Offshore Wind Power Limited

West of Orkney Offshore EIA Report

Volume 2, Supporting Study 11: Underwater Noise Modelling Report

WO1-WOW-CON-EV-RP-0050: Approved by S.Kerr
Document Control 13/09/2023

ASSIGNMENT	**L100632-S05**
DOCUMENT	**L-100632-S05-A-REPT-006**

XODUS

Aberdeen

Xodus House
50 Huntly Street . Aberdeen
AB10 1RS . UK

T +44 (0)1224 628300
E david.bloxsom@xodusgroup.com

www.xodusgroup.com

Submitted to:	Submitted by:
David Bloxsom Xodus	Tim Mason Subacoustech Environmental Ltd Unit 2, Muira Industrial Estate William Street Southampton SO14 5QH United Kingdom
Tel: +44 (0)207 2462995	Tel: +44 (0)23 80 236 330
E-mail: david.bloxsom@xodusgroup.com Website: www.xodusgroup.com	E-mail: tim.mason@subacoustech.com Website: www.subacoustech.com

---

West of Orkney Windfarm:
Underwater Noise Assessment

Richard Barham, Tim Mason

16 February 2023

Subacoustech Environmental Report No.
P325R0303

Document No.	Date	Written	Approved	Distribution
P325R0301	*01/12/2022*	*R Barham*	*T Mason*	*D Bloxsom (Xodus)*
P325R0302	*15/02/2023*	*R Barham*	*T Mason*	*D Bloxsom (Xodus)*
P325R0303	*16/02/2023*	*R Barham*	*T Mason*	*D Bloxsom (Xodus)*

This report is a controlled document. The report documentation page lists the version number, record of changes, referencing information, abstract and other documentation details.

List of contents

Glossary

Term	Definition
Decibel (dB)	A customary scale commonly used (in various ways) for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be $10\log_{10}(actual/reference)$ where $(actual/reference)$ is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is $20\log_{10}(actual\,pressure/reference\,pressure)$. The standard reference for underwater sound is 1 micro pascal (µPa). 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)	A permanent total or partial loss of hearing caused by acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the air, 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)	The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.
Sound Exposure Level, cumulative (SEL_{cum})	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.

Term	Definition
Sound Pressure Level (SPL)	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})	The highest (zero-peak) positive or negative sound pressure, in decibels.
Temporary Threshold Shift (TTS)	Temporary reduction of hearing acuity because of exposure to sound over time. Exposure to high levels of sound over relatively short time periods could cause the same level of TTS as exposure to lower levels of sound over longer time periods. 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. Examples of this are the dB(A), where the overall sound level has been adjusted to account for the hearing ability of humans in air, or the filters used by Southall *et al*. (2019) for marine mammals.

Acronyms

Acronym	Definition
ADD	Acoustic Deterrent Device
BGS	British Geological Survey
EIA	Environmental Impact Assessment
EMODnet	European Marine Observation and Data Network
FPSO	Floating Production Storage and Offloading
GIS	Geographic Information System
HE	High Explosive
HF	High-Frequency Cetaceans (Marine mammal hearing group from Southall *et al*., 2019)
INSPIRE	Impulse Noise Sound Propagation and Range Estimator (Subacoustech Environmental’s noise model for estimating impact piling noise)
LF	Low-Frequency Cetaceans (Marine mammal hearing group from Southall *et al*., 2019)
MTD	Marine Technology Directorate
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPL	National Physical Laboratory
OAA	Option Agreement Area
PCW	Phocid Carnivores in Water (Marine mammal hearing group from Southall *et al*., 2019)
PPV	Peak Particle Velocity
PTS	Permanent Threshold Shift
RMS	Root Mean Square
SE	Sound Exposure
SEL	Sound Exposure Level
SEL_{cum}	Cumulative Sound Exposure Level
SEL_{ss}	Single Strike Sound Exposure Level
SPL	Sound Pressure Level
SPL_{peak}	Peak Sound Pressure Level
$SPL_{peak\text{-}to\text{-}peak}$	Peak-to-peak Sound Pressure Level
SPL_{RMS}	Root Mean Square Sound Pressure Level

Acronym	Definition
TNT	Trinitrotoluene (explosive)
TTS	Temporary Threshold Shift
UXO	Unexploded Ordnance
VHF	Very High-Frequency Cetaceans (Marine mammal hearing group from Southall *et al*., 2019)
WTG	Wind Turbine Generator

Units

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

1 Introduction

The applicant, Offshore Wind Power Limited (OWPL) is proposing the development of the West of Orkney Windfarm ('the Project') located around 28 km off the west coast of Orkney and 23 km from the north coast of Scotland. As part of the Offshore Environmental Impact Assessment (EIA), Subacoustech Environmental Ltd. have undertaken detailed modelling and analysis in relation to the effect of underwater noise on marine mammals and fish at the site.

The offshore Project area includes the Option Agreement Area (OAA) and the offshore export cable corridor (ECC), within which all offshore infrastructure will be located. The OAA covers an area of 657 km^2 and the project will deploy up to 125 Wind Turbine Generators (WTGs). The location of site is shown in Figure 1-1.

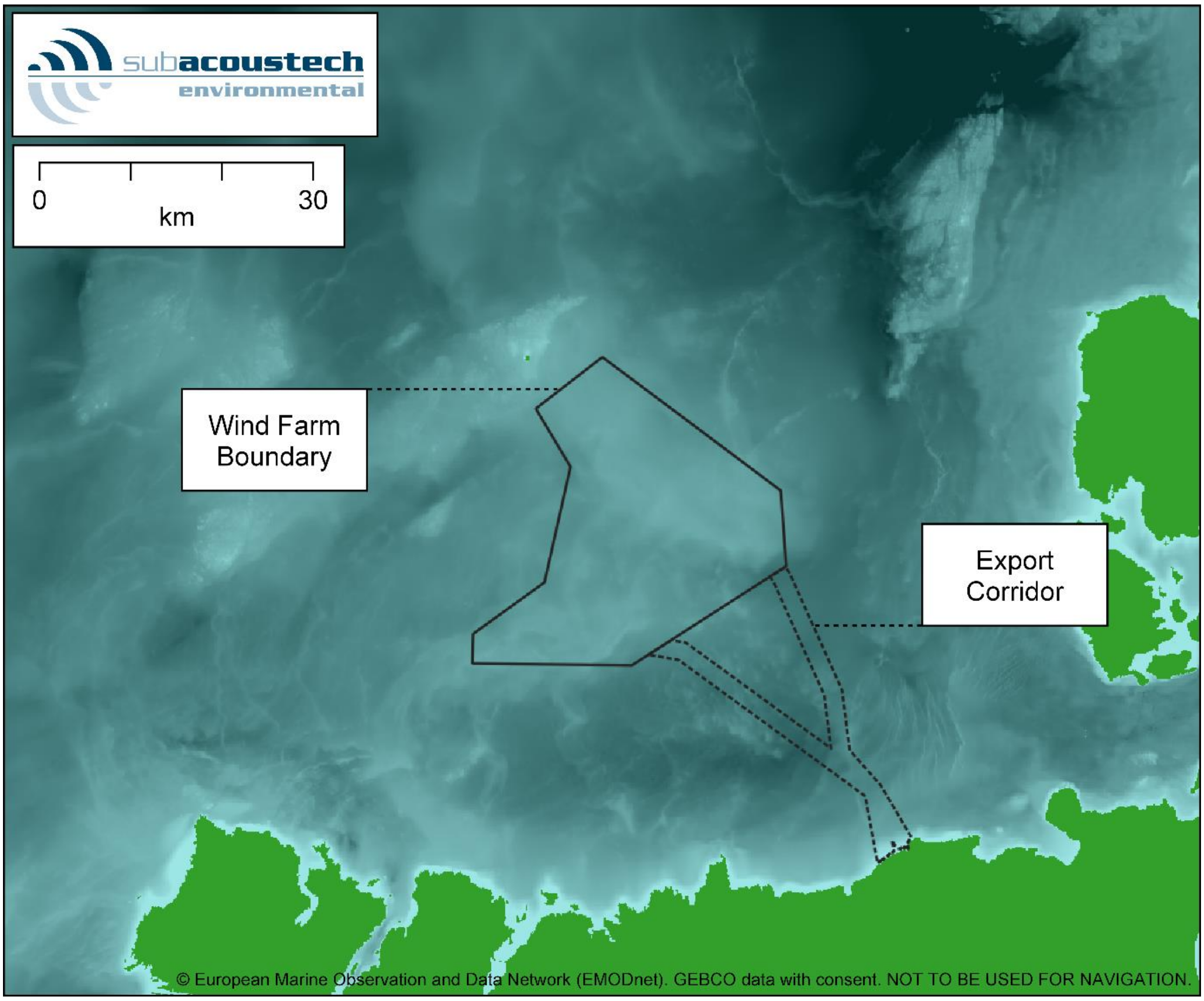


Figure 1-1 Overview map showing the offshore Project area (including windfarm boundary presenting the OAA and the offshore ECC) and the surrounding bathymetry and coastline

This Supporting Study presents a detailed assessment of the potential underwater noise during construction and operation of the offshore Project, and includes the following:

- Background information covering the units used for measuring and assessing underwater noise and a review of the underwater noise metrics and criteria used to assess the possible environmental effect in marine receptors (section 2);

- Discussion of the modelling approach, input parameters and assumptions of the detailed noise 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 the other noise sources expected around the construction and operation of the offshore Project including cable laying, dredging, drilling, rock placement, suction bucket installation, vessel movements, operational WTG noise and unexploded ordnance (UXO) clearance (section 5); and
- Summary and conclusions (section 6).

Additional modelling results are presented in Appendix A.

2 Background to underwater noise metrics

2.1 Underwater noise

Sound travels much faster in water (approximately 1500 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. As an example, background noise levels in the sea of 130 dB re 1 µPa for UK coastal waters are not uncommon (Nedwell *et al*., 2003; Nedwell *et al*., 2007).

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

2.1.1 Units of measurement

Sound measurements underwater are usually expressed using the decibel (dB) scale, which is a logarithmic measure of sound. A logarithmic scale is used because, rather than equal increments of sound having an equal increase in effect, typically each doubling of sound level will cause a roughly equal increase of “loudness.”

Any quantity expressed in this scale is termed a “level.” If the unit is sound pressure, expressed on the dB scale, it will be termed a “sound pressure level.”

The fundamental definition of the dB scale is given by:

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

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

The dB scale represents a ratio. It is therefore used with a reference unit, which expresses the base from which the ratio is expressed. The reference quantity is conventionally smaller than the smallest value to be expressed on the scale so that any level quoted is positive. For example, a reference quantity of 20 µPa is used for sound in air since that is the lower threshold of human hearing.

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

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

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

2.1.2 Sound Pressure Level (SPL)

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

Where SPL is used to characterise transient pressure waves, such as that from impact piling, seismic airgun or underwater blasting, it is critical that the period over which the RMS level is calculated is quoted. For instance, in the case of a pile strike lasting 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 or Sound Exposure Levels (SELs).

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

2.1.3 Peak Sound Pressure Level (SPL_{peak})

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

A further variation of this is the peak-to-peak SPL ($SPL_{peak\text{-}to\text{-}peak}$) where the maximum variation of the pressure from positive to negative 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 (see section 2.1.1).

2.1.4 Sound Exposure Level (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 sums the acoustic energy over a measurement period, 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 Pascals, T is the total duration of sound in seconds, and t is time in seconds. The SE is a measurement of acoustic energy and has units of Pascal squared seconds (Pa^2s).

To press 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 SEL is then defined by:

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

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

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

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

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

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” SEL or SEL_{ss}. A cumulative SEL, or SEL_{cum}, accounts for the exposure from multiple impulse or pile strikes over time, where the number of impulses replaces the T in the equation above, leading to:

$$SEL_{cum} = SEL + 10 \times \log_{10} X$$

Where SEL is the sound exposure level of one impulse and X is the total number of impulses or strikes.

Unless otherwise defined, all SEL noise levels in this report are referenced to 1 µPa^{2}s.

2.2 Analysis of environmental effects

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 blasting or impact piling, as these sources are likely to have the greatest immediate environmental impact and therefore the clearest observable effects, although interest in chronic noise exposure is increasing.

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

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

The following sections discuss the underwater noise criteria used in this study with respect to species of marine mammals and fish that may be present around the offshore Project.

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

- Southall *et al*. (2019) marine mammal exposure criteria; 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.

2.2.1 Marine mammals

The Southall *et al*. (2019) paper is effectively an update of the previous Southall *et al*. (2007) paper and provides identical thresholds to those from the National Marine Fisheries Service (NMFS) (2018) guidance for marine mammals (although it names marine mammal categories slightly differently).

The Southall *et al*. (2019) guidance groups marine mammals into groups of similar species and applies filters to the unweighted noise to approximate the hearing 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 waters north of Scotland and around Orkney.

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)

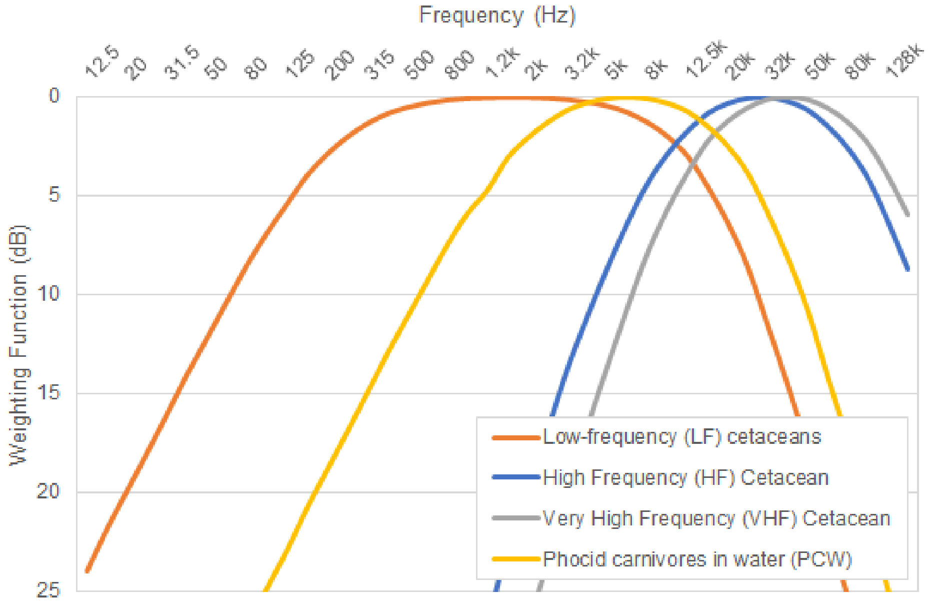


Figure 2-1 Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HD), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al., 2019)

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

Southall *et al*. (2019) presents single strike, unweighted peak criteria (SPL_{peak}) and cumulative weighted sound exposure criteria (SEL_{cum}, i.e., can include the accumulated exposure of multiple pulses) for both permanent threshold shift (PTS), where unrecoverable (but incremental) hearing damage may occur, and temporary threshold shift (TTS), where a temporary reduction in hearing sensitivity may occur in individual receptors. These dual criteria (SPL_{peak} and SEL_{cum}) are only used for impulsive noise: the criteria set giving the greatest calculated range is typically used as the relevant impact range.

As sound pulses propagate through the environment and dissipate, they also lose their most injurious characteristics (e.g., rapid pulse rise time and high peak sound pressure) and become more like a “non-pulse” at greater distances; Southall *et al*. (2019) briefly discusses this. Active research is currently underway into the identification of the distance at which the pulse can be considered effectively non-impulsive, and Hastie *et al*. (2019) have analysed a series of impulsive data to investigate it. Although the situation is complex, the paper reported that most of the signals crossed their threshold for rapid rise time and high peak sound pressure characteristics associated with impulsive noise at around 3.5 km from the source. Southall (2021) discusses this further and suggests that the impulsive characteristics can correspond with significant energy content of the pulse above 10 kHz. This will naturally change depending on the noise source and the environment over which it travels.

Research by Martin *et al*. (2020) casts doubt on these findings, showing that noise in this category should be considered impulsive as long as it is above effective quiet, or a noise sufficiently low enough that it does not contribute significantly to any auditory impairment or injury. To provide as much detail as possible, both impulsive and non-impulsive criteria from Southall *et al*. (2019) have been included in this study.

Although the use of impact ranges derived using the impulsive criteria are recommended for all but the clearly non-impulsive sources (such as drilling), it should be recognised that where calculated ranges are beyond 3.5 km, they would be expected to become increasingly less impulsive and harmful, and the impact range is therefore likely to be somewhere between the modelled impulsive and non-impulsive impact range. Where the impulsive impact range is significantly greater than 3.5 km, the non-impulsive range should be considered.

Table 2-2 and Table 2-3 present the unweighted SPL_{peak} and weighted SEL_{cum} criteria for marine mammals from Southall *et al*. (2019) covering both impulsive and non-impulsive noise.

Table 2-2 Single strike SPL_{peak} criteria for PTS and TTS in marine mammals (Southall et al., 2019)

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

Table 2-3 Impulsive and non-impulsive SEL_{cum} criteria for PTS and TTS in marine mammals (Southall et al., 2019)

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

Where SEL_{cum} 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, the following flee speeds have been used for each marine mammal group:

- 2.1 m/s for low-frequency cetaceans (LF) (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 swim much faster under stress conditions (Kastelein *et al*., 2018), especially at the start of any noisy process when the receptor will be closest to the noise source.

2.2.2 Fish and other megafauna

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

The Popper *et al*. (2014) study groups species of fish by whether they possess a swim bladder, and whether it is involved in its hearing; groups for sea turtles and fish eggs and larvae are also included. The guidance also gives specific criteria (as both unweighted SPL_{peak} and unweighted SEL_{cum} values) for a variety of noise sources. (It is recognised that these are related to sound pressure, whereas more recent documents (e.g., Popper and Hawkins, 2019) clearly state that many fish species are most sensitive to particle motion. This is discussed in section 2.2.2.1.)

For this study, criteria for impact piling, continuous noise sources, and explosions have been considered; these are summarised in Table 2-4 to Table 2-6.

Table 2-4 Criteria for mortality and potential mortal injury, recoverable injury, and TTS in species of fish from impact piling noise (Popper et al., 2014)

Type of animal	**Mortality and potential mortal injury**	**Impairment**	
		Recoverable injury	**TTS**
Fish: no swim bladder	> 219 dB SEL_{cum} > 213 dB SPL_{peak}	> 216 dB SEL_{cum} > 213 dB SPL_{peak}	>> 186 dB SEL_{cum}
Fish: swim bladder is not involved in hearing	210 dB SEL_{cum} > 207 dB SPL_{peak}	203 dB SEL_{cum} > 207 dB SPL_{peak}	> 186 dB SEL_{cum}
Fish: swim bladder involved in hearing	207 dB SEL_{cum} > 207 dB SPL_{peak}	203 dB SEL_{cum} > 207 dB SPL_{peak}	186 dB SEL_{cum}
Sea turtles	> 210 dB SEL_{cum} > 207 dB SPL_{peak}	See Table 2-7	
Eggs and larvae	> 210 dB SEL_{cum} > 207 dB SPL_{peak}		

Table 2-5 Criteria for recoverable injury and TTS in species of fish from continuous noise sources (Popper et al., 2014)

Type of animal	**Impairment**	
	Recoverable injury	**TTS**
Fish: swim bladder involved in hearing	170 dB SPL_{RMS} for 48 hrs	158 dB SPL_{RMS} for 12 hours

Table 2-6 Criteria for potential mortal injury in species of fish from explosions (Popper et al., 2014)

Type of animal	Mortality and potential mortal injury
Fish: no swim bladder	229 – 234 dB SPL$_{peak}$
Fish: swim bladder is not involved in hearing	229 – 234 dB SPL$_{peak}$
Fish: swim bladder involved in hearing	229 – 234 dB SPL$_{peak}$
Sea turtles	229 – 234 dB SPL$_{peak}$
Eggs and larvae	> 13 mm/s peak velocity

Where insufficient data are available, Popper *et al*. (2014) also gives qualitative criteria that summarise the effect of the noise as having either a high, moderate, or low effect on an individual in either the near-field (tens of metres), intermediate-field (hundreds of metres), or far-field (thousands of metres). These qualitative effects are reproduced in Table 2-7 to Table 2-9.

Table 2-7 Summary of the qualitative effects on species of fish from impact piling noise (Popper et al., 2014) (N = Near-field; I = Intermediate-field; F = Far-field)

Type of animal	Impairment			Behaviour
	Recoverable injury	TTS	Masking	
Fish: no swim bladder	See Table 2-4		(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing			(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder involved in hearing			(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate
Sea turtles	(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	(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 2-8 Summary of the qualitative effects on fish from continuous noise from Popper et al. (2014) (N = Near-field; I = Intermediate-field; F = Far-field)

Type of animal	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 is not involved in hearing	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder involved in hearing	(N) Low (I) Low (F) Low	See Table 2-5		(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

Table 2-9 Summary of the qualitative effects on species of fish from explosions (Popper et al., 2014) (N = Near-field; I = Intermediate-field; F = Far-field)

Type of animal	Impairment			Behaviour
	Recoverable injury	TTS	Masking	
Fish: no swim bladder	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing	(N) High (I) High (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) High (F) Low
Fish: swim bladder involved in hearing	(N) High (I) High (F) Low	(N) High (I) High (F) Low	N/A	(N) High (I) High (F) Low
Sea turtles	(N) High (I) High (F) Low	(N) High (I) High (F) Low	N/A	(N) High (I) High (F) Low
Eggs and larvae	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low

Both fleeing animal and stationary animal models have been used to cover the $\mathrm{SEL}_{\mathrm{cum}}$ criteria for fish. It is recognised that there is limited evidence for fish fleeing from high level noise sources in the wild, and it would reasonably be expected that the reaction would differ between species. Most species are likely to move away from a sound that is loud enough to cause harm (Dahl *et al*., 2015; Popper *et al*., 2014), some may seek protection in the sediment and others may dive deeper in the water column. For those species that flee, the speed chosen for this study of 1.5 m/s is relatively slow in relation to data from Hirata (1999) and thus is considered somewhat conservative.

Although it is feasible that some species will not flee, those that are likely to remain are thought more likely to be benthic species or species without a swim bladder; these are the least sensitive species.

For example, from Popper *et al*. (2014): “There is evidence (e.g., Goertner *et al*., 1994; Stephenson *et al*., 2010; Halvorsen *et al*., 2012) that little or no damage occurs to fish without a swim bladder except at very short ranges from an in-water explosive event. Goertner (1978) showed that the range from an explosive event over which damage may occur to a non-swim bladder fish is in the order of 100 times less than that for swim bladder fish.”

Stationary animal modelling has been included in this study, acknowledging the limited evidence for fish fleeing behaviour as a result of noise exposure, and other modelling for similar EIA projects. However, basing the modelling on a stationary (zero flee speed) receptor is likely to greatly overestimate the potential risk to fish species, assuming that an individual would remain in the high noise level region of the water column for the whole duration of piling, especially when considering the precautionary nature of the parameters already built into the cumulative exposure calculations.

2.2.2.1 Particle motion

The criteria defined in the above section define the noise impacts on fishes in terms of sound pressure or sound pressure-associated functions (i.e., SEL). It has been identified by researchers (e.g., Popper and Hawkins, 2019; Nedelec *et al*., 2016; Radford *et al.,* 2012) that many species of fish, as well as invertebrates, actually detect particle motion rather than acoustic pressure. Particle motion describes the back-and-forth movement of a tiny theoretical ‘element’ of water, substrate or other media as a sound wave passes, rather than the pressure caused by the action of the force created by this movement. Particle motion 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. Note that species in the “Fish: swim bladder involved in hearing” category, the species most sensitive to noise, are sensitive to sound pressure.

Popper and Hawkins (2018) state that in derivation of the sound pressure-based criteria in Popper *et al.* (2014) it may be the unmeasured particle motion detected by the fish, to which the fish were responding: there is a relationship between particle motion and sound pressure in a medium. This relationship is very difficult to define where the sound field is complex, such as close to the noise source or where there are multiple reflections of the sound wave in shallow water. Even these terms “shallow” and “close” do not have simple definitions.

The primary reason for the continuing use of sound pressure as the criteria, despite particle motion appearing to be the physical measure to which so many fish react or sense, is a lack of data (Popper and Hawkins, 2018) both in respect of predictions of the particle motion level as a consequence of a noise source such as piling, and a lack of knowledge of the sensitivity of a fish, or a wider category of fish, to a particle motion value. There continue to be calls for additional research on the levels of and effects with respect to levels of particle motion. Until sufficient data are available to enable revised thresholds based on the particle motion metric, Popper and Hawkins (2019) states that “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.”.

3 Modelling methodology

To estimate the underwater noise levels likely to arise during the construction and operation of the offshore Project, 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). As such, the noise related to impact piling activities 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 5.1) is a semi-empirical underwater noise propagation model based around a combination of numerical modelling, based around a combined geometric and energy flow/hysteresis loss method, and actual measured data. It is designed to calculate the propagation of noise in shallow (i.e., less than 100 m), mixed water, typical of the conditions around the UK. The model has been tuned for accuracy using over 80 datasets of underwater noise propagation from monitoring around offshore piling activities. The bathymetry around the offshore Project is particularly deep, and likely to lead to greater underwater noise levels than are typical for much of the water around the British Isles. The impact hammer predicted is also larger than any currently available or sampled in similar waters. The model is designed to extrapolate the existing knowledge to these parameters and designed to give a precautionary but realistic prediction of noise. While the depth of water is greater than that in the available knowledgebase, the increase in depth is still generally regarded as ‘shallow’ in respect of the propagation of underwater sound, and so not expected to lead to a significant change in the acoustic conditions. Extrapolations such as this are normal for these projects

The model provides estimates of unweighted SPL_{peak}, SEL_{ss}, and SEL_{cum} noise levels, as well as various other weighted noise metrics. Calculations are made along 180 equally spaced radial transects (one every two degrees). For each modelling run a criterion level can be specified allowing a contour to be drawn, within which a given effect may occur. These results can then be plotted over digital bathymetry data so that impact ranges can be clearly visualised, as necessary. INSPIRE also produces these contours as 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, ramp up profile, 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 construction and operation of the offshore Project, and these are discussed in section 5.

3.1 Modelling confidence

INSPIRE is semi-empirical and thus a validation process is inherently built into the development process. Whenever a new set of good, reliable, impact piling measurement data is gathered through offshore surveys it is compared against the outputted levels from INSPIRE and, if necessary, the model can be adjusted accordingly. Currently over 80 separate impact piling noise datasets from all around the UK 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, as well as in Thompson *et al.* (2013).

The current version of INSPIRE (version 5.1) is the product of re-analysing all the impact piling noise measurements in Subacoustech Environmental’s measurement database and cross-referencing it with blow energy data from piling logs. This gave a database of single strike noise levels referenced to a specific blow energy at a specific range. This analysis showed that, based on the most up to date measurement data for large piles at high blow energies, the previous versions of INSPIRE tended to overestimate the predicted noise levels at these blow energies.

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. When modelling using the upper bounds of this range, in combination with other worst-case parameter selections, conservatism can be compounded and create excessively overcautious predictions, especially when calculating SEL_{cum}. With this in mind, the current version of the INSPIRE model attempts to calculate closer to the average fit of the measured noise levels at all ranges.

Figure 3-1 presents a small selection of 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 version 5.1, matching the pile size, blow energy and range from the measured data. These show the fit to the data, with the INSPIRE model 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 the influence on the SEL_{cum} will be minimal.

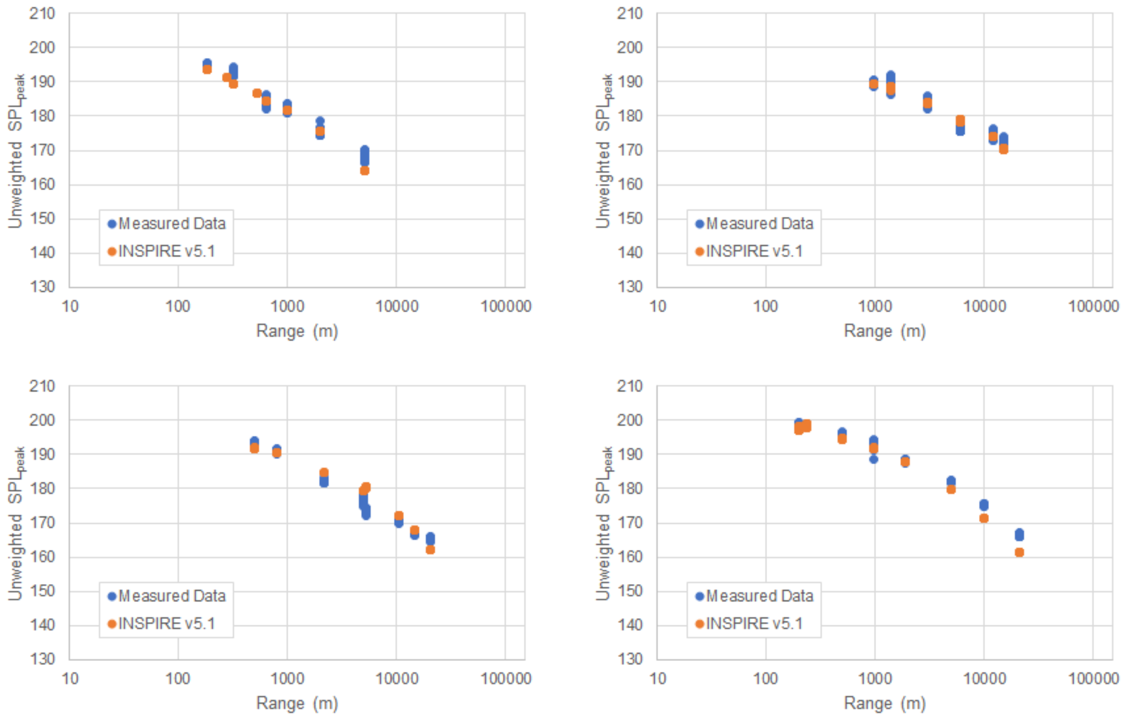


Figure 3-1 Comparison between example measured impact piling data (blue points) and modelled data using INSPIRE version 5.1 (orange points)[1]

3.2 Modelling parameters

3.2.1 Modelling locations

Modelling for WTG foundation impact piling has been undertaken at three representative locations at the extents of the offshore Project area, in order to investigate attenuation into the surrounding waters as well as piling into deeper water (SE). These include deep water, and closest to land. These locations are summarised in Table 3-1 and Figure 3-2.

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

Modelling locations	North West (NW)	South East (SE)	South West (SW)
Latitude	59.0604°N	58.9020°N	58.7835°N
Longitude	004.3284°W	003.9128°W	004.4989°W
Water depth	54 m	70 m	54 m

---

[1] Top Left: 1.8 m pile, Irish Sea, 2010; Top Right: 9.5 m pile, North Sea, 2020; Bottom Left: 6.1 m pile, Southern North Sea, 2009; Bottom Right: 6 m pile, Southern North Sea, 2009.

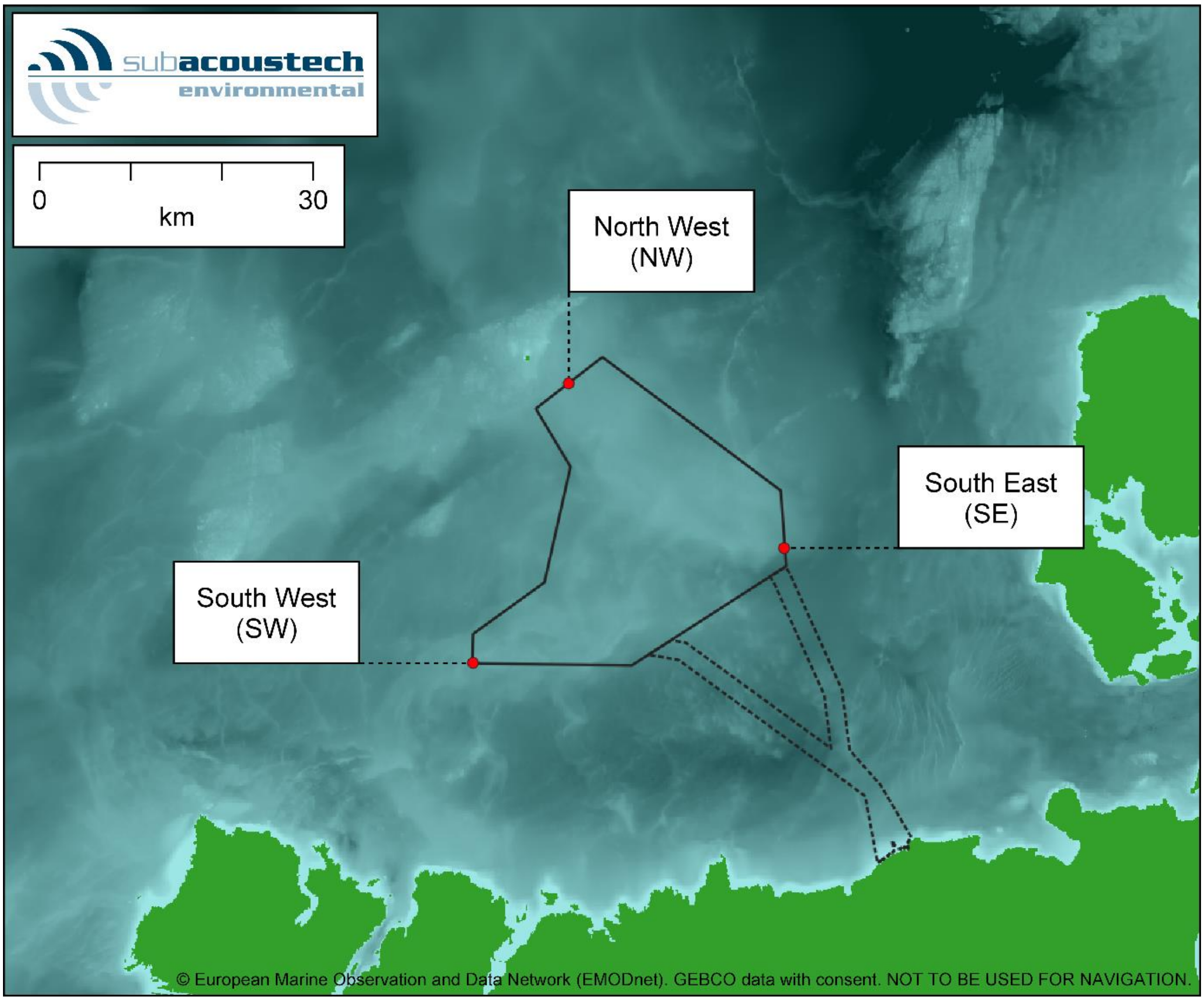


Figure 3-2 Approximate positions of the modelling locations at the offshore Project

3.2.2 WTG foundation and impact piling parameters

Four foundation scenarios have been considered for this study covering both monopile and jacket pile foundations, based on driveability in hard and soft sediments; these are:

- A monopile foundation in hard sediment, installing a 14 m diameter pile with a maximum blow energy of 5,000 kJ, with one monopile installed in a 24-hour period;
- A monopile foundation in soft sediment, installing a 14 m diameter pile with a maximum blow energy of 3,000 kJ, with up to one monopile installed in a 24-hour period;
- A jacket pile foundation in hard sediment, installing 3 m diameter piles with a maximum blow energy of 3,000 kJ, with two piles installed in a 24-hour period; and
- A jacket pile foundation in soft sediment, installing 3 m diameter piles with a maximum blow energy of 3,000 kJ, with four piles installed in a 24-hour period.

For $\mathrm{SEL}_{\mathrm{cum}}$ criteria, the soft start and ramp up of the blow energies along with the total duration of piling and strike rate must also be considered. The scenarios used for modelling are summarised in

Table 3-2 to Table 3-4.

In a 24-hour period there is a possibility that either a single monopile foundation or up to four piles in a single jacket foundation can be driven at a single location. There is also the potential for two piling operations to occur concurrently when installing jacket pile foundations.

The only difference between the hard and soft sediment jacket pile foundation scenarios is the number of piles that can be installed in a 24-hour period.

It is worth stating that these ramp ups assume a long duration at maximum energy, which is highly precautionary.

Table 3-2 Summary of the soft start and ramp up scenario used for the monopile foundation (hard sediment) modelling

Monopile (Hard)	**750 kJ**		**1,250 kJ**	**2,500 kJ**	**3,750 kJ**	**5,000 kJ**
Number of strikes	60	400	400	400	400	45,500
Duration	10 mins	10 mins	10 mins	10 mins	10 mins	910 mins
Strike rate	6 bl/min	40 blows/min				50 bl/min
Single pile: 47,160 strikes, 16 hours total duration						

Table 3-3 Summary of the soft start and ramp up scenario used for the monopile foundation (soft sediment) modelling

Monopile (Soft)	**450 kJ**		**750 kJ**	**1,500 kJ**	**2,250 kJ**	**3,000 kJ**
Number of strikes	60	400	400	400	400	21,500
Duration	10 mins	10 mins	10 mins	10 mins	10 mins	430 mins
Strike rate	6 bl/min	40 blows/min				50 bl/min
Single pile: 23,160 strikes, 8 hours duration						

Table 3-4 Summary of the soft start and ramp up scenario used for both the hard and soft sediment jacket pile foundation modelling

Jacket pile (Hard + Soft)	**450 kJ**		**750 kJ**	**1,500 kJ**	**2,250 kJ**	**3,000 kJ**
Number of strikes	60	400	400	400	400	9,500
Duration	10 mins	10 mins	10 mins	10 mins	10 mins	190 mins
Strike rate	6 bl/min	40 blows/min				50 bl/min
Single pile: 11,160 strikes, 4 hours duration 2 piles (hard sediment): 22,320 strikes, 8 hours duration 4 piles (soft sediment): 44,640 strikes, 16 hours total duration						

Where multiple location concurrent piling has been modelled, the following scenarios have been considered:

- Jacket pile foundation (hard sediment) concurrent location piling scenario:
    - Two sequentially installed piles at the SE location; and
    - Two sequentially installed piles at the SW location.
- Jacket pile foundation (soft sediment) concurrent location piling scenario:
    - Four sequentially installed piles at the SE location; and
    - Four sequentially installed piles at the SW location.

3.2.3 Source levels

Noise modelling requires knowledge of the source level, which is the theoretical noise level at one metre from the noise source. The INSPIRE model assumes that the noise source – that is, the hammer striking the pile – acts as an effective single point, as it will appear at distance. The source level 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 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.

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). 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 unweighted, single strike $\mathrm{SPL}_{\mathrm{peak}}$ and $\mathrm{SEL}_{\mathrm{ss}}$ source levels estimated for this study are provided in Table 3-5. These figures are presented in accordance with typical requirements by regulatory authorities, although as indicated above they are not necessarily compatible or comparable with any other model or predicted source level. In each case, the differences in source level for each location are minimal.

Table 3-5 Summary of the unweighted source levels used for modelling

Source levels	**Location**	Unweighted $\mathrm{SPL}_{\mathrm{peak}}$	Unweighted $\mathrm{SEL}_{\mathrm{ss}}$
Monopile foundation (Hard sediment) 14 m / 5,000 kJ	NW	242.8 dB re 1 µPa @ 1 m	223.9 dB re 1 µPa²s @ 1 m
	SE	242.8 dB re 1 µPa @ 1 m	223.9 dB re 1 µPa²s @ 1 m
	SW	242.8 dB re 1 µPa @ 1 m	223.9 dB re 1 µPa²s @ 1 m
Monopile foundation (Soft sediment) 14 m / 3,000 kJ	NW	241.9 dB re 1 µPa @ 1 m	222.8 dB re 1 µPa²s @ 1 m
	SE	241.9 dB re 1 µPa @ 1 m	222.8 dB re 1 µPa²s @ 1 m
	SW	241.9 dB re 1 µPa @ 1 m	222.8 dB re 1 µPa²s @ 1 m
Jacket foundation (Hard/Soft Sediment) 3 m / 3,000 kJ	NW	241.5 dB re 1 µPa @ 1 m	222.3 dB re 1 µPa²s @ 1 m
	SE	241.6 dB re 1 µPa @ 1 m	222.3 dB re 1 µPa²s @ 1 m
	SW	241.5 dB re 1 µPa @ 1 m	222.3 dB re 1 µPa²s @ 1 m

3.2.4 Predicted noise levels at 750 m from the source

In addition to the source levels given above, it is also useful to look at the potential noise levels at a range of 750 m from the source, which is commonly used as a reference distance in reporting from piling for underwater noise studies at offshore wind farms (originally required in German regulations (BSH, 2013)), and has the advantage of being comparable with other modelling and measurements. A summary of the unweighted noise levels at a range of 750 m are given in Table 3-6 considering the maximum predicted level at each location during maximum blow energy.

Table 3-6 Summary of the predicted maximum unweighted $\mathrm{SPL}_{\mathrm{peak}}$ and $\mathrm{SEL}_{\mathrm{ss}}$ noise levels at a range of 750 m when considering maximum blow energy

Predicted level at 750 m range	**Location**	Unweighted $\mathrm{SPL}_{\mathrm{peak}}$	Unweighted $\mathrm{SEL}_{\mathrm{ss}}$
Monopile foundation (Hard sediment) 14 m / 5,000 kJ	NW	202.5 dB re 1 µPa	184.2 dB re 1 µPa²s
	SE	202.6 dB re 1 µPa	184.4 dB re 1 µPa²s
	SW	202.5 dB re 1 µPa	184.2 dB re 1 µPa²s
Monopile foundation (Soft sediment) 14 m / 3,000 kJ	NW	201.6 dB re 1 µPa	183.2 dB re 1 µPa²s
	SE	201.8 dB re 1 µPa	183.3 dB re 1 µPa²s
	SW	201.6 dB re 1 µPa	183.2 dB re 1 µPa²s
Jacket foundation (Hard/Soft Sediment) 3 m / 3,000 kJ	NW	201.3 dB re 1 µPa	182.6 dB re 1 µPa²s
	SE	201.4 dB re 1 µPa	182.8 dB re 1 µPa²s
	SW	201.3 dB re 1 µPa	182.6 dB re 1 µPa²s

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, which will change throughout the day and year. As it is not known when any piling will occur, an average of all measurements is used, taken over a variety of times and conditions. Data from the British Geological Survey (BGS) show that the seabed in and around the offshore Project is generally made up of variations of gravel and sand.

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

3.3 Cumulative SELs and fleeing receptors

Expanding on the information in section 2.2 regarding $\mathrm{SEL}_{\mathrm{cum}}$ and the fleeing animal model used for modelling, it is important to understand the meaning of the results presented in the following sections.

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

To help explain this, it is helpful to examine how the multiple pulse $\mathrm{SEL}_{\mathrm{cum}}$ ranges are calculated. As explained in Section 2.1.4, the $\mathrm{SEL}_{\mathrm{cum}}$ is a measure of the total received noise over a whole operation: in the cases of the Southall *et al*. (2019) and Popper *et al*. (2014) criteria this covers noise in a 24-hour period unless otherwise specified.

When considering a stationary receptor (i.e., one that stays at the same position throughout piling), calculating the $\mathrm{SEL}_{\mathrm{cum}}$ is fairly straightforward: all the noise levels produced and received at a single point along a transect are aggregated to calculate the $\mathrm{SEL}_{\mathrm{cum}}$. 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 $\mathrm{SEL}_{\mathrm{cum}}$. 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) while the receptor is fleeing is noted. For example, if a noise event 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 $\mathrm{SEL}_{\mathrm{cum}}$ value over the entire operation. The faster an animal is fleeing the greater 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 3-3 and Figure 3-4 show the difference in the received SEL from a stationary receptor and a fleeing receptor travelling at a constant speed of 1.5 m/s (the flee speed used for fish in this study), using the monopile foundation (hard sediment) scenario at the SE location for a single pile installation.

The received $\mathrm{SEL}_{\mathrm{ss}}$ from the stationary receptor, as illustrated in Figure 3-3, 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 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 10 minutes of the piling scenario, where the blow energy is 750 kJ, at a rate of 1.5 m/s, the fleeing receptor has the potential to move 0.9 km away. After the full piling installation of 8 hours, the receptor has the potential to be over 40 km from the pile, although it is recognised that at large distances from the source the receptor is likely to not be swimming directly away from it.

Figure 3-4 shows the effect these different received levels have when calculating the SEL_{cum}. It clearly shows the difference in cumulative effect of the 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 219.4 dB re 1 µPa²s. If the receptor were to remain stationary throughout the piling operation it would receive a cumulative level of 264.3 dB re 1 µPa²s, whereas when fleeing at 1.5 m/s over the same scenario would result in a cumulative received level of just 221.9 dB re 1 µPa²s for the receptor.

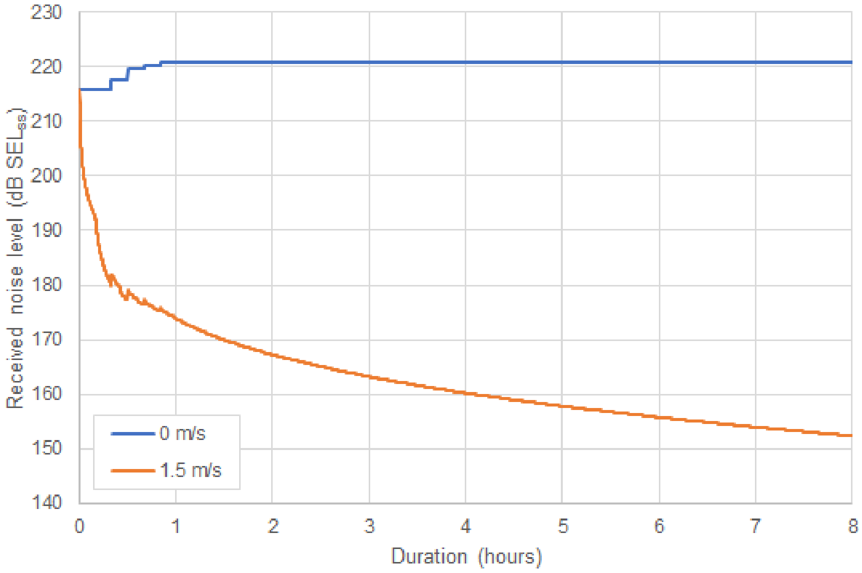


Figure 3-3 Received single-strike noise levels (SEL_{ss}) for receptors during the monopile foundation (hard sediment) parameters at the SE location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source

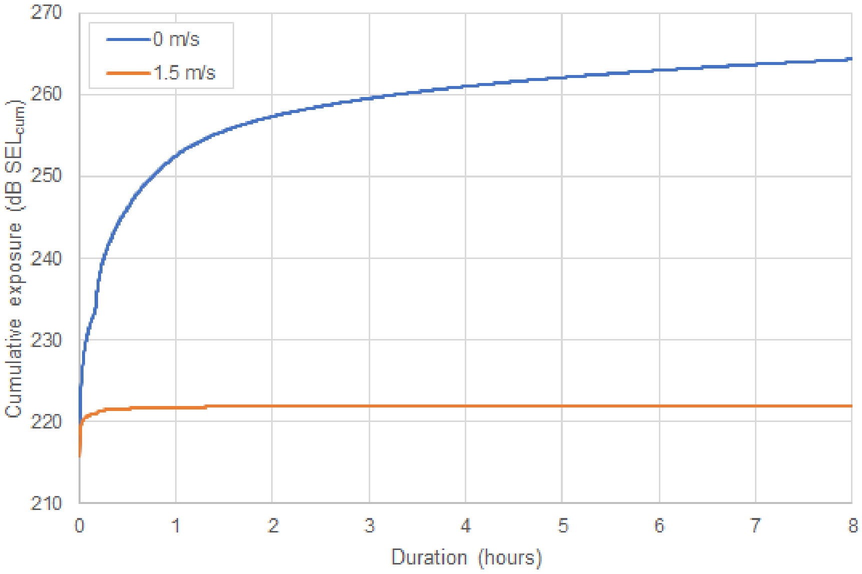


Figure 3-4 Cumulative received noise levels (SEL_{cum}) for receptors during monopile foundation (hard sediment) parameters at the SE location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source

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 criteria, and if the receptor were to start fleeing from a range further than the modelled value it would receive a noise exposure below the criteria. This is illustrated in Figure 3-5.

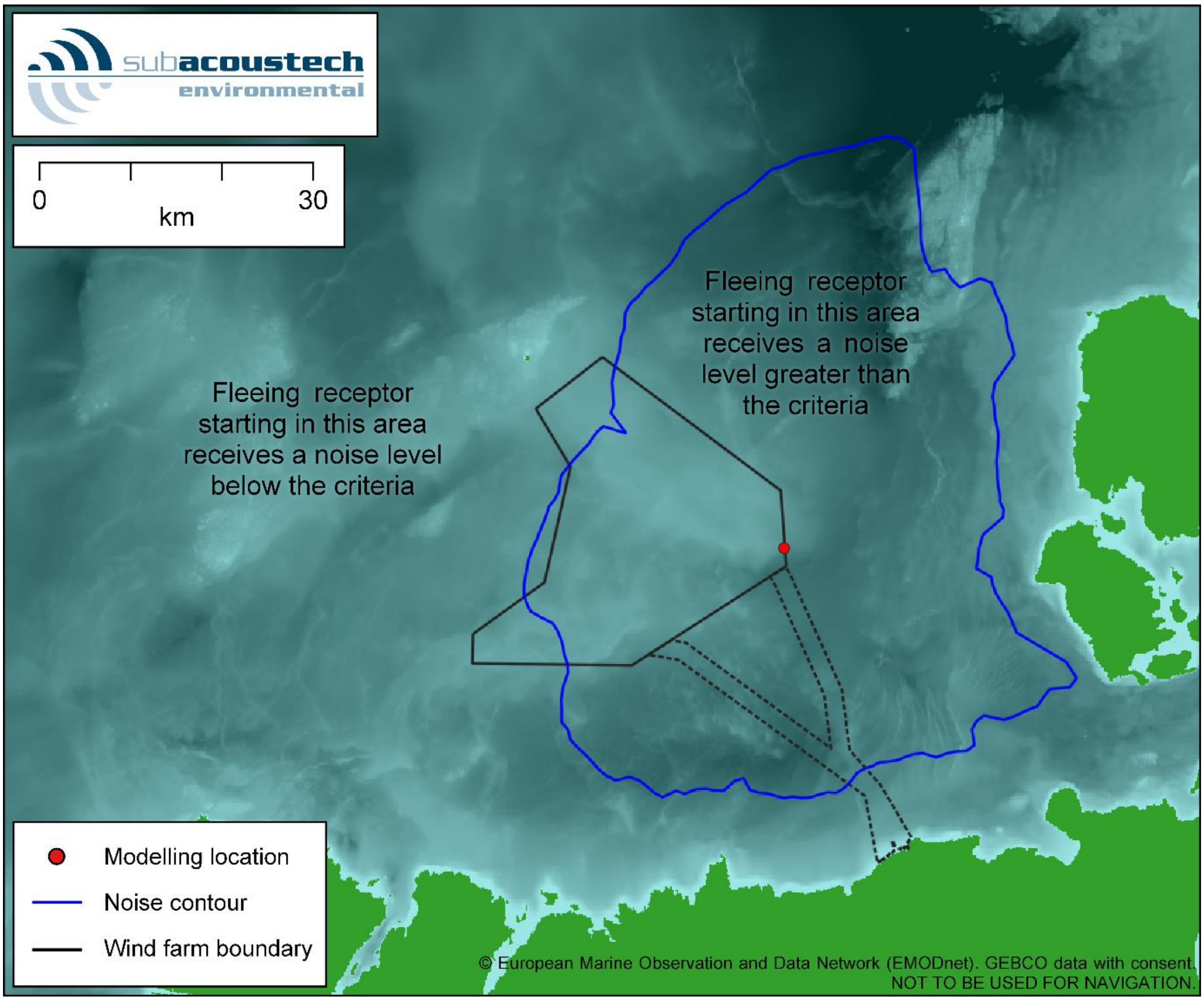


Figure 3-5 Plot showing a fleeing animal SEL_{cum} criteria contour and the areas where the cumulative noise exposure will exceed the impact criteria

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 modelling 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 cumulative SEL impact range from INSPIRE was calculated to be below 1.8 km, it can safely be assumed that the ADD will be effective in eliminating the risk of injury on the receptor. The noise from an ADD is of a much lower level than impact piling, and as such the overall effect on the SEL_{cum} exposure on a receptor would be minimal.

3.3.1 The effects of input parameters on SELs 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 SEL_{cum} and a fleeing animal model, some of these parameters can have a greater influence than others.

Parameters like hammer blow energy can have a clear effect on impact ranges, with higher energies resulting in higher 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 low blow energies to higher ones requires careful consideration for fleeing animals, as the levels while the receptors are relatively close 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 on the $\mathrm{SEL}_{\mathrm{cum}}$. The faster the strike rate, the shorter the distance the receptor can flee between each pile strike, which leads to greater exposure.

In general, the greatest impacts are found when a receptor is close to the noise source. For example, if high blow energies or a fast strike rate are used at the start of the piling activities, bigger increases in impact ranges will result; conversely keeping energies low for longer and slowing the strike rate down in the initial period is beneficial.

The other main element that can cause big differences in calculated impact ranges is the bathymetry, as deep-water results in a slower attenuation of noise and high noise levels travelling further. However, it is not always feasible to limit piling activity in or near to deep water.

4 Modelling results

This section presents the modelled impact ranges for impact piling noise following the parameters detailed in section 3.2, covering the Southall *et al*. (2019) marine mammal criteria (section 2.2.1) and the Popper *et al*. (2014) fish criteria (section 2.2.2). To aid navigation Table 4-1 contains a list of the impact range tables included in this section. Concurrent location modelling results are present in section 4.3. The biggest modelled ranges are predicted for the monopile foundation (hard sediment), scenario at the SE modelling location.

For the results presented 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. 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 pile. These ranges are given as “less than” this limit (e.g., “<100 m”).

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

Table 4-1 Summary of the impact piling modelling results tables presented in this section

Table (page)	Parameters (section)		Criteria		
Table 4-2 (p23)	Monopile foundation (4.1)	NW (4.1.1)	Southall *et al*. (2019)	Unweighted SPL$_{peak}$	Hard sediment
Table 4-3 (p24)					Soft sediment
Table 4-4 (p24)				Weighted SEL$_{cum}$ (Impulsive)	Hard sediment
Table 4-5 (p24)					Soft sediment
Table 4-6 (p24)			Popper *et al*. (2014)	Unweighted SPL$_{peak}$	Hard sediment
Table 4-7 (p25)					Soft sediment
Table 4-8 (p25)				Weighted SEL$_{cum}$ (Pile driving)	Hard sediment
Table 4-9 (p25)					Soft sediment
Table 4-10 (p26)		SE (4.1.2)	Southall *et al*. (2019)	Unweighted SPL$_{peak}$	Hard sediment
Table 4-11 (p26)					Soft sediment
Table 4-12 (p26)				Weighted SEL$_{cum}$ (Impulsive)	Hard sediment
Table 4-13 (p27)					Soft sediment
Table 4-14 (p27)			Popper *et al*. (2014)	Unweighted SPL$_{peak}$	Hard sediment
Table 4-15 (p27)					Soft sediment
Table 4-16 (p27)				Weighted SEL$_{cum}$ (Pile driving)	Hard sediment
Table 4-17 (p28)					Soft sediment
Table 4-18 (p28)		SW (4.1.3)	Southall *et al*. (2019)	Unweighted SPL$_{peak}$	Hard sediment
Table 4-18 (p28)					Soft sediment
Table 4-20 (p29)				Weighted SEL$_{cum}$ (Impulsive)	Hard sediment
Table 4-21 (p29)					Soft sediment
Table 4-22 (p29)			Popper *et al*. (2014)	Unweighted SPL$_{peak}$	Hard sediment
Table 4-23 (p29)					Soft sediment
Table 4-24 (p30)				Weighted SEL$_{cum}$ (Pile driving)	Hard sediment
Table 4-25 (p30)					Soft sediment
Table 4-26 (p31)	Jacket pile foundation (4.2)	NW (4.2.1)	Southall *et al*. (2019)	Unweighted SPL$_{peak}$	
Table 4-27 (p31)				Weighted SEL$_{cum}$ (Impulsive)	Hard sediment
Table 4-28 (p31)					Soft sediment
Table 4-29 (p32)			Popper *et al*. (2014)	Unweighted SPL$_{peak}$	
Table 4-30 (p32)				Weighted SEL$_{cum}$ (Pile driving)	Hard sediment
Table 4-31 (p32)					Soft sediment
Table 4-32 (p33)		SE (4.2.2)	Southall *et al*. (2019)	Unweighted SPL$_{peak}$	
Table 4-33 (p33)				Weighted SEL$_{cum}$ (Impulsive)	Hard sediment
Table 4-34 (p33)					Soft sediment
Table 4-35 (p33)				Unweighted SPL$_{peak}$	
Table 4-36 (p34)					Hard sediment

Table (page)	Parameters (section)		Criteria		
Table 4-37 (p34)			Popper *et al*. (2014)	Weighted SEL_{cum} (Pile driving)	Soft sediment
Table 4-38 (p34)		SW (4.2.3)	Southall *et al*. (2019)	Unweighted SPL_{peak}	
Table 4-39 (p35)				Weighted SEL_{cum} (Impulsive)	Hard sediment
Table 4-40 (p35)					Soft sediment
Table 4-41 (p35)			Popper *et al*. (2014)	Unweighted SPL_{peak}	
Table 4-42 (p36)				Weighted SEL_{cum} (Pile driving)	Hard sediment
Table 4-43 (p36)					Soft sediment

4.1 Monopile foundations

Table 4-2 to Table 4-25 present the modelling results for the monopile foundation modelling scenarios using the parameters presented in section 3.2, in terms of the Southall *et al*. (2019) marine mammal criteria (section 2.2.1) and the Popper *et al*. (2014) fish criteria (section 2.2.2).

The largest marine mammal impact ranges are predicted at the SE modelling location due primarily to the surrounding deep water at this location. Maximum PTS injury ranges are predicted for LF cetaceans using the SEL_{cum} criteria, with ranges of up to 47 km, for VHF cetaceans PTS ranges are predicted up to 17 km for the same scenario.

For fish, the largest recoverable injury ranges (203 dB SEL_{cum} threshold) for monopiles are predicted to be 25 km assuming a stationary receptor at the deeper SE location; if a fleeing animal is assumed, these ranges are reduced to 3.9 km.

It is worth noting that larger impact ranges are predicted for the hard sediment scenarios than for the soft sediment, this is due to the higher blow energies and longer overall piling duration for this scenario.

Modelling at several of the locations have large differences between the minimum range and the maximum and mean ranges (see for example in Table 4-4 the difference between the minimum and maximum impact ranges for LF cetacean PTS). These small ranges are due to the noise interacting with the Sule Skerry and Sule Stack islands to the northwest of the OAA, which limits the noise propagation and leads to low “minimum” ranges.

4.1.1 NW location

Table 4-2 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (hard sediment) modelling at the NW location

Southall *et al*. (2019) Unweighted SPL_{peak}		**Monopile foundation, hard sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	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)	1.5 km^2	700 m	700 m	700 m
	PCW (218 dB)	0.01 km^2	60 m	60 m	60 m
TTS	LF (213 dB)	0.05 km^2	120 m	120 m	120 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	9.2 km^2	1.7 km	1.7 km	1.7 km
	PCW (212 dB)	0.07 km^2	150 m	150 m	150 m

Table 4-3 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (soft sediment) modelling at the NW location

Southall *et al*. (2019) Unweighted SPL_{peak}		**Monopile foundation, soft sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	610 m	610 m	610 m
	PCW (218 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.04 km^2	110 m	110 m	110 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	7.1 km^2	1.5 km	1.5 km	1.5 km
	PCW (212 dB)	0.05 km^2	130 m	130 m	130 m

Table 4-4 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (hard sediment) modelling at the NW location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Monopile foundation, hard sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	3,000 km^2	44 km	3.1 km	30 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	490 km^2	16 km	2.4 km	12 km
	PCW (185 dB)	< 0.1 km^2	100 m	< 100 m	< 100 m
TTS	LF (168 dB)	19,000 km^2	155 km	4.1 km	72 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	7,500 km^2	69 km	4.0 km	48 km
	PCW (170 dB)	1,500 km^2	31 km	3.0 km	22 km

Table 4-5 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (soft sediment) modelling at the NW location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Monopile foundation, soft sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	2,400 km^2	40 km	2.6 km	27 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	340 km^2	13 km	1.9 km	10 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	15,000 km^2	109 km	3.7 km	66 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	6,300 km^2	63 km	3.9 km	44 km
	PCW (170 dB)	1,300 km^2	28 km	2.7 km	20 km

Table 4-6 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (hard sediment) modelling at the NW location

Popper *et al*. (2014) Unweighted SPL_{peak}	**Monopile foundation, hard sediment**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.05 km^2	120 m	120 m	120 m
207 dB	0.3 km^2	320 m	320 m	320 m

Table 4-7 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (soft sediment) modelling at the NW location

Popper *et al*. (2014) Unweighted SPL_{peak}	**Monopile foundation, soft sediment**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.04 km^2	110 m	110 m	110 m
207 dB	0.2 km^2	280 m	280 m	280 m

Table 4-8 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (hard sediment) modelling at the NW location assuming both a fleeing and stationary animal

Popper *et al*. (2014) Unweighted SEL_{cum}		**Monopile foundation, hard sediment**			
		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	16 km^2	3.0 km	130 m	2.2 km
	186 dB	4,100 km^2	52 km	3.6 km	36 km
Stationary (0 m/s)	219 dB	36 km^2	3.5 km	3.4 km	3.4 km
	216 dB	79 km^2	5.1 km	4.8 km	5.0 km
	210 dB	310 km^2	11 km	5.0 km	9.9 km
	207 dB	580 km^2	15 km	5.0 km	14 km
	203 dB	1,200 km^2	23 km	5.0 km	20 km
	186 dB	12,000 km^2	83 km	5.0 km	61 km

Table 4-9 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (soft sediment) modelling at the NW location assuming both a fleeing and stationary animal

Popper *et al*. (2014) Unweighted SEL_{cum}		**Monopile foundation, soft sediment**			
		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	4.0 km^2	1.5 km	< 100 m	1.1 km
	186 dB	3,300 km^2	46 km	3.2 km	32 km
Stationary (0 m/s)	219 dB	11 km^2	1.9 km	1.9 km	1.9 km
	216 dB	26 km^2	2.9 km	2.8 km	2.9 km
	210 dB	120 km^2	6.4 km	5.0 km	6.2 km
	207 dB	240 km^2	9.2 km	5.0 km	8.6 km
	203 dB	550 km^2	15 km	5.0 km	13 km
	186 dB	8,000 km^2	67 km	5.0 km	50 km

4.1.2 SE location

Table 4-10 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (hard sediment) modelling at the SE location

Southall *et al*. (2019) Unweighted SPL_{peak}		**Monopile foundation, hard sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	720 m	710 m	710 m
	PCW (218 dB)	0.01 km^2	60 m	60 m	60 m
TTS	LF (213 dB)	0.05 km^2	130 m	120 m	130 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	9.9 km^2	1.8 km	1.8 km	1.8 km
	PCW (212 dB)	0.07 km^2	150 m	150 m	150 m

Table 4-11 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (soft sediment) modelling at the SE location

Southall *et al*. (2019) Unweighted SPL_{peak}		**Monopile foundation, soft sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	630 m	620 m	620 m
	PCW (218 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.04 km^2	110 m	110 m	110 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	7.6 km^2	1.6 km	1.5 km	1.6 km
	PCW (212 dB)	0.05 km^2	130 m	130 m	130 m

Table 4-12 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (hard sediment) modelling at the SE location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Monopile foundation, hard sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	2,700 km^2	47 km	20 km	29 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	620 km^2	17 km	11 km	14 km
	PCW (185 dB)	0.2 km^2	350 m	< 100 m	210 m
TTS	LF (168 dB)	11,000 km^2	112 km	26 km	56 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	5,900 km^2	72 km	24 km	42 km
	PCW (170 dB)	1,600 km^2	32 km	16 km	22 km

Table 4-13 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (soft sediment) modelling at the SE location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL$_{cum}$		**Monopile foundation, soft sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	2,300 km^2	42 km	19 km	27 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	450 km^2	14 km	9.0 km	12 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	10,000 km^2	104 km	25 km	53 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	5,100 km^2	66 km	24 km	39 km
	PCW (170 dB)	1,400 km^2	29 km	15 km	21 km

Table 4-14 Summary of the unweighted SPL$_{peak}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (hard sediment) modelling at the SE location

Popper *et al*. (2014) Unweighted SPL$_{peak}$	**Monopile foundation, hard sediment**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.05 km^2	130 m	120 m	130 m
207 dB	0.3 km^2	330 m	320 m	330 m

Table 4-15 Summary of the unweighted SPL$_{peak}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (soft sediment) modelling at the SE location

Popper *et al*. (2014) Unweighted SPL$_{peak}$	**Monopile foundation, soft sediment**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.04 km^2	110 m	110 m	110 m
207 dB	0.3 km^2	280 m	280 m	280 m

Table 4-16 Summary of the unweighted SEL$_{cum}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (hard sediment) modelling at the SE location assuming both a fleeing and stationary animal

Popper *et al*. (2014) Unweighted SEL$_{cum}$		**Monopile foundation, hard sediment**			
		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	180 m	< 100 m	< 100 m
	203 dB	32 km^2	3.9 km	2.1 km	3.2 km
	186 dB	3,600 km^2	55 km	22 km	33 km
Stationary (0 m/s)	219 dB	41 km^2	3.7 km	3.5 km	3.6 km
	216 dB	93 km^2	5.7 km	5.1 km	5.4 km
	210 dB	400 km^2	12 km	10 km	11 km
	207 dB	760 km^2	17 km	13 km	16 km
	203 dB	1,600 km^2	25 km	18 km	22 km
	186 dB	9,000 km^2	88 km	28 km	52 km

Table 4-17 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (soft sediment) modelling at the SE location assuming both a fleeing and stationary animal

Popper *et al*. (2014) Unweighted SEL_{cum}		**Monopile foundation, soft sediment**			
		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	11 km^2	2.4 km	1.0 km	1.8 km
	186 dB	3,000 km^2	49 km	21 km	31 km
Stationary (0 m/s)	219 dB	12 km^2	2.0 km	1.9 km	1.9 km
	216 dB	28 km^2	3.1 km	2.9 km	3.0 km
	210 dB	150 km^2	7.2 km	6.3 km	6.8 km
	207 dB	300 km^2	10 km	8.8 km	9.8 km
	203 dB	720 km^2	16 km	13 km	15 km
	186 dB	6,600 km^2	69 km	28 km	45 km

4.1.3 SW location

Table 4-18 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (hard sediment) modelling at the SW location

Southall *et al*. (2019) Unweighted SPL_{peak}		**Monopile foundation, hard sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	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)	1.5 km^2	700 m	700 m	700 m
	PCW (218 dB)	0.01 km^2	60 m	60 m	60 m
TTS	LF (213 dB)	0.05 km^2	120 m	120 m	120 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	9.3 km^2	1.7 km	1.7 km	1.7 km
	PCW (212 dB)	0.07 km^2	150 m	150 m	150 m

Table 4-19 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (soft sediment) modelling at the SW location

Southall *et al*. (2019) Unweighted SPL_{peak}		**Monopile foundation, soft sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	610 m	610 m	610 m
	PCW (218 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.04 km^2	110 m	110 m	110 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	7.2 km^2	1.5 km	1.5 km	1.5 km
	PCW (212 dB)	0.05 km^2	130 m	130 m	130 m

Table 4-20 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (hard sediment) modelling at the SW location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		Monopile foundation, hard sediment			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	2,100 km^2	34 km	16 km	26 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	490 km^2	14 km	10 km	13 km
	PCW (185 dB)	< 0.1 km^2	130 m	< 100 m	< 100 m
TTS	LF (168 dB)	12,000 km^2	103 km	21 km	57 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	5,400 km^2	57 km	19 km	40 km
	PCW (170 dB)	1,300 km^2	25 km	14 km	20 km

Table 4-21 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (soft sediment) modelling at the SW location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		Monopile foundation, soft sediment			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	1,800 km^2	30 km	15 km	24 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	360 km^2	12 km	9.1 km	11 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	10,000 km^2	88 km	20 km	53 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	4,500 km^2	50 km	19 km	37 km
	PCW (170 dB)	1,100 km^2	23 km	13 km	19 km

Table 4-22 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (hard sediment) modelling at the SW location

Popper *et al*. (2014) Unweighted SPL_{peak}	Monopile foundation, hard sediment			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.05 km^2	120 m	120 m	120 m
207 dB	0.3 km^2	320 m	320 m	320 m

Table 4-23 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (soft sediment) modelling at the SW location

Popper *et al*. (2014) Unweighted SPL_{peak}	Monopile foundation, soft sediment			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.04 km^2	110 m	110 m	110 m
207 dB	0.2 km^2	280 m	280 m	280 m

Table 4-24 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (hard sediment) modelling at the SW location assuming both a fleeing and stationary animal

Popper *et al*. (2014) Unweighted SEL_{cum}		**Monopile foundation, hard sediment**			
		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	20 km^2	2.9 km	2.0 km	2.5 km
	186 dB	3,000 km^2	41 km	17 km	30 km
Stationary (0 m/s)	219 dB	37 km^2	3.5 km	3.4 km	3.4 km
	216 dB	83 km^2	5.3 km	5.0 km	5.2 km
	210 dB	360 km^2	11 km	9.9 km	11 km
	207 dB	670 km^2	16 km	13 km	15 km
	203 dB	1,400 km^2	23 km	19 km	21 km
	186 dB	8,500 km^2	69 km	23 km	50 km

Table 4-25 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (soft sediment) modelling at the SW location assuming both a fleeing and stationary animal

Popper *et al*. (2014) Unweighted SEL_{cum}		**Monopile foundation, soft sediment**			
		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	5.7 km^2	1.6 km	950 m	1.3 km
	186 dB	2,500 km^2	35 km	17 km	28 km
Stationary (0 m/s)	219 dB	11 km^2	1.9 km	1.9 km	1.9 km
	216 dB	26 km^2	3.0 km	2.8 km	2.9 km
	210 dB	130 km^2	6.7 km	6.2 km	6.5 km
	207 dB	270 km^2	9.7 km	8.7 km	9.3 km
	203 dB	630 km^2	15 km	13 km	14 km
	186 dB	5,800 km^2	54 km	23 km	42 km

4.2 Jacket pile foundations

Table 4-26 to Table 4-43 present the modelling results for the jacket pile foundation modelling scenarios using the parameters presented in section 3.2, in terms of the Southall *et al*. (2019) marine mammal criteria (section 2.2.1) and the Popper *et al*. (2014) fish criteria (section 2.2.2).

The predicted ranges are smaller than those predicted for the monopile foundations, due to the smaller pile diameters and lower overall number of pile strikes.

For jacket piles, the largest marine mammal impact ranges are predicted at the SE modelling location when considering the soft sediment scenario, due to the additional pile strikes. Maximum PTS injury ranges are predicted for LF cetaceans using the SEL_{cum} criteria, with ranges of up to 40 km, for VHF cetaceans PTS ranges are predicted up to 14 km for the same scenario.

When considering the Popper *et al*. (2014) fish criteria, the largest recoverable injury ranges (203 dB SEL_{cum} threshold) for jacket piles are predicted to be 20 km assuming a stationary receptor; if a fleeing animal is assumed, these ranges are predicted up to 1.8 km.

Larger impact ranges are seen for the soft sediment scenarios due to four piles being installed in 24 hours as opposed to two, however these are only apparent for the stationary animal results and the largest of the fleeing ranges.

4.2.1 NW location

Table 4-26 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the jacket pile foundation modelling at the NW location

Southall *et al*. (2019) Unweighted SPL_{peak}		**Jacket pile foundation**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	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)	1.0 km^2	580 m	580 m	580 m
	PCW (218 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	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)	6.4 km^2	1.4 km	1.4 km	1.4 km
	PCW (212 dB)	0.04 km^2	120 m	120 m	120 m

Table 4-27 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the jacket pile foundation (hard sediment, 2 piles installed per 24 hours) modelling at the NW location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Jacket pile foundation, hard sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	2,200 km^2	38 km	2.6 km	26 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	320 km^2	13 km	1.9 km	10 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	14,000 km^2	99 km	3.7 km	64 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	6,200 km^2	61 km	3.9 km	43 km
	PCW (170 dB)	1,200 km^2	27 km	2.6 km	19 km

Table 4-28 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the jacket pile foundation (soft sediment, 4 piles installed per 24 hours) modelling at the NW location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Jacket pile foundation, soft sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	2,200 km^2	38 km	2.6 km	26 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	330 km^2	13 km	1.9 km	10 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	15,000 km^2	121 km	3.7 km	66 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	6,400 km^2	63 km	3.9 km	44 km
	PCW (170 dB)	1,200 km^2	27 km	2.6 km	20 km

Table 4-29 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the jacket pile foundation modelling at the NW location

Popper *et al*. (2014) Unweighted SPL_{peak}	**Jacket pile foundation**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.03 km²	100 m	100 m	100 m
207 dB	0.2 km²	260 m	260 m	260 m

Table 4-30 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the jacket pile foundation (hard sediment, 2 piles installed per 24 hours) modelling at the NW location assuming both a fleeing and stationary animal

Popper *et al*. (2014) Unweighted SEL_{cum}		**Jacket pile foundation, hard sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 m/s)	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	1.4 km²	930 m	< 100 m	640 m
	186 dB	2,900 km²	43 km	3.2 km	30 km
Stationary (0 m/s)	219 dB	8.2 km²	1.7 km	1.6 km	1.6 km
	216 dB	20 km²	2.5 km	2.5 km	2.5 km
	210 dB	95 km²	5.7 km	5.0 km	5.5 km
	207 dB	190 km²	8.2 km	5.0 km	7.8 km
	203 dB	450 km²	13 km	5.0 km	12 km
	186 dB	7,100 km²	64 km	5.0 km	47 km

Table 4-31 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the jacket pile foundation (soft sediment, 4 piles installed per 24 hours) modelling at the NW location assuming both a fleeing and stationary animal

Popper *et al*. (2014) Unweighted SEL_{cum}		**Jacket pile foundation, soft sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 m/s)	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	1.5 km²	1.0 km	< 100 m	660 m
	186 dB	3,000 km²	44 km	3.2 km	30 km
Stationary (0 m/s)	219 dB	20 km²	2.5 km	2.5 km	2.5 km
	216 dB	45 km²	3.8 km	3.7 km	3.8 km
	210 dB	190 km²	8.2 km	5.0 km	7.8 km
	207 dB	370 km²	12 km	5.0 km	11 km
	203 dB	830 km²	18 km	5.0 km	16 km
	186 dB	9,900 km²	74 km	5.0 km	55 km

4.2.2 SE location

Table 4-32 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the jacket pile foundation modelling at the SE location

Southall *et al*. (2019) Unweighted SPL_{peak}		**Jacket pile foundation**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	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)	1.1 km^2	600 m	590 m	590 m
	PCW (218 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	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)	7.0 km^2	1.5 km	1.5 km	1.5 km
	PCW (212 dB)	0.05 km^2	120 m	120 m	120 m

Table 4-33 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the jacket pile foundation (hard sediment, 2 piles installed per 24 hours) modelling at the SE location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Jacket pile foundation, hard sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	2,200 km^2	40 km	18 km	26 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	430 km^2	13 km^2	8.9 km	12 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	9,700 km^2	101 km	25 km	52 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	5,000 km^2	65 km	24 km	39 km
	PCW (170 dB)	1,300 km^2	28 km	15 km	21 km

Table 4-34 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the jacket pile foundation (soft sediment, 4 piles installed per 24 hours) modelling at the SE location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Jacket pile foundation, soft sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	2,200 km^2	40 km	18 km	26 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	440 km^2	14 km	8.9 km	12 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	9,900 km^2	103 km	25 km	53 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	5,100 km^2	66 km	24 km	39 km
	PCW (170 dB)	1,400 km^2	29 km	15 km	21 km

Table 4-35 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the jacket pile foundation modelling at the SE location

Popper *et al*. (2014) Unweighted SPL_{peak}	**Jacket pile foundation**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.03 km^2	100 m	100 m	100 m
207 dB	0.2 km^2	270 m	270 m	270 m

Table 4-36 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the jacket pile foundation (hard sediment, 2 piles installed per 24 hours) modelling at the SE location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Jacket pile foundation, hard sediment**			
		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	5.8 km^2	1.8 km	650 m	1.3 km
	186 dB	2,800 km^2	45 km	21 km	29 km
Stationary (0 m/s)	219 dB	9.0 km^2	1.7 km	1.7 km	1.7 km
	216 dB	22 km^2	2.7 km	2.6 km	2.6 km
	210 dB	120 km^2	6.4 km	5.6 km	6.1 km
	207 dB	240 km^2	9.4 km	8.0 km	8.8 km
	203 dB	600 km^2	15 km	12 km	14 km
	186 dB	6,100 km^2	65 km	28 km	44 km

Table 4-37 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the jacket pile foundation (soft sediment, 4 piles installed per 24 hours) modelling at the SE location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Jacket pile foundation, soft sediment**			
		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	5.9 km^2	1.8 km	680 m	1.3 km
	186 dB	2,800 km^2	47 km	21 km	30 km
Stationary (0 m/s)	219 dB	22 km^2	2.7 km	2.6 km	2.6 km
	216 dB	52 km^2	4.2 km	3.9 km	4.1 km
	210 dB	250 km^2	9.4 km	8.0 km	8.8 km
	207 dB	480 km^2	13 km	11 km	12 km
	203 dB	1,100 km^2	20 km	15 km	19 km
	186 dB	7,700 km^2	78 km	28 km	48 km

4.2.3 SW location

Table 4-38 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the jacket pile foundation modelling at the SW location

Southall *et al.* (2019) Unweighted SPL_{peak}		**Jacket pile foundation**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	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)	1.0 km^2	580 m	580 m	580 m
	PCW (218 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	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)	6.5 km^2	1.5 km	1.4 km	1.4 km
	PCW (212 dB)	0.04 km^2	120 m	120 m	120 m

Table 4-39 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the jacket pile foundation (hard sediment, 2 piles installed per 24 hours) modelling at the SW location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Jacket pile foundation, hard sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	1,700 km^2	30 km	15 km	23 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	340 km^2	12 km	9.1 km	10 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	9,800 km^2	85 km	20 km	52 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	4,400 km^2	49 km	19 km	36 km
	PCW (170 dB)	1,100 km^2	22 km	13 km	18 km

Table 4-40 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the jacket pile foundation (soft sediment, 4 piles installed per 24 hours) modelling at the SW location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Jacket pile foundation, soft sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	1,700 km^2	30 km	15 km	23 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	350 km^2	12 km	9.1 km	11 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	10,000 km^2	90 km	20 km	53 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	4,500 km^2	51 km	19 km	37 km
	PCW (170 dB)	1,100 km^2	22 km	13 km	18 km

Table 4-41 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the jacket pile foundation modelling at the SW location

Popper *et al*. (2014) Unweighted SPL_{peak}	**Jacket pile foundation**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.03 km^2	100 m	100 m	100 m
207 dB	0.2 km^2	260 m	260 m	260 m

Table 4-42 Summary of the unweighted SEL$_{cum}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the jacket pile foundation (hard sediment, 2 piles installed per 24 hours) modelling at the SW location assuming both a fleeing and stationary animal

Popper *et al*. (2014) Unweighted SEL$_{cum}$		**Jacket pile foundation, hard sediment**			
		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	2.2 km^2	1.1 km	530 m	840 m
	186 dB	2,200 km^2	33 km	16 km	26 km
Stationary (0 m/s)	219 dB	8.2 km^2	1.7 km	1.6 km	1.6 km
	216 dB	20 km^2	2.6 km	2.5 km	2.5 km
	210 dB	100 km^2	5.9 km	5.5 km	5.7 km
	207 dB	210 km^2	8.6 km	7.8 km	8.3 km
	203 dB	520 km^2	14 km	12 km	13 km
	186 dB	5,300 km^2	51 km	23 km	40 km

Table 4-43 Summary of the unweighted SEL$_{cum}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the jacket pile foundation (soft sediment, 4 piles installed per 24 hours) modelling at the SW location assuming both a fleeing and stationary animal

Popper *et al*. (2014) Unweighted SEL$_{cum}$		**Jacket pile foundation, soft sediment**			
		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	1.1 km	550 m	850 m
	186 dB	2,300 km^2	34 km	16 km	26 km
Stationary (0 m/s)	219 dB	20 km^2	2.6 km	2.5 km	2.5 km
	216 dB	46 km^2	3.9 km	3.7 km	3.8 km
	210 dB	210 km^2	8.6 km	7.8 km	8.3 km
	207 dB	420 km^2	12 km	11 km	12 km
	203 dB	930 km^2	19 km	16 km	17 km
	186 dB	7,000 km^2	60 km	23 km	46 km

4.3 Concurrent location piling

Additional modelling has been carried out to investigate the potential impacts of two piling installations occurring simultaneously at separated foundation locations across the OAA. Only the jacket pile foundation scenarios from the previous section have been considered, with concurrent piling operations occurring at the SE and SW locations, giving a worst case spread of locations and covering the area where an offshore platform may be installed by the cable corridor. All modelling in this section assumes that the two piling operations start at the same time.

When considering SEL$_{cum}$ modelling, piling from multiple sources has the ability to increase impact ranges significantly as, in this case, it introduces double the number of pile strikes to the water. Figure 4-1 shows the TTS contours for fish from Popper *et al*. (2014) (186 dB SEL$_{cum}$) for a fleeing receptor as an example. The blue contours show the impact from each modelling location individually, and the red contour shows the increase in impact when all three sources occur simultaneously, resulting in a contour encircling them all. The total cumulative area may not necessarily be greater than the two individual areas independently as there can be some overlap between them.

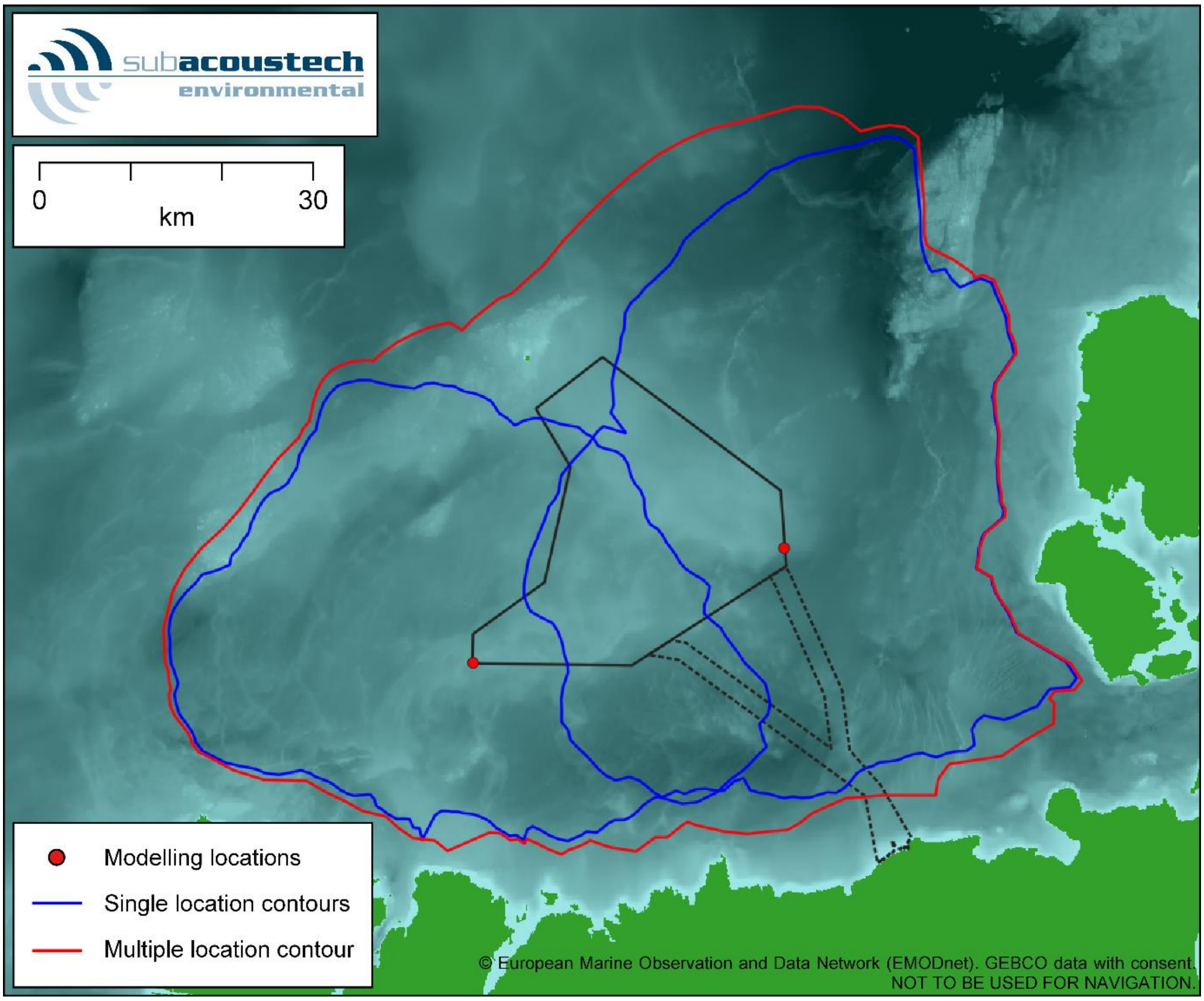


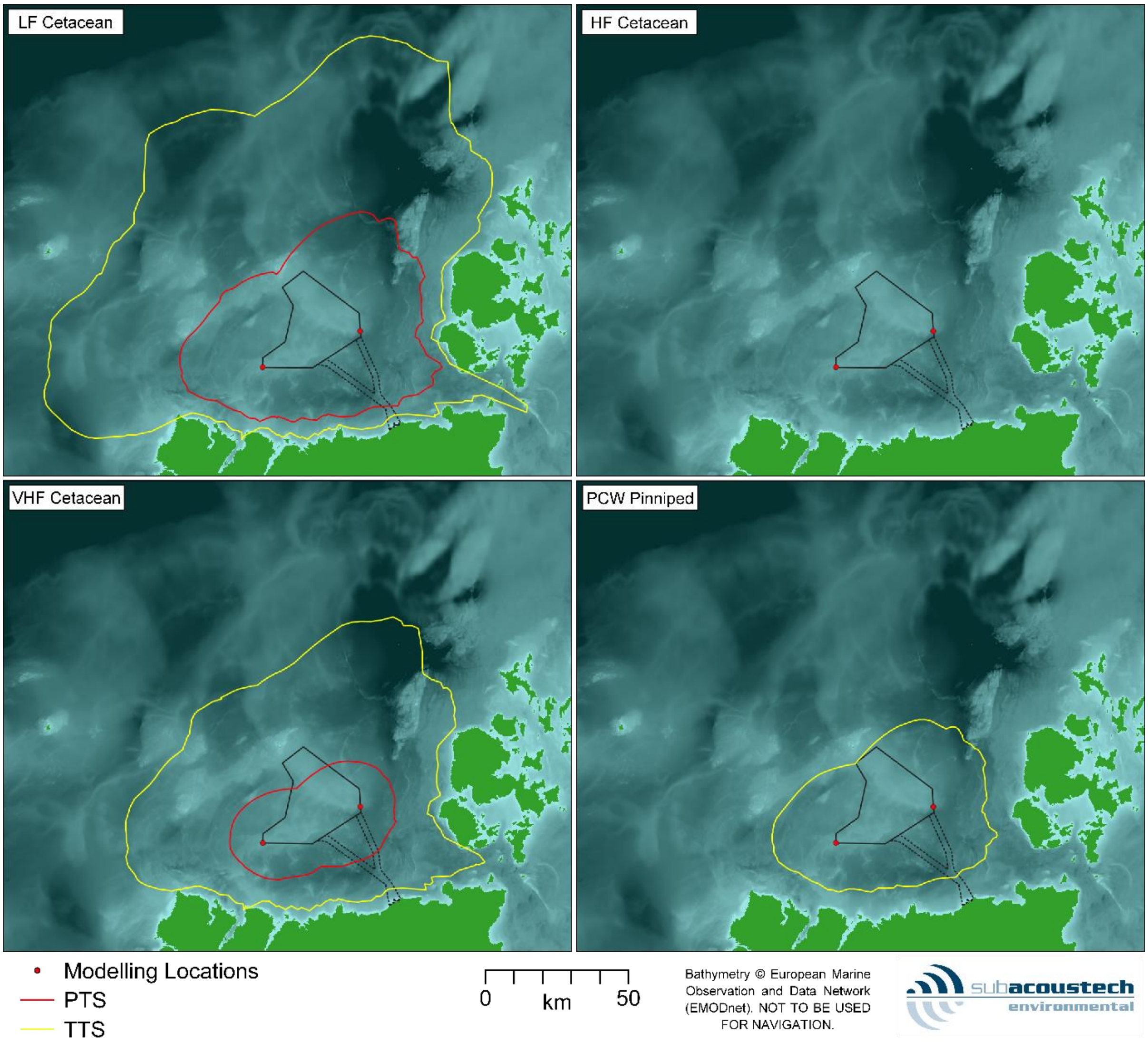
Figure 4-1 Contour plot showing the interaction between two noise sources when occurring simultaneously at the SE and SW locations (TTS in fish, 186 dB SEL$_{cum}$, fleeing animal)

The scenarios modelled were chosen to provide the greatest geographical spread of impact range contours across the OAA. In a modelling scenario where piles are installed immediately adjacent to each other, there would be an expansion of the single location contour in all directions, but less than the East-West spread seen in Figure 4-1. It is understood that for operational and safety reasons, the course or route of piling rigs would be designed to ensure that they would not be positioned near to each other at any time during piling, so immediately adjacent scenarios should not occur. Thus, the ‘separated’ scenario here represents a worst case.

Sections 4.3.1 and 4.3.2 present contour plots for the multiple location piling scenarios alongside tables showing the increases in overall area. For fleeing animals, the differences between the hard sediment and soft sediment scenarios are minimal. Fields with a dash “-” show where there is no in-combination effect when piling occurs at the three locations simultaneously, generally where the individual ranges are small enough that the distant site does not produce an influencing additional exposure. Contours that are too small to be seen clearly at the scale of the figures have not been included. Impact ranges have not been presented in this section as there are multiple starting points for receptors. Only areas are provided as results, as there is no individual single ‘impact range’ from multiple locations.

As with the previous section, the non-impulsive criteria from Southall *et al*. (2019) have also been modelled and are presented in Appendix A.

4.3.1 Jacket pile foundation (hard sediment) scenario

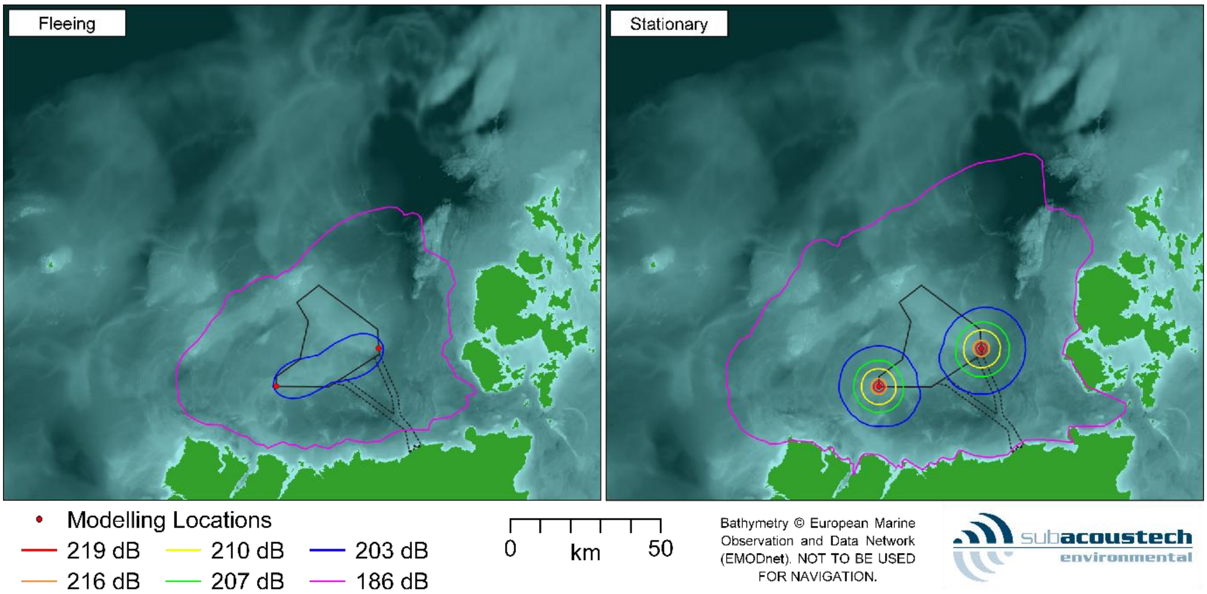


Bathymetry © European Marine Observation and Data Network (EMODnet). NOT TO BE USED FOR NAVIGATION.

Figure 4-2 Contour plots showing the in-combination impacts of concurrent installation of jacket pile foundations (hard sediment, 2 piles installed at each location per 24 hours) at two locations across the OAA for marine mammals using the impulsive Southall et al. (2019) criteria assuming a fleeing animal

Table 4-44 Summary of the impact areas for the installation of jacket pile foundations (hard sediment, 2 piles installed at each location per 24 hours) at two locations across the OAA for marine mammals using the impulsive Southall et al. (2019) criteria assuming a fleeing animal

Jacket pile foundation Southall *et al*. (2019) Weighted SEL$_{cum}$		**SE location**	**SW location**	**In-combination area**
PTS (Impulsive)	LF (183 dB)	2,200 km^2	1,700 km^2	4,500 km^2
	HF (185 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (155 dB)	430 km^2	340 km^2	1,700 km^2
	PCW (185 dB)	< 0.1 km^2	< 0.1 km^2	-
TTS (Impulsive)	LF (168 dB)	9,700 km^2	9,800 km^2	15,000 km^2
	HF (170 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (140 dB)	5,000 km^2	4,400 km^2	8,300 km^2
	PCW (170 dB)	1,300 km^2	1,100 km^2	3,300 km^2



Bathymetry © European Marine Observation and Data Network (EMODnet). NOT TO BE USED FOR NAVIGATION.

Figure 4-3 Contour plots showing the in-combination impacts of concurrent installation of jacket foundations (hard sediment, 2 piles installed at each location per 24 hours) at two locations across the OAA for fish using the pile driving Popper et al. (2014) criteria assuming both fleeing and stationary animals

Table 4-45 Summary of the impact areas for the installation of jacket pile foundations (hard sediment, 2 piles installed at each location per 24 hours) at two locations across the OAA for fish using the pile driving Popper et al. (2014) criteria assuming both fleeing and stationary animals

Jacket pile foundation Popper *et al*. (2014) Unweighted SEL_{cum}		**SE location**	**SW location**	**In-combination area**
Fleeing (1.5 ms^{-1})	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	5.8 km^2	2.2 km^2	430 km^2
	186 dB	2,800 km^2	2,200 km^2	5,300 km^2
Stationary	219 dB	9.0 km^2	8.2 km^2	18 km^2
	216 dB	22 km^2	20 km^2	44 km^2
	210 dB	120 km^2	100 km^2	230 km^2
	207 dB	240 km^2	210 km^2	480 km^2
	203 dB	600 km^2	520 km^2	1,200 km^2
	186 dB	6,100 km^2	5,300 km^2	8,900 km^2

4.3.2 *Jacket pile foundation (soft sediment) scenario*

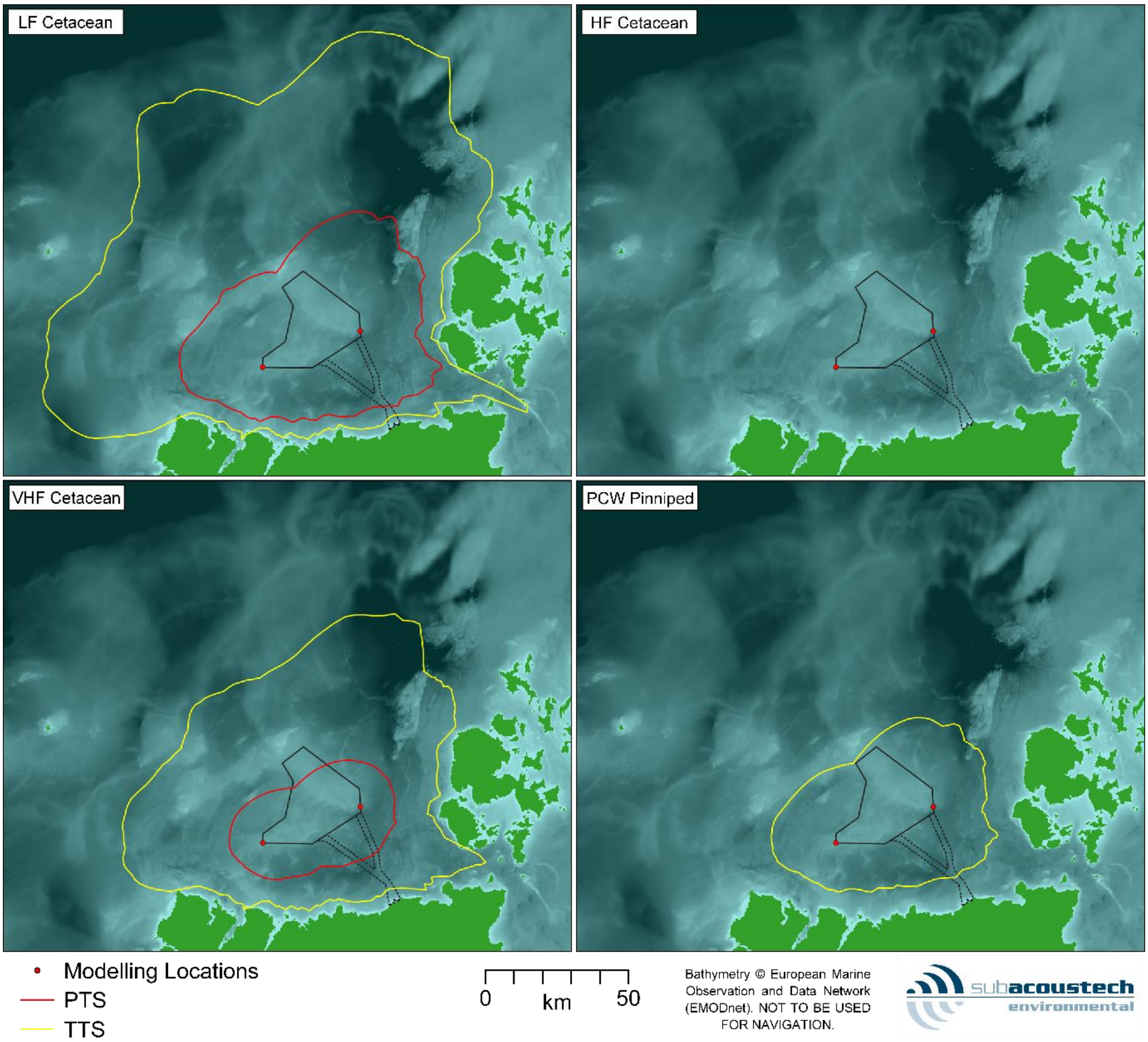


Figure 4-4 Contour plots showing the in-combination impacts of concurrent installation of jacket pile foundations (soft sediment, 4 piles installed at each location per 24 hours) at two locations across the OAA for marine mammals using the impulsive Southall et al. (2019) criteria assuming a fleeing animal

Table 4-46 Summary of the impact areas for the installation of jacket pile foundations (soft sediment, 4 piles installed at each location per 24 hours) at two locations across the OAA for marine mammals using the impulsive Southall et al. (2019) criteria assuming a fleeing animal

Jacket pile foundation Southall *et al*. (2019) Weighted SEL$_{cum}$		**SE location**	**SW location**	**In-combination area**
PTS (Impulsive)	LF (183 dB)	2,200 km^2	1,700 km^2	4,500 km^2
	HF (185 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (155 dB)	440 km^2	350 km^2	1,700 km^2
	PCW (185 dB)	< 0.1 km^2	< 0.1 km^2	-
TTS (Impulsive)	LF (168 dB)	9,900 km^2	10,000 km^2	16,000 km^2
	HF (170 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (140 dB)	5,100 km^2	4,500 km^2	8,600 km^2
	PCW (170 dB)	1,400 km^2	1,100 km^2	3,400 km^2

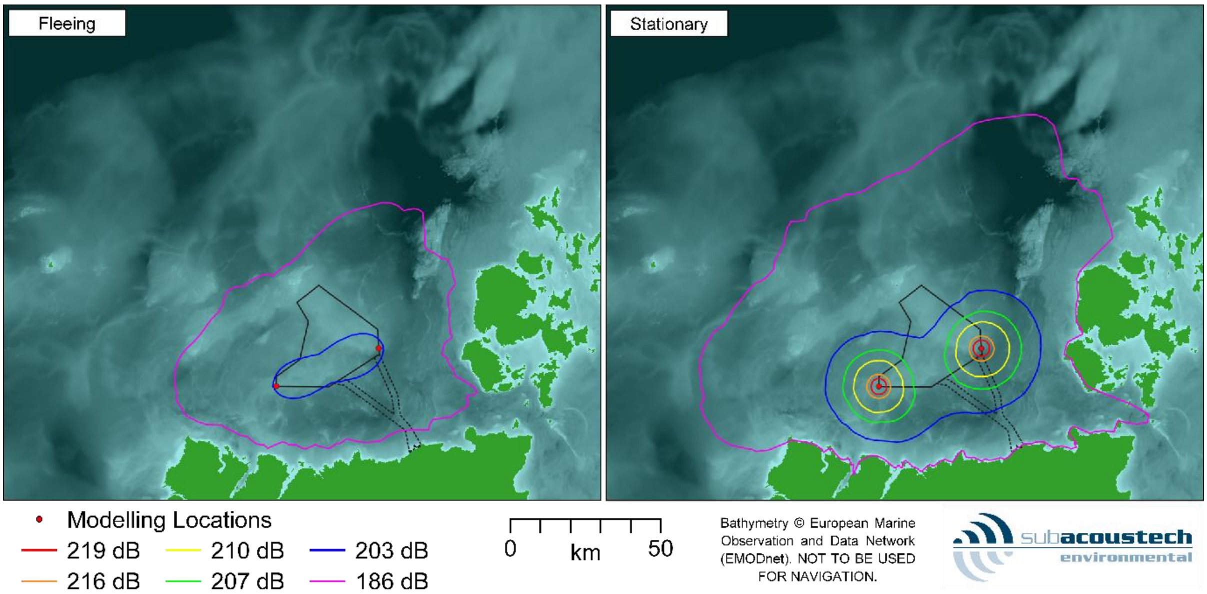


Figure 4-5 Contour plots showing the in-combination impacts of concurrent installation of jacket foundations (soft sediment, 4 piles installed at each location per 24 hours) at two locations across the OAA for fish using the pile driving Popper et al. (2014) criteria assuming both fleeing and stationary animals

Table 4-47 Summary of the impact areas for the installation of jacket pile foundations (soft sediment, 4 piles installed at each location per 24 hours) at two locations across the OAA for fish using the pile driving Popper et al. (2014) criteria assuming both fleeing and stationary animals

Jacket pile foundation Popper *et al*. (2014) Unweighted SEL$_{cum}$		**SE location**	**SW location**	**In-combination area**
Fleeing (1.5 ms^{-1})	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	5.9 km^2	2.3 km^2	430 km^2
	186 dB	2,800 km^2	2,300 km^2	5,400 km^2
Stationary	219 dB	22 km^2	20 km^2	44 km^2
	216 dB	52 km^2	46 km^2	100 km^2
	210 dB	250 km^2	210 km^2	480 km^2
	207 dB	480 km^2	420 km^2	970 km^2
	203 dB	1,100 km^2	930 km^2	2,300 km^2
	186 dB	7,700 km^2	7,000 km^2	11,000 km^2

5 Other noise sources

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

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

Table 5-1 Summary of the possible noise making activities at the offshore Project other than impact piling

Activity	Description
Cable laying	Noise from the cable laying vessel and any other associated noise during the offshore cable installation.
Dredging	Dredging may be required on site for seabed preparation work for certain foundation options, as well as for the export cable, inter-array cables and interconnector cable installation. Suction dredging has been assumed as a worst-case.
Drilling	There is the potential for WTG foundations to be installed using drilling depending on seabed type or if a pile refuses during impact piling operations.
Rock placement	Potentially 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 offshore cable installation.
Suction bucket installation	An alternative method for fixing the WTG foundations to the seabed. Underwater suction pumps are the primary source of noise.
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 WTG	Noise transmitted through the water from operational WTG. The Project Design Envelope gives WTGs with power outputs of between 18 and 30 MW.
UXO clearance	There is a possibility that Unexploded Ordnance (UXO) may exist within the offshore Project area, which would need to be cleared before construction can begin.

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 acceptable. 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 large operation WTG noise or UXO detonation). 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 model at this stage. The limitations of this approach are noted, including the lack of frequency or bathymetric dependence.

Most of these activities are considered in section 5.1 with operational WTG noise and UXO clearance assessed in sections 5.2 and 5.3 respectively.

5.1 Noise making activities

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

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

Predicted source levels and propagation calculations for the construction activities are presented in Table 5-2 along with a summary of the number of datasets used in each case. As previously, all $\mathrm{SEL_{cum}}$ criteria use the same assumptions as presented in section 2.2, and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. It should be noted 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 offshore Project.

Table 5-2 Summary of the estimated unweighted source levels and transmission losses for the different considered noise sources related to construction

Source	Estimated unweighted source level	Transmission loss parameters	Comments
Cable laying	171 dB re 1 µPa @ 1 m (RMS)	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 (RMS)	N: 19, α: 0.0009	Based on three datasets from backhoe dredgers.
Dredging (Suction)	186 dB re 1 µPa @ 1 m (RMS)	N: 19, α: 0.0009	Based on five datasets from suction and cutter suction dredgers.
Drilling	169 dB re 1 µPa @ 1 m (RMS)	N: 16, α: 0.0006	Based on six datasets from various drilling operations covering ground investigations and pile installation. A 200kW drill has been assumed for modelling.
Rock placement	172 dB re 1 µPa @ 1 m (RMS)	N: 12, α: 0.0005	Based on four datasets from rock placement vessel '*Rollingstone*.'
Trenching	172 dB re 1 µPa @ 1 m (RMS)	N: 13, α: 0.0004	Based on three datasets of measurements from trenching vessels more than 100 m in length.
Suction bucket installation	192 dB re 1 µPa @ 1 m (RMS)	N: 19, α: 0.0009	Based on a review by Koschinski and Lüdemann (2019).
Vessel noise (large)	168 dB re 1 µPa @ 1 m (RMS)	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 (RMS)	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.

The estimations used for suction bucket installation are based on a review by Koschinski and Lüdemann (2019), which states that the noise of suction pumps used at the Borkum Riffgrund 2 offshore wind farm could not be measured above background levels (137 dB) at a range of 750 m. Therefore, the estimated source level given in Table 5-2 is highly precautionary.

For $\mathrm{SEL_{cum}}$ 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 considered both fleeing and stationary animals have been included for all SEL_{cum} criteria.

To account for the weightings required for modelling using the Southall *et al*. (2019) criteria (see section 2.2.1), reductions in source level have been applied to the various noise sources; Figure 5-1 shows the representative noise measurements used for this, which have been adjusted for the source levels given in Table 5-2. Details of the reductions in sources levels for each of the weightings used for modelling are given in Table 5-3.

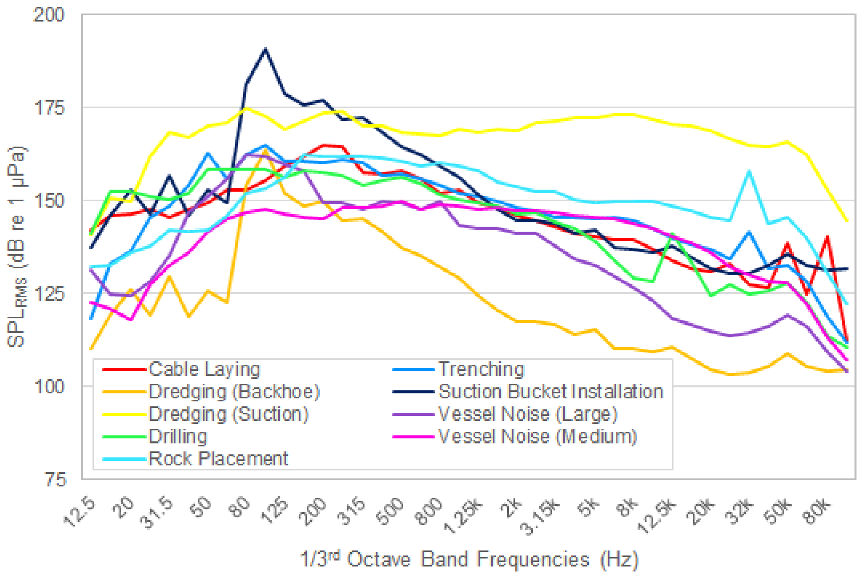


Figure 5-1 Summary of the 1/3rd octave frequency bands to which the Southall et al. (2019) weightings were applied in the simple modelling

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 source level from the unweighted level (Southall *et al*., 2019)**			
	LF	**HF**	**VHF**	**PCW**
Cable laying	3.6 dB	22.9 dB	23.9 dB	13.2 dB
Dredging	2.5 dB	7.9 dB	9.6 dB	4.2 dB
Drilling	4.0 dB	25.8 dB	48.7 dB	13.2 dB
Rock placement	1.6 dB	11.9 dB	12.5 dB	8.2 dB
Trenching	4.1 dB	23.0 dB	25.0 dB	13.7 dB
Suction bucket installation	2.5 dB	7.9 dB	9.6 dB	4.2 dB
Vessel noise	5.5 dB	34.4 dB	38.6 dB	17.4 dB

Table 5-4 to Table 5-6 summarise the predicted impact range 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 strike) 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 noise source at the start of the activity to acquire the necessary exposure to induce PTS as per Southall *et al*. (2019). 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 a minimal risk.

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

All sources presented here result in much lower levels than 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, fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}	**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	110 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	230 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	990 m	< 100 m
Trenching	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Suction bucket installation	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	740 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, stationary animal

Southall *et al.* (2019) Weighted SEL$_{cum}$	**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
Suction bucket installation	130 m	< 100 m	1.1 km	< 100 m	1.3 km	770 m	6.8 km	830 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 the source itself is moving in most cases.

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) Unweighted SPL$_{RMS}$	**Recoverable injury** 170 dB (48 hours)	**TTS** 158 dB (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
Suction bucket installation	< 50 m	60 m
Vessel noise (large)	< 50 m	< 50 m
Vessel noise (medium)	< 50 m	< 50 m

5.2 Operational WTG noise

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

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

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

where C is a fixed constant and the coefficients α, β, and γ are derived from the empirical data for the 17 datasets. Tougaard *et al.* (2020) presents the turbine size as a power output in MW, but as this has not been finalised, an equivalent figure in terms of rotor diameter has been used instead.

WTGs with rotor diameters measuring 250, 265, 300, and 330 m have been proposed and have been modelled for this study. The maximum turbine sizes considered within the offshore Project design are much larger than those used for the estimation above, so caution must be used when considering the results presented in this section; no empirical data is available for large wind turbine generators (WTGs) close to the specifications proposed here. Figure 5-2 presents a level against range plot for the four turbine sizes using the Tougaard *et al*. (2020) calculation, assuming an average 6 m/s wind speed. Although wind speeds (and thus operational noise levels) may be greater than this, this will not represent the typical condition. It is also worth noting that the background noise level will also naturally increase, somewhat offsetting any additional impact this may have.

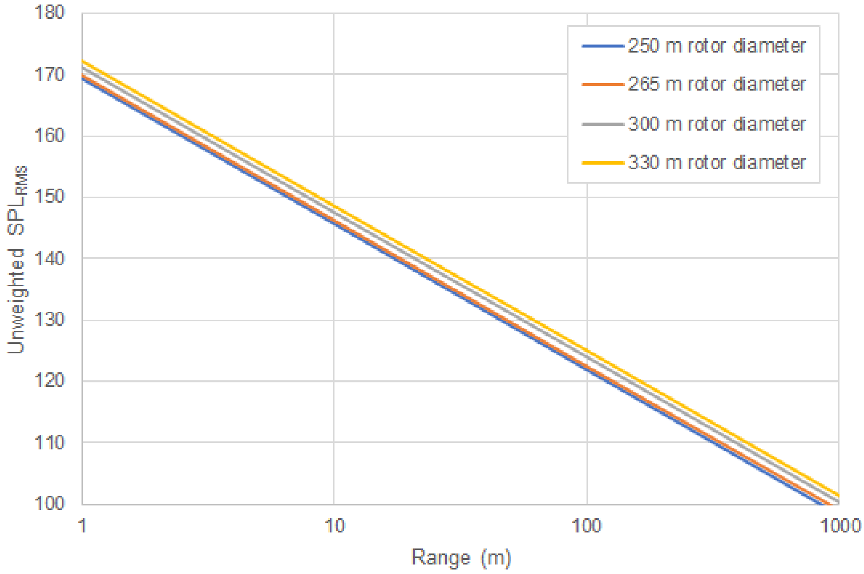


Figure 5-2 Predicted unweighted SPL$_{RMS}$ from operational WTGs with rotor diameters of between 250 m and 330 m using the calculation from Tougaard et al. (2020)

Using these data, a summary of the predicted impact ranges has been produced, shown in Table 5-7 to Table 5-9. All SEL$_{cum}$ criteria use the same assumptions as presented in section 2.2, and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. Operational WTG noise is considered a non-impulsive, or continuous, source.

For SEL$_{cum}$ calculations, it has been assumed that the operational WTG noise is present 24 hours a day, and similarly to the noise sources in section 5.1, both fleeing and stationary animals have been included for all SEL$_{cum}$ criteria due to the low noise levels considered.

Table 5-7 Summary of the operational WTG noise impact ranges using the non-impulsive noise criteria from Southall et al. (2019) for marine mammals assuming a fleeing receptor

Southall *et al.* (2019) Weighted SEL_{cum}	**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
250 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
265 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
300 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
330 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-8 Summary of the operational WTG noise impact ranges using the non-impulsive noise criteria from Southall et al. (2019) for marine mammals assuming a stationary receptor

Southall *et al.* (2019) Weighted SEL_{cum}	**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
250 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
265 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
300 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
330 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-9 Summary of the operational WTG noise impact ranges using the continuous noise criteria from Popper et al. (2014) for fish (swim bladder involved in hearing)

Popper *et al*. (2014) Unweighted SPL_{RMS}	**Recoverable injury** 170 dB (48 hours)	**TTS** 158 dB (12 hours)
250 m	< 50 m	< 50 m
265 m	< 50 m	< 50 m
300 m	< 50 m	< 50 m
330 m	< 50 m	< 50 m

The results show that, for operational WTGs, injury risk is minimal. Also, the Tougaard *et al* (2020) equation shows that, although increasing the wind speed increases the noise output, the absolute noise levels do not lead to significant increases in the impact ranges, as can be seen from the consistency of the results. Taking the results from this and the previous section (5.1) and comparing them to the impact piling results in section 4, it is clear that noise from impact piling results in much greater noise levels and impact ranges, and hence should be considered the activity which has the potential to have the greatest effect during the construction and lifecycle of the offshore Project.

Stöber & Thomsen (2021) produced a similar study of an operational wind turbine dataset to Tougaard et al. (2020) and raises the potential for behavioural disturbance caused by larger WTGs. While prospective turbine sizes are increasing, Stöber & Thomsen conclude that these might only have limited impacts related to behavioural response on marine mammals and fish, although there is considerable uncertainty in criteria available to assess these. However, based on the highly precautionary NOAA Level B behavioural threshold (120 dB SPL_{RMS}, see NOAA, 2005) that the study utilises, it is estimated that the WTGs may only reach that threshold at around 200 m away. As the distance between WTGs is considerably greater than 400 m, twice this distance, this would indicate that any array effect from the WTGs is not expected.

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 offshore Project area. These would need to be cleared before any construction can begin. When modelling potential noise from UXO clearance, a variety of explosive types need to be considered, with the potential that many have been subject to degradation and burying over time. Two otherwise identical explosive devices are likely to produce different blasts in the case where one has spent an extended period on the seabed. 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 offshore Project area has been estimated as 247 kg, this has been modelled alongside smaller 25 and 130 kg devices. In each case, an additional donor weight of 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 impact of noise impacts from high order UXO clearance, caused by detonation of the main charge of the UXO. Deflagration is such an alternative technique, intended to result in a 'low order' burn of the explosive material in a UXO, which destroys, but does not detonate, the internal explosive.

Deflagration is a safer technique for UXO disposal as it is intended to avoid the high pressures associated with an explosion, which would lead to an increased risk of adverse effects to marine life. Where the UXO device cannot be moved, deflagration represents a significant improvement over high-order clearance in respect to environmental effects.

Where the technique proceeds as intended, it is still not without noise impact. The process requires an initial shaped explosive donor charge, typically of the order of 50 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 determined according to the size of UXO on which it is placed. A prediction of this impact is based on a charge weight of 0.05 kg, which would reasonably be expected for deflagration or similar techniques. The worst-case scenario would of course be a high order detonation with maximum pressures from complete detonation of the UXO, and this has also been used in the calculation of impact 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 SPL_{peak}:

$$SPL_{peak} = 52.4 \times 10^{6} \left(\frac{R}{W^{1/3}}\right)^{-1.13}$$

and for SEL_{ss}

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

where W is the equivalent charge weight for TNT in kilograms 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, SPL_{peak} 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 SEL calculations.

A further limitation in the Soloway and Dahl (2014) equations that must be considered 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 with 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 5-10.

Table 5-10 Summary of the unweighted SPL_{peak} and SEL_{ss} source levels used for UXO clearance modelling

Charge weight	**SPL_{peak} source level**	**SEL_{ss} source level**
Low order (0.05 kg)	264.5 dB re 1 µPa @ 1 m	210.7 dB re 1 µPa^{2}s @ 1 m
3.1 kg + donor	278.9 dB re 1 µPa @ 1 m	222.9 dB re 1 µPa^{2}s @ 1 m
25 kg + donor	285.4 dB re 1 µPa @ 1 m	228.4 dB re 1 µPa^{2}s @ 1 m
130 kg + donor	290.4 dB re 1 µPa @ 1 m	232.6 dB re 1 µPa^{2}s @ 1 m
247 kg + donor	292.4 dB re 1 µPa @ 1 m	234.3 dB re 1 µPa^{2}s @ 1 m

5.3.3 Impact ranges

Table 5-11 to Table 5-14 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 2-6). A UXO detonation source is defined as a single pulse, and as such the SEL_{cum} criteria from Southall *et al*. (2019) have been given as SEL_{ss} in the tables below. Thus, 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 5-11 to Table 5-14 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 5-11 Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, unweighted SPL_{peak} noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al.* (2019) Unweighted SPL_{peak}	**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 (0.05 kg)	100 m	30 m	580 m	110 m	190 m	60 m	1.0 km	210 m
3.1 kg + donor	440 m	140 m	2.5 km	490 m	820 m	260 m	4.6 km	910 m
25 kg + donor	870 m	280 m	4.9 km	960 m	1.6 km	520 m	9.0 km	1.7 km
130 kg + donor	1.4 km	460 m	8.1 km	1.5 km	2.6 km	860 m	14 km	2.9 km
247 kg + donor	1.7 km	570 m	9.9 km	1.9 km	3.2 km	1.0 km	18 km	3.6 km

Table 5-12 Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, weighted SEL_{ss} noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al.* (2019) Weighted SEL_{ss}	**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 (0.05 kg)	100 m	< 50 m	< 50 m	< 50 m	1.4 km	< 50 m	420 m	260 m
3.1 kg + donor	900 m	< 50 m	280 m	160 m	12 km	70 m	1.6 km	2.2 km
25 kg + donor	2.3 km	< 50 m	600 m	420 m	31 km	160 m	2.5 km	5.6 km
130 kg + donor	4.9 km	< 50 m	990 m	880 m	60 km	310 m	3.2 km	11 km
247 kg + donor	6.7 km	< 50 m	1.1 km	1.1 km	77 km	400 m	3.6 km	14 km

Table 5-13 Summary of the PTS and TTS impact ranges for UXO detonation using the non-impulsive, weighted SEL_{ss} noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al*. (2019) Weighted SEL_{ss}	**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 (0.05 kg)	< 50 m	< 50 m	< 50 m	< 50 m	210 m	< 50 m	60 m	< 50 m
3.1 kg + donor	60 m	< 50 m	< 50 m	< 50 m	1.8 km	< 50 m	370 m	320 m
25 kg + donor	140 m	< 50 m	< 50 m	< 50 m	4.8 km	< 50 m	770 m	850 m
130 kg + donor	290 m	< 50 m	70 m	50 m	9.9 km	90 m	1.2 km	1.7 km
247 kg + donor	400 m	< 50 m	100 m	70 m	13 km	110 m	1.4 km	2.3 km

Table 5-14 Summary of the impact ranges for UXO detonation using the unweighted SPL_{peak} explosion noise criteria from Popper et al. (2014) for species of fish

Popper *et al*. (2014) Unweighted SPL_{RMS}	**Mortality and potential mortal injury**	
	234 dB	229 dB
Low order (0.05 kg)	< 50 m	< 50 m
3.1 kg + donor	100 m	160 m
25 kg + donor	180 m	310 m
130 kg + donor	310 m	510 m
247 kg + donor	380 m	630 m

5.3.4 Summary

The maximum PTS range calculated UXO is 9.9 km for the VHF cetacean category, when considering the unweighted SPL_{peak} criteria for the largest high-order clearance. For SEL_{ss} criteria, the largest PTS range is calculated for LF cetaceans with a predicted impact of 6.7 km using the impulsive noise criteria. As explained earlier, this assumes no degradation of the UXO and no smoothing of the pulse over that distance, which is very precautionary. Although an assumption of non-pulse could under-estimate the potential impact (Martin *et al*., 2020) (the equivalent range based on LF cetacean non-pulse criteria is 400 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 have undertaken a study on behalf of Xodus to assess the potential underwater noise and its effects during the construction and operation of the proposed West of Orkney Windfarm, located off the west coast of Orkney and the north coast of Scotland.

The level of underwater noise from the installation of turbine foundations 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 as well as account for changes in water depth around the site. At each location, four modelling scenarios were considered:

- Two monopile scenarios considering 14 m diameter piles installed using maximum hammer energies of 5,000 kJ and 3,000 kJ; and
- Two jacket pile scenarios considering 3 m diameter piles installed using a maximum hammer energy of 3,000 kJ.

The loudest levels of noise and greatest impact ranges were largely predicted for the monopile scenarios at the SE modelling location. Smaller ranges are predicted at the other locations due to shallower conditions and, in the case of the SW location, shallower water towards the coast.

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

For marine mammals, maximum PTS ranges were predicted for LF cetaceans, with ranges of up to 47 km based on the monopile foundation scenario. For fish, the largest recoverable injury ranges (203 dB SEL_{cum}) were predicted to be 3.9 km for a fleeing receptor, increasing to a maximum of 25 km for a stationary receptor.

Noise sources other than piling were considered using a high-level, simple modelling approach, including cable laying, dredging, drilling, rock placement, suction bucket installation, vessel movements, and operational WTG noise. The predicted noise levels for the other construction noise sources and during WTG operation are well below those predicted for impact piling noise. The risk of any potentially injurious effects to fish or marine mammals from these sources are expected to be minimal as the noise emissions from these are close to, or below, the appropriate injury criteria even when very close to the source of the noise.

UXO clearance has also been considered at the offshore Project area, and for the expected UXO clearance noise, there is a risk of PTS up to 9.9 km for the largest, 247 kg, UXO device considered, using the unweighted SPL_{peak} criteria for VHF cetaceans. However, this is likely to be highly precautionary as the impact range is based on a worst-case criterion and calculation methodology that does not account for any smoothing of the pulse over long ranges, which would reduce the pulse peak and other characteristics of the sound that cause injury.

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

References

1. Andersson M H, Andersson S, Ahlsén J, Andersson B L, Hammar J, Persson L K G, Pihl J, Sigray P, Wilkström A (2017). *A framework for regulating underwater noise during pile driving*. A technical Vindval report, ISBN 978-91-620-6775-5, Swedish Environmental Protection Agency, Stockholm, Sweden.
2. Arons A B (1954). *Underwater explosion shock wave parameters at large distances from the charge.* J. Acoust. Soc. Am. 26, 343-346.
3. Bailey H, Thompson P (2006). *Quantitive analysis of bottlenose dolphin movement patterns and their relationship with foraging.* Journal of Animal Ecology 75: 456-465.
4. Bailey H, Brookes K L, Thompson P M (2014) *Assessing environmental impacts of offshore wind farms: lessons learned and recommendations for the future.* Aquatic Biosystems 2014, 10:8.
5. Bebb A H, Wright H C (1953). *Injury to animals from underwater explosions.* Medical Research Council, Royal Navy Physiological Report 53/732, Underwater Blast Report 31, January 1953.
6. Bebb A H, Wright H C (1954a). *Lethal conditions from underwater explosion blast.* RNP Report 51/654, RNPL 3/51, National Archives Reference ADM 298/109, March 1954.
7. Bebb A H, Wright H C (1954b). *Protection from underwater explosion blast. III. Animal experiments and physical measurements.* RNP Report 57/792, RNPL 2/54, March 1954.
8. Bebb A H, Wright H C (1955). *Underwater explosion blast data from the Royal Navy Physiological Labs 1950/1955.* Medical Research Council, April 1955.
9. BSH (2013): Standard “Investigation of the Impacts of Offshore Wind Turbines on the Marine Environment (StUK4)”.
10. Cheong S-H, Wang L., Lepper P, Robinson S (2020). *Characterization of Acoustic Fields Generated by UXO Removal, Phase 2*. NPL Report AC 19, National Physical Laboratory.
11. Cudahy E A, Parvin S (2001). *The effects of underwater blast on divers.* Report 1218, Naval Submarine Medical Research Laboratory: #63706N M0099.001-5901.
12. Dahl P H, de Jong C A, Popper A N (2015). *The underwater sound field from impact pile driving and its potential effects on marine life.* Acoustics Today, Spring 2015, Volume 11, Issue 2.
13. Goertner J F (1978). *Dynamical model for explosion injury to fish.* Naval Surface Weapons Center, White Oak Lab, Silver Spring, MD. Report No. NSWC/WOL.TR-76-155.
14. Goertner J F, Wiley M L, Young G A, McDonald W W (1994). *Effects of underwater explosions on fish without swim bladders.* Naval Surface Warfare Center. Report No. NSWC/TR-76-155.
15. Halvorsen M B, Casper B C, Matthew D, Carlson T J, Popper A N (2012). *Effects of exposure to pile driving sounds on the lake sturgeon, Nila tilapia, and hogchoker.* Proc. Roy. Soc. B 279: 4705-4714.
16. Hastie G, Merchant N D, Götz T, Russell D J F, Thompson P, Janik V M (2019). *Effects of impulsive noise on marine mammals: Investigating range-dependent risk.* Ecological Applications 29(5). DOI: 10.1002/ eap.1906.
17. Hastings M C, Popper A N (2005). *Effects of sound on fish.* Report to the California Department of Transport, under Contract No. 43A01392005, January 2005.

18. Hawkins A D, Roberts L, Cheesman S (2014). *Responses of free-living coastal pelagic fish to impulsive sounds.* J. Acoust. Soc. Am. 135: 3101-3116.
19. Heaney K D, Ainslie M A, Halvorsen M B, Seger K D, Müller R A J, Nijhof M J J, Lippert T (2020). *A parametric analysis and sensitivity study of the acoustic propagation for renewable energy sources.* Sterling (VA): U.S. Department of the Interior, Bureau of Ocean Management. Prepared by CSA Ocean Sciences Inc. OCS Study BOEM 2020-011, 165 p.
20. Hirata K (1999). *Swimming speeds of some common fish.* National Maritime Research Institute (Japan). Data sourced from Iwai T, Hisada M (1998). Fishes – Illustrated book of Gakken (in Japanese). Accessed on 8th November 2022 at https://www.nmri.go.jp/archives/eng/khirata/fish/general/speed/speede.htm
21. Kastelein R A, van de Voorde S, Jennings N (2018). *Swimming speed of a harbor porpoise (Phocoena phocoena) during playbacks of offshore pile driving sounds.* Aquatic Mammals. 2018, 44(1), 92-99, DOI 10.1578/AM.44.1.2018.92.
22. Koschinski S, Lüdemann K (2019). *Noise mitigation for the construction of increasingly large offshore wind turbines: Technical options for complying with noise limits*. Report on behalf of BfN, Bonn, Germany, pp. 1-42.
23. Marine Technical Directorate Ltd (MTD) (1996). *Guidelines for the safe use of explosives underwater.* MTD Publication 96/101. ISBN 1 870553 23 3.
24. Martin S B, Lucke K, Barclay D R (2020). *Techniques for distinguishing between impulsive and non-impulsive sound in the context of regulating sound exposure for marine mammals.* The Journal of the Acoustical Society of America 147, 2159.
25. McCauley E D, Fewtrell K, Duncan A J, Jenner C, Jenner M-N, Penrose J D, Prince R I T, Adhitya A, Murdoch J, McCabe K (2000). *Marine seismic survey – A study of environmental implications.* Appea Journal, pp 692-708.
26. National Marine Fisheries Service (NMFS) (2018). *Revisions to: Technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing (version 2.0): Underwater thresholds for onset of permanent and temporary threshold shifts.* U.S. Dept. of Commer., NOAA. NOAA Technical Memorandum NMFS-OPR-59.
27. Nedelec S L, Campbell J, Radford A N, Simpson S D, Merchant N D (2016). *Particle motion: The missing link in underwater acoustic ecology.* Methods Ecol. Evol. 7, 836 – 842.
28. Nedwell J R, Langworthy J, Howell D (2003). *Assessment of subsea noise and vibration from offshore wind turbines and its impact on marine wildlife. Initial measurements of underwater noise during construction of offshore wind farms, and comparisons with background noise.* Subacoustech Report No. 544R0423, published by COWRIE, May 2003.
29. Nedwell J R, Parvin S J, Edwards B, Workman R, Brooker A G, Kynoch J E (2007). *Measurement and interpretation of underwater noise during construction and operation of offshore windfarms in UK waters.* Subacoustech Report No. 544R0738 to COWRIE. ISBN: 978-09554276-5-4.
30. National Oceanic and Atmospheric Administration (NOAA) (2005). Endangered fish and wildlife; Notice of intent to prepare an Environmental Impact Statement. Federal Register 70: 1871-1875.
31. Popper A N, Hawkins A D, Fay R R, Mann D A, Bartol S, Carlson T J, Coombs S, Ellison W T, Gentry R L, Halvorsen M B, Løkkeborg S, Rogers P H, Southall B L, Zeddies D G, Tavolga W N (2014). *Sound exposure guidelines for Fishes and Sea Turtles.* Springer Briefs in Oceanography, DOI 10.1007/978-3-319-06659-2.

32. Popper A N, Hawkins A D (2018). *The importance of particle motion to fishes and invertebrates.* J. Acoust. Soc. Am. 143, 470 – 486.
33. Popper A N, Hawkins A D (2019). *An overview in fish bioacoustics and the impacts of anthropogenic sounds on fishes.* Journal of Fish Biology, 1-22. DOI: 10.111/jfp.13948.
34. Radford C A, Montgomery J C, Caiger P, Higgs D M (2012). *Pressure and particle motion detection thresholds in fish: a re-examination of salient auditory cues in teleosts.* Journal of Experimental Biology, 215, 3429 – 3435.
35. Rawlins J S P (1987). *Problems in predicting safe ranges from underwater explosions.* Journal of Naval Science, Volume 13, No. 4, pp 235-246.
36. Robinson S P, Lepper P A, Hazelwood R A (2014). *Good practice guide for underwater noise measurement.* National Measurement Office, Marine Scotland, The Crown Estate. NPL Good Practice Guide No. 133, ISSNL 1368-6550.
37. Scottish National Heritage (SNH) (2016). *Assessing collision risk between underwater turbines and marine wildlife.* SNH guidance note.
38. Soloway A G, Dahl P H (2014). *Peak sound pressure and sound exposure level from underwater explosions in shallow water.* The Journal of the Acoustical Society of America, 136(3), EL219 – EL223. http://dx.doi.org/10.1121/1.4892668.
39. Southall B L, Bowles A E, Ellison W T, Finneran J J, Gentry R L, Green Jr. C R, Kastak D, Ketten D R, Miller J H, Nachtigall P E, Richardson W J, Thomas J A, Tyack P L (2007). *Marine mammal noise exposure criteria: Initial scientific recommendations.* Aquatic Mammals, 33 (4), pp 411-509.
40. Southall B L, Finneran J J, Reichmuth C, Nachtigall P E, Ketten D R, Bowles A E, Ellison W T, Nowacek D P, Tyack P L (2019). *Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects.* Aquatic Mammals 2019, 45 (20, 125-232) DOI 10.1578/AM.45.2.2019.125.
41. Southall B L (2021). *Evolutions in marine mammal noise exposure criteria.* Acoustics Today 17(2) https://doi.org/10.1121/AT.2021.17.2.52.
42. Stephenson J R, Gingerich A J, Brown R S, Pflugrath B D, Deng Z, Carlson T J, Langeslay M J, Ahmann M L, Johnson R L, Seaburg A G (2010). *Assessing barotrauma in neutrally and negatively buoyant juvenile salmonids exposed to simulated hydro-turbine passage using a mobile aquatic barotrauma laboratory.* Fisheries Research Volume 106, Issue 3, pp 271-278, December 2010.
43. Stöber U, Thomsen F (2021). *How could operational underwater sound from future offshore wind turbines impact marine life.* The Journal of the Acoustical Society of America, 149, 1791-1795. https://doi.org/10.1121/10.0003760.
44. Thompson P M, Hastie G D, Nedwell J, Barham R, Brookes K L, Cordes L S, Bailey H, McLean N (2013). *Framework for assessing impacts of pile-driving noise from offshore wind farm construction on a harbour seal population*. Environmental Impact Assessment Review 43 (2013) 73-85.
45. Tougaard J, Hermannsen L, Madsen P T (2020). *How loud is the underwater noise from operating offshore wind turbines?* J Acoust. Soc. Am. 148 (5). doi.org/10.1121/10.0002453.
46. von Benda-Beckamnn A M, Aarts G, Sertlek H Ö, Lucke K, Verboom W C, Kastelein R A, Ketten D R, van Bemmelen R, Lamm F-P A, Kirkwood R J, Ainslie M A (2015). Assessing the impact of underwater clearance of unexploded ordnance on harbour porpoises (Phocoena phocoena)

in the southern North Sea. Aquatic Mammals 2015, 41(4), pp 503-523, DOI 10.1578/AM.41.4.2015.503.

Appendix A Additional modelling results

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

A.1 Single location modelling

Table A 1 to Table A 12 present the modelling results considering single locations for the non-impulsive Southall *et al*. (2019) criteria.

Monopile foundations

Table A 1 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the monopile foundation (hard sediment) modelling at the NW location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Monopile foundation, hard sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (199 dB)	4.5 km²	1.8 km	< 100 m	1.2 km
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	5,300 km²	60 km	3.5 km	40 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	830 km²	21 km	2.8 km	16 km
	PCW (181 dB)	21 km²	3.3 km	350 m	2.5 km

Table A 2 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the monopile foundation (soft sediment) modelling at the NW location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Monopile foundation, soft sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (199 dB)	0.2 km²	500 m	< 100 m	180 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	4,500 km²	55 km	3.2 km	37 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	600 km²	18 km	2.3 km	14 km
	PCW (181 dB)	11 km²	2.4 km	< 100 m	1.8 km

Table A 3 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the monopile foundation (hard sediment) modelling at the SE location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Monopile foundation, hard sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (199 dB)	14 km²	2.7 km	1.0 km	2.0 km
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	4,300 km²	63 km	22 km	36 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	970 km²	22 km	13 km	18 km
	PCW (181 dB)	370 km²	4.1 km	2.4 km	3.4 km

Table A 4 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the monopile foundation (soft sediment) modelling at the SE location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Monopile foundation, soft sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (199 dB)	2.4 km²	1.3 km	< 100 m	790 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	3,800 km²	58 km	21 km	34 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	740 km²	18 km	12 km	15 km
	PCW (181 dB)	22 km²	3.2 km	1.7 km	2.6 km

Table A 5 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the monopile foundation (hard sediment) modelling at the SW location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Monopile foundation, hard sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (199 dB)	6.6 km²	1.8 km	930 m	1.4 km
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	3,700 km²	47 km	18 km	33 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	780 km²	18 km	12 km	16 km
	PCW (181 dB)	25 km²	3.2 km	2.3 km	2.8 km

Table A 6 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the monopile foundation (soft sediment) modelling at the SW location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL$_{cum}$		**Monopile foundation, soft sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (199 dB)	0.4 km^2	580 m	< 100 m	330 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	LF (179 dB)	3,200 km^2	42 km	17 km	31 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	590 km^2	16 km	11 km	14 km
	PCW (181 dB)	14 km^2	2.4 km	1.6 km	2.1 km

Jacket pile foundations

Table A 7 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the jacket pile foundation (hard sediment, 2 piles installed per 24 hours) modelling at the NW location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL$_{cum}$		**Jacket pile foundation, hard sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (199 dB)	< 0.1 km^2	200 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	LF (179 dB)	4,200 km^2	53 km	3.2 km	26 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	570 km^2	17 km	2.3 km	13 km
	PCW (181 dB)	8.7 km^2	2.1 km	< 100 m	1.6 km

Table A 8 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the jacket pile foundation (soft sediment, 4 piles installed per 24 hours) modelling at the NW location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL$_{cum}$		**Jacket pile foundation, soft sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	LF (179 dB)	4,200 km^2	53 km	3.2 km	36 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	590 km^2	18 km	2.3 km	14 km
	PCW (181 dB)	8.9 km^2	2.2 km	< 100 m	1.6 km

Table A 9 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the jacket pile foundation (hard sediment, 2 piles installed per 24 hours) modelling at the SE location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL$_{cum}$		**Jacket pile foundation, hard sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (199 dB)	1.2 km^2	950 m	< 100 m	530 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	LF (179 dB)	3,600 km^2	56 km	21 km	33 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	720 km^2	17 km	12 km	15 km
	PCW (181 dB)	19 km^2	3.0 km	1.6 km	2.4 km

Table A 10 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the jacket pile foundation (soft sediment, 4 piles installed per 24 hours) modelling at the SE location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL$_{cum}$		**Jacket pile foundation, soft sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (199 dB)	1.2 km^2	950 m	< 100 m	530 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	LF (179 dB)	3,600 km^2	57 km	21 km	33 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	730 km^2	18 km	12 km	15 km
	PCW (181 dB)	19 km^2	3.0 km	1.6 km	2.4 km

Table A 11 Summary of the weighted SEL$_{cum}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the jacket pile foundation (hard sediment, 2 piles installed per 24 hours) modelling at the SW location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL$_{cum}$		**Jacket pile foundation, hard sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (199 dB)	< 0.1 km^2	300 m	< 100 m	130 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	LF (179 dB)	3,000 km^2	40 km	17 km	30 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	580 km^2	16 km	11 km	14 km
	PCW (181 dB)	11 km^2	2.2 km	1.5 km	1.9 km

Table A 12 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the jacket pile foundation (soft sediment, 4 piles per 24 hours) modelling at the SW location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Jacket pile foundation, soft sediment**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (199 dB)	< 0.1 km^2	300 m	< 100 m	130 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	LF (179 dB)	3,000 km^2	41 km	17 km	30 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	580 km^2	16 km	11 km	14 km
	PCW (181 dB)	11 km^2	2.2 km	1.5 km	1.9 km

A.2 Concurrent location modelling

Figure A 1 and Figure A 2 and Table A 13 and Table A 14 expand on the results presented in section 4.3 for concurrent multiple location piling, covering the non-impulsive criteria from Southall *et al*. (2019) for marine mammals. As before, contours too small to be seen at scale have not been included and impact ranges have not been presented as there are multiple starting points for receptors. Fields denoted with a dash “-” show where there is no in-combination effect when piles are installed concurrently.

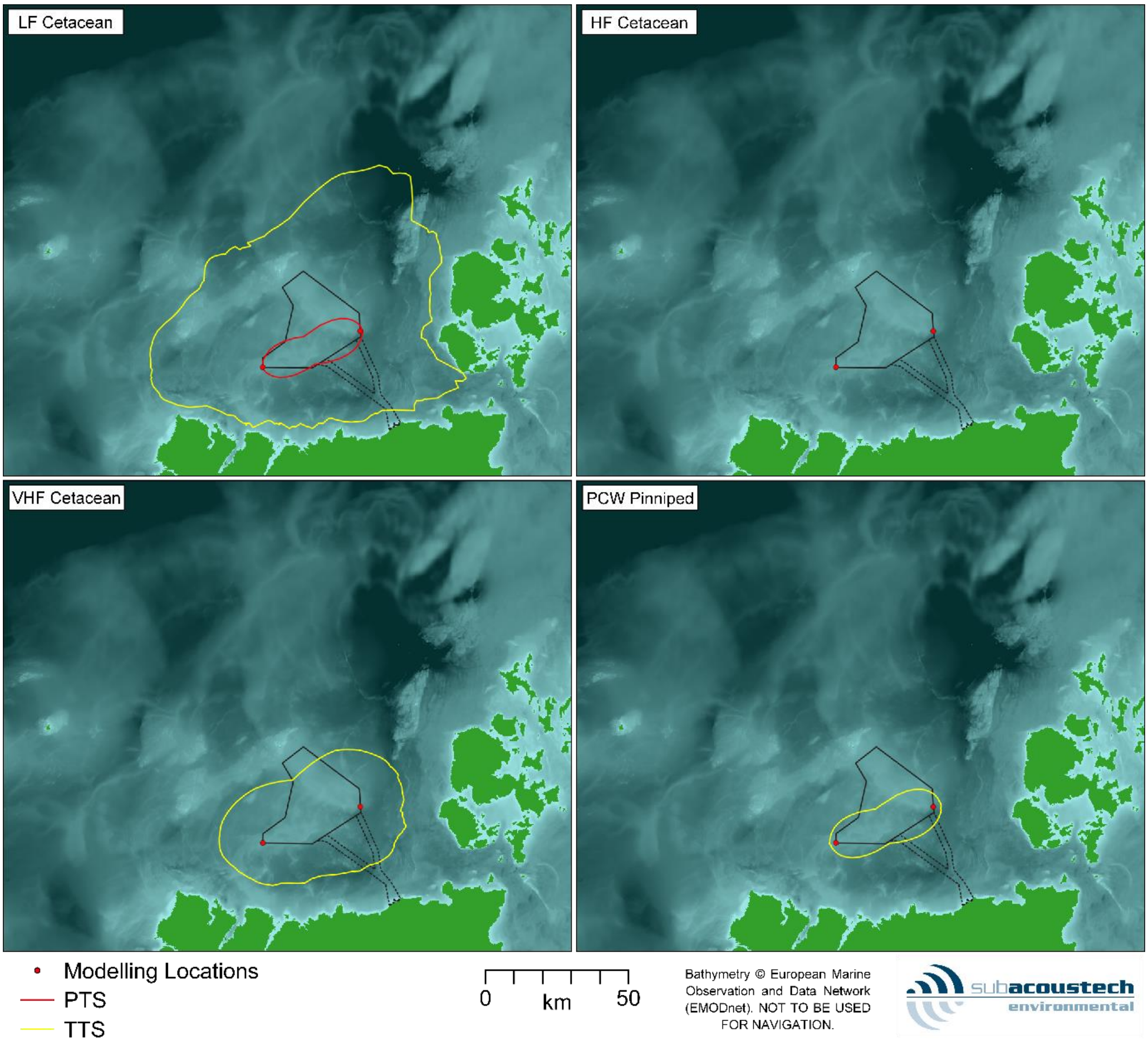


Figure A 1 Contour plots showing the in-combination impacts of concurrent installation of jacket pile foundations (hard sediment, 2 piles installed at each location per 24 hours) at two locations across the OAA for marine mammals using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal

Table A 13 Summary of the impact areas for the installation of jacket pile foundations (hard sediment, 2 piles installed at each location per 24 hours) at two locations across the OAA for marine mammals using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal

Jacket pile foundation Southall *et al*. (2019) Weighted SEL_{cum}		**SE location**	**SW location**	**In-combination area**
PTS (Non-impulsive)	LF (199 dB)	1.2 km²	< 0.1 km²	4,500 km²
	HF (198 dB)	< 0.1 km²	< 0.1 km²	-
	VHF (173 dB)	< 0.1 km²	< 0.1 km²	1,700 km²
	PCW (201 dB)	< 0.1 km²	< 0.1 km²	-
TTS (Non-impulsive)	LF (179 dB)	3,600 km²	3,000 km²	15,000 km²
	HF (178 dB)	< 0.1 km²	< 0.1 km²	-
	VHF (153 dB)	720 km²	580 km²	8,300 km²
	PCW (181 dB)	19 km²	11 km²	3,300 km²

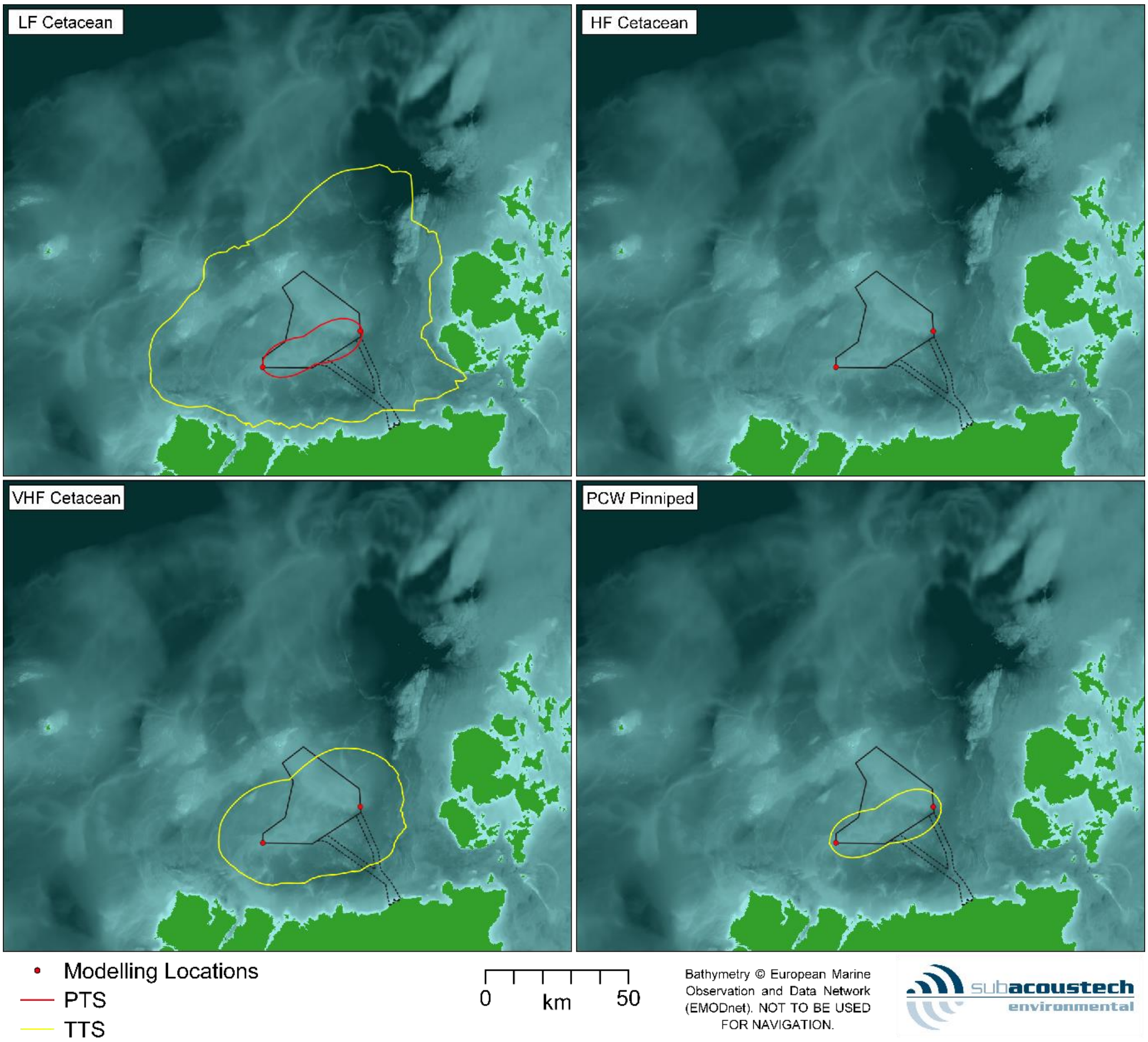


Figure A 2 Contour plots showing the in-combination impacts of concurrent installation of jacket pile foundations (soft sediment, 4 piles installed at each location per 24 hours) at two locations across the OAA for marine mammals using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal

Table A 14 Summary of the impact areas for the installation of jacket pile foundations (soft sediment, 4 piles installed at each location per 24 hours) at two locations across the OAA for marine mammals using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal

Jacket foundation Southall *et al*. (2019) Weighted SEL$_{cum}$		**SE location**	**SW location**	**In-combination area**
PTS (Non-impulsive)	LF (199 dB)	1.2 km^2	< 0.1 km^2	4,500 km^2
	HF (198 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (173 dB)	< 0.1 km^2	< 0.1 km^2	1,700 km^2
	PCW (201 dB)	< 0.1 km^2	< 0.1 km^2	-
TTS (Non-impulsive)	LF (179 dB)	3,600 km^2	3,000 km^2	16,000 km^2
	HF (178 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (153 dB)	730 km^2	580 km^2	8,600 km^2
	PCW (181 dB)	19 km^2	11 km^2	3,400 km^2

Report documentation page

- This is a controlled document.
- Additional copies should be obtained through the Subacoustech Environmental librarian.
- If copied locally, each document must be marked “Uncontrolled copy”.
- Amendment shall be by whole document replacement.
- Proposals for change to this document should be forwarded to Subacoustech Environmental.

Document No.	Draft	Date	Details of change
P325R0300	01	23/11/2022	Initial writing and internal review
P325R0301	02	01/12/2022	Amendments following client comments and updated modelling
P325R0302	-	15/02/2023	Fixed discrepancy in UXO clearance section
P325R0303	-	16/02/2023	

Originator’s current report number	P325R0303
Originator’s name and location	R Barham; Subacoustech Environmental Ltd.
Contract number and period covered	P325; August 2022 – February 2023
Sponsor’s name and location	David Bloxsom; Xodus
Report classification and caveats in use	COMMERCIAL IN CONFIDENCE
Date written	November 2022 – February 2023
Pagination	Cover + iv + 64
References	46
Report title	West of Orkney Windfarm: Underwater Noise Assessment
Translation/Conference details (if translation, give foreign title/if part of a conference, give conference particulars)	
Title classification	Unclassified
Author(s)	Richard Barham, Tim Mason
Descriptors/keywords	
Abstract	
Abstract classification	Unclassified; Unlimited distribution