW corner, piled anchor (more likely, 5 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	9,100 km^2	66 km	44 km	54 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	1,100 km^2	22 km	18 km	19 km
	PCW (181 dB)	110 km^2	6.6 km	5.6 km	6.0 km

Table A 5 Summary of the $L_{E,p,24h,wtd}$ *impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the worst case OEP pile foundation modelling at the central modelling location assuming a fleeing animal.*

Southall *et al.* (2019) $L_{E,p,24h,wtd}$		**Centre, OEP pile (worst case, 6 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	14,000 km^2	87 km	51 km	65 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	2,000 km^2	29 km	22 km	25 km
	PCW (181 dB)	250 km^2	10 km	7.6 km	8.9 km

Table A 6 Summary of the $L_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the more likely OEP pile foundation modelling at the central modelling location assuming a fleeing animal.

Southall *et al.* (2019) $L_{E,p,24h,wtd}$		**Centre, OEP pile (more likely, 3 piles)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	13,000 km^2	83 km	51 km	64 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	1,900 km^2	28 km	21 km	24 km
	PCW (181 dB)	230 km^2	9.7 km	7.5 km	8.6 km

A.2 Multiple location modelling

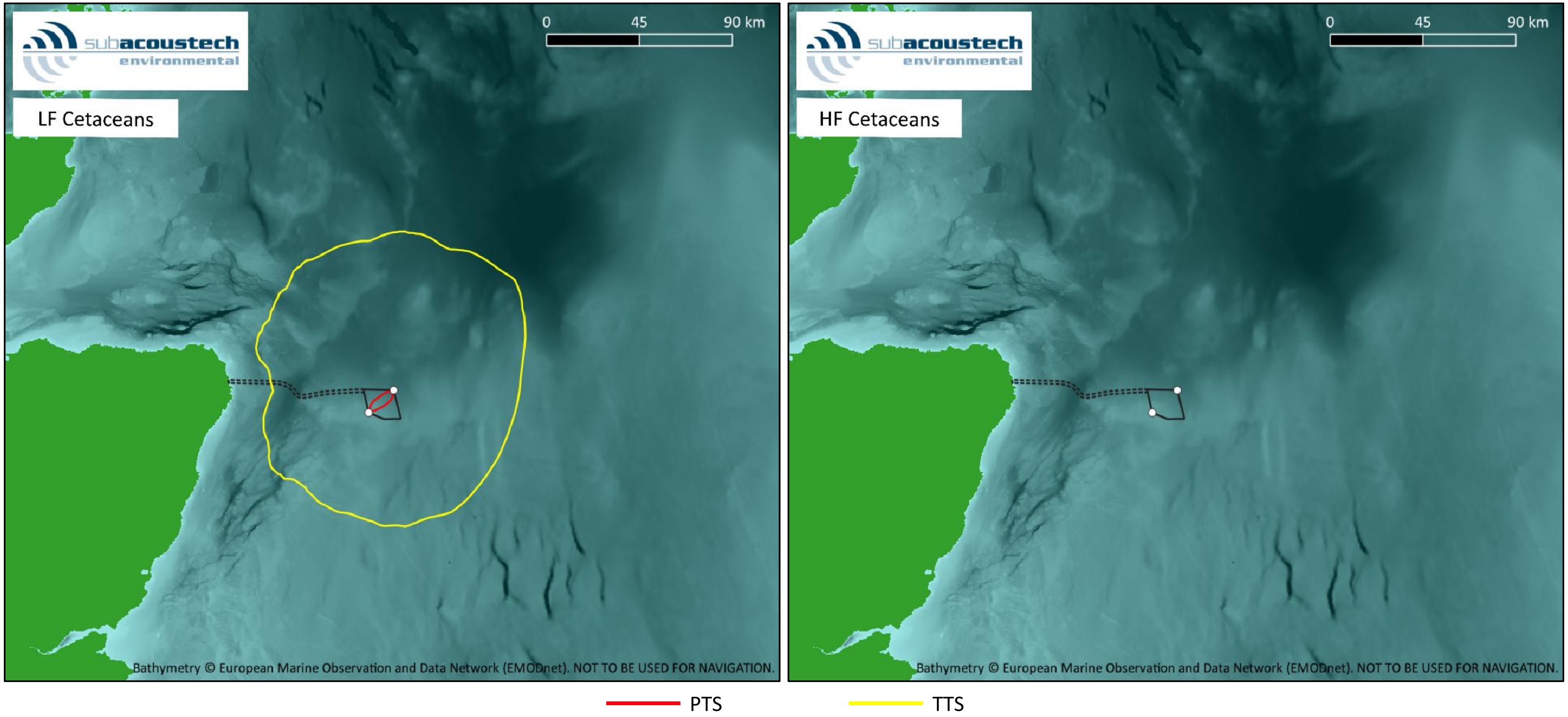

Figure A 1 Contour plots showing the in-combination impacts of concurrent installation of piled anchors at the NE and SW corner modelling locations for LF and HF cetaceans using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal.

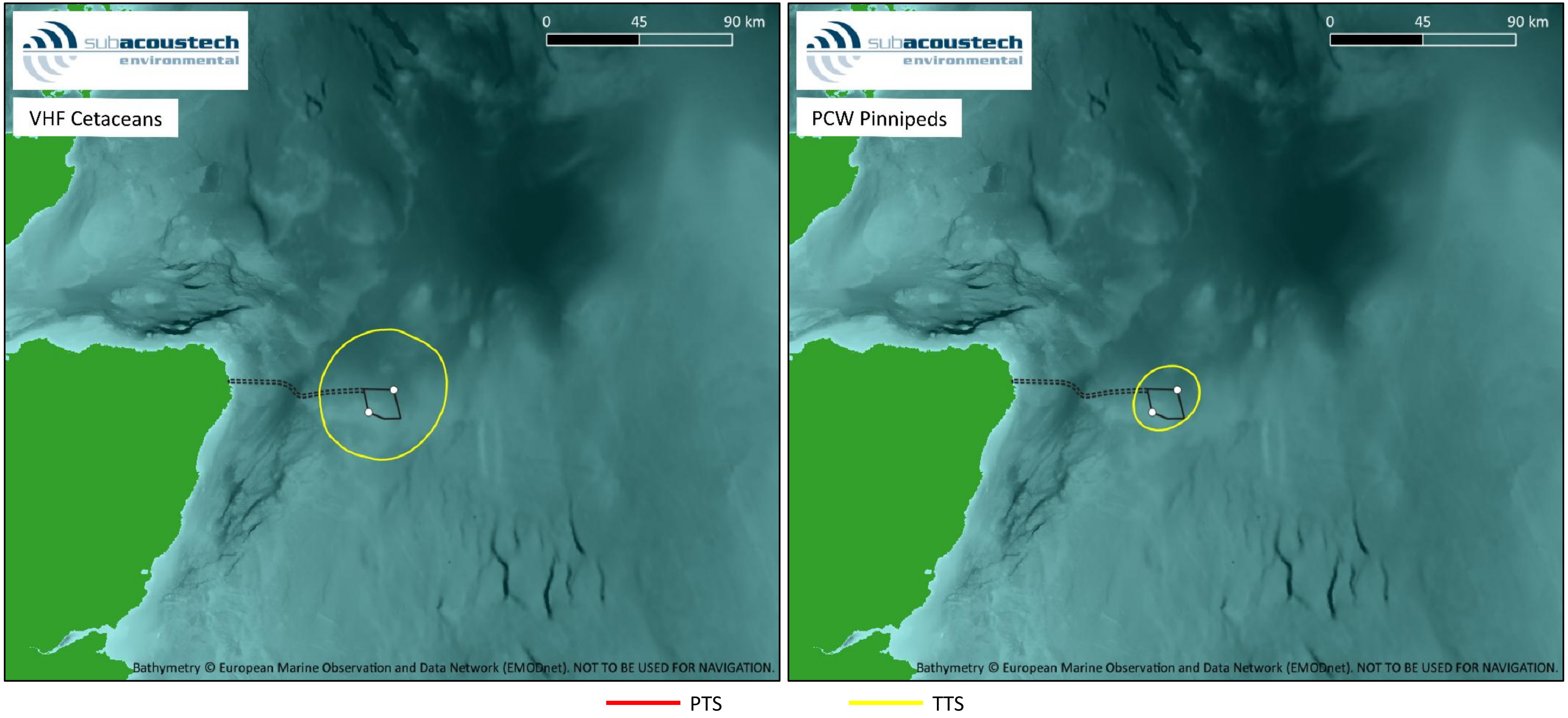

Figure A 2 Contour plots showing the in-combination impacts of concurrent installation of piled anchors at the NE and SW corner modelling locations for VHF cetaceans and PCW pinnipeds using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal.

Table A 7 Summary of the impact areas for the installation of pile anchors at the NE and SW corner modelling locations for marine mammals using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal.

Piled anchors (Southall *et al.*, 2019) $L_{E,p,24h,wtd}$		NE corner	SW corner	In-combination area
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 0.1 km^2	57 km^2
	HF (198 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (173 dB)	< 0.1 km^2	< 0.1 km^2	-
	PCW (201 dB)	< 0.1 km^2	< 0.1 km^2	-
TTS (Non-impulsive)	LF (179 dB)	11,000 km^2	9,100 km^2	15,000 km^2
	HF (178 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (153 dB)	1,400 km^2	1,100 km^2	3,000 km^2
	PCW (181 dB)	150 km^2	110 km^2	770 km^2

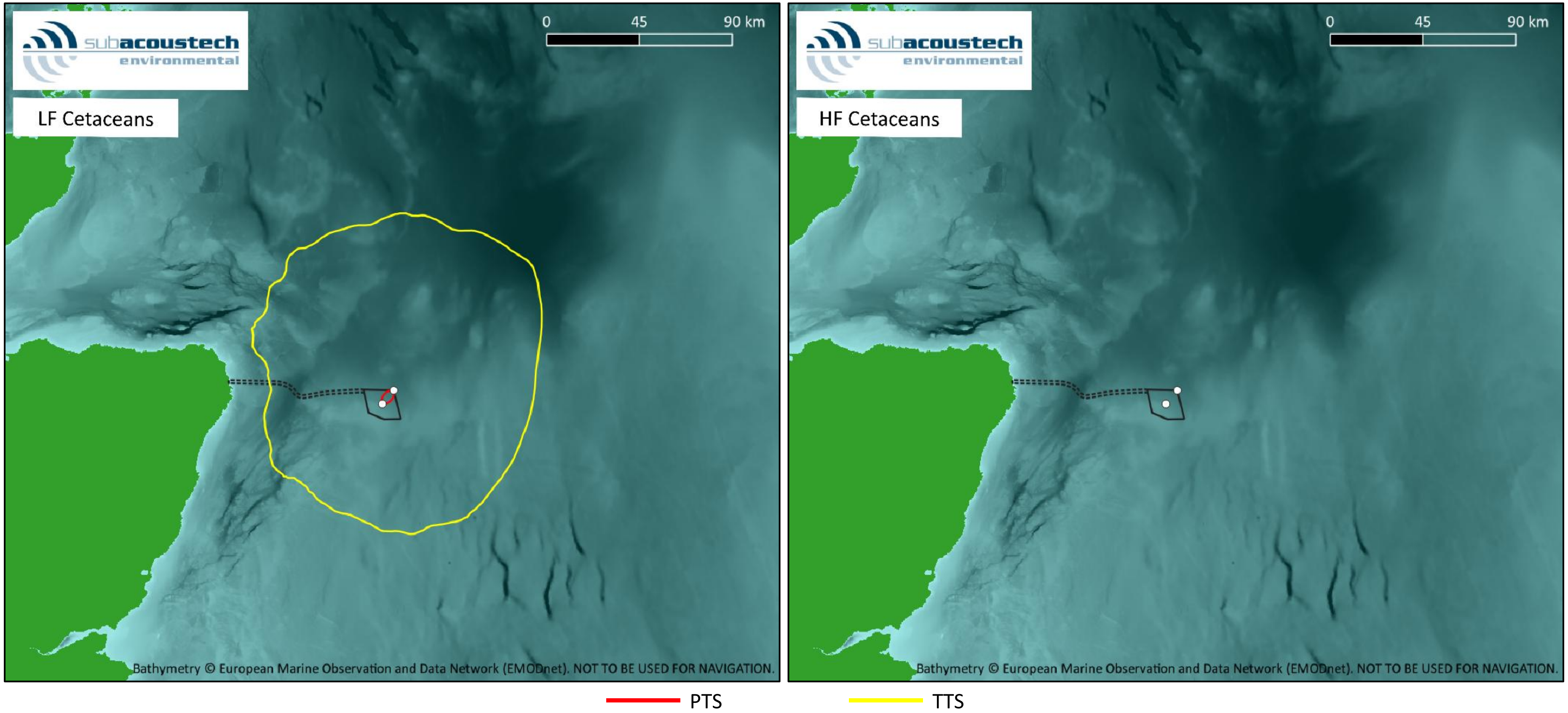

Figure A 3 Contour plots showing the in-combination impacts of concurrent installation of piled anchors at the NE corner modelling location and OEP piles at the Centre modelling location for LF and HF cetaceans using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal.

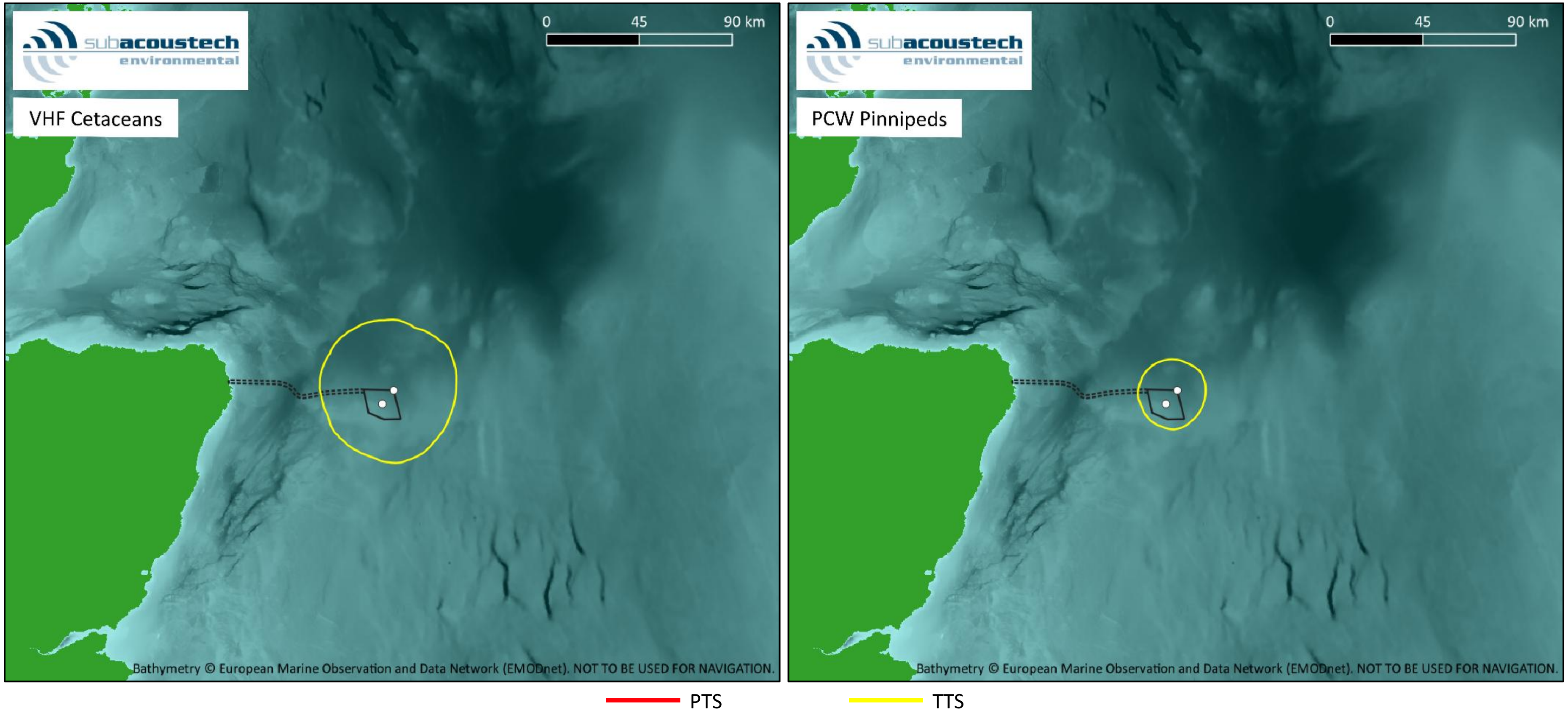

Figure A 4 Contour plots showing the in-combination impacts of concurrent installation of piled anchors at the NE corner modelling location and OEP piles at the Centre modelling location for VHF cetaceans and PCW pinnipeds using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal.

Table A 8 Summary of the impact areas for the installation of piled anchor at the NE corner modelling location and OEP piles at the Centre modelling location for marine mammals using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal.

OEP pile + piled anchor (Southall *et al.*, 2019) $L_{E,p,24h,wtd}$		**NE corner**	**Centre location**	**In-combination area**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 0.1 km^2	28 km^2
	HF (198 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (173 dB)	< 0.1 km^2	< 0.1 km^2	-
	PCW (201 dB)	< 0.1 km^2	< 0.1 km^2	-
TTS (Non-impulsive)	LF (179 dB)	11,000 km^2	13,000 km^2	17,000 km^2
	HF (178 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (153 dB)	1,400 km^2	1,900 km^2	3,600 km^2
	PCW (181 dB)	150 km^2	230 km^2	860 km^2

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P346R0201	01	15/05/2024	Addition of second concurrent piling modelling results
P346R0202	-	28/05/2024	Amendments following client comments
P346R0203	-	24/06/2024	Issue to client

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