Arklow Bank Wind Park 2

Environmental Impact Assessment Report

Volume III, Appendix 11.1: Underwater Noise Assessment (Revised March 2026)

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Arklow Bank Wind Park 2: Underwater Noise Assessment (Revised March 2026)

Richard Barham, Tim Mason

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Submitted to: Ellen MacMahon

Tel: +44 (0)1626 323 890

Website: www.gobeconsultants.com

Submitted by: Richard Barham

Tel: +44 (0)23 80 236 330

Website: www.subacoustech.com

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Statement of Authority

Tim Mason, BEng (Hons) MIOA - Underwater Noise Lead Continuous post-graduate consultancy experience since 2001 in design and impact assessment of underwater and airborne noise situations. Responsible for project management and QA in addition to technical consultancy and reporting. Acts as a technical specialist for examinations with respect to underwater noise and its effects on marine life. Experienced in a wide range of acoustic disciplines in addition to underwater noise modelling and monitoring; other disciplines include road, rail and construction noise impacts, planning and architectural acoustics, vibration and noise nuisance. Tim has delivered presentations on underwater noise impacts at national and international conferences and has been invited to speak on underwater noise at the Royal Society.
Richard Barham, BSc (Hons) AMIOA - Underwater Noise Modelling Specialist 15 years' experience in the development and execution of underwater noise models. Oversees development of the Impulse Noise Sound Propagation and Range Estimator (INSPIRE) underwater noise model and the INSPIRE Light model, a cut down version of INSPIRE which can be used in meetings and workshops. Experienced with the RAMSGeo and dBSea acoustic models. Involved with noise measurements and data analysis of various sources of underwater noise including impact piling, drilling vessel noise and diving equipment. Highly skilled in technical report writing and graphic representation of data.

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Executive Summary

Subacoustech Environmental, on behalf of GoBe Consultants, has undertaken a study in order to assess the potential underwater noise and its effects during impact piling at Arklow Bank Wind Park 2 (ABWP2). This study follows from the previous underwater noise modelling undertaken as part of the Environmental Impact Assessment Report (EIAR). This revision takes into account the Further Information Request [doc no. ABP-319864-24).

Impact piling is required at ABWP2 to install foundations for wind turbine generators (WTG) and offshore platforms (OSP). Modelling of underwater noise generated by impact piling was undertaken at five representative locations, with the loudest levels predicted at the Central location for the installation of WTG foundations, primarily due to the deeper water at that location.

The modelling results were analysed in terms of relevant noise metrics and criteria to assess the effects of impact piling noise on marine mammals and fish, which have been used to aid biological assessments. For marine mammals the largest auditory injury (including permanent threshold shift (PTS)) onset ranges were predicted for LF cetaceans, which includes minke whale, with maximum impact ranges out to 7.1 km. For fish, the largest recoverable injury ranges were predicted to be 6.0 km for a stationary receptor, reducing to less than 50 m when assuming a moving receptor.

As part of the assessment, a Mitigated piling ramp-up scenario has been modelled to show the potential effects of modifying the durations, strike rate and blow energies on the Precautionary ramp-up scenario. These modifications resulted in maximum PTS ranges of 870 m for LF cetaceans, and maximum fish recoverable injury ranges of 5.5 km for a stationary receptor.

Additionally, the effect of physical mitigation, in the form of a low-noise hammer (or other system capable of reducing noise levels by 4 dB), has also been considered on the Precautionary ramp-up scenario. When the noise reduction from a noise abatement system is considered, PTS onset ranges for LF cetaceans are reduced to 720 m, and recoverable injury ranges for stationary fish are expected to be reduced to 3.4 km.

A review was undertaken of various underwater noise requirements or limits for offshore wind farm installation in use in the European Union (EU), as requested in the Further Information Request item 9 a ii. Of those considered, ABWP2 believes the Danish requirements, as noted in the GOMOREUS report (Tougaard *et al.,* 2025) for the Marine Institute, offer the best combination of consideration of the varying sensitivities of different species groups expected to be present in Irish waters, the site specific characteristics in comparison to Danish waters (primarily the depths and varying bathymetry, and as it includes the total noise produced by an impact piling event. The Danish requirements introduce the concept of r_{safe}, which is the distance within which a receptor species (typically marine mammals, although in principle this could include any species with available impact threshold) would receive sufficient noise exposure to exceed a PTS threshold. ABWP2 intends to use an r_{safe} target of 1 km, and would ensure marine mammals would not be present in this zone at the start of piling. This is typically through the use of Marine Mammal Observers and/or Acoustic Deterrent Devices. Modelling shows that this target can be achieved using either the low noise hammer (or other technique offering 4 dB noise reduction) with Precautionary ramp-up scenario, and the Mitigated ramp up scenario, without additional noise abatement.

Noise sources other than impact piling were considered using higher-level methodologies, and these included cable laying, dredging, drilling, rock placement, trenching, vessel noise, and operational WTG noise. All these sources were predicted to have a much smaller impact compared to impact piling noise.

Noise from unexploded ordnance (UXO) clearance showed there is a risk of PTS onset out to 990 m with use of the expected low-order UXO clearance technique. This considered the unweighted peak criteria for the very high-frequency (VHF) cetaceans hearing group, which includes harbour porpoise. In the event that a high-order detonation does occur, the maximum PTS onset range is predicted to be 14 km from detonation of the largest considered device (800 kg + donor charge), using the same VHF cetacean criteria. It should be noted that this is likely to be highly precautionary as the impact range is based on a precautionary 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. High-order detonation is not a proposed UXO clearance methodology.

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

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

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Terminology

Term	Definition
Decibel (dB)	A customary scale commonly used (in various ways) for reporting levels of sound. The dB represents a ratio/comparison of a sound measurement (e.g., sound pressure) over a fixed reference level. The dB symbol is followed by a reference value (e.g., re 1 µPa).
Peak pressure	The highest pressure above or below ambient that is associated with a sound wave.
Permanent Threshold Shift (PTS)	Noise threshold that represents the onset level of a permanent impairment hearing caused by acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the ear, and thus a permanent reduction of hearing acuity.
Root Mean Square (RMS)	The square root of the arithmetic average of a set of squared instantaneous values. Used for presentation of an average sound pressure level.
r_{safe}	As per Danish guidance, the distance at which a marine mammal must be at the start of piling to avoid PTS noise exposure
Sound Exposure Level (SEL or $L_{E,p}$)	The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.
Sound Exposure Level, cumulative (SEL_{cum} or $L_{E,p,t}$)	Single value for the collected, combined total of sound exposure over a specified time or multiple instances of a noise source.
Sound Exposure Level, single strike (SEL_{ss} or $L_{E,p,ss}$)	Calculation of the sound exposure level representative of a single noise impulse, typically a pile strike.
Sound Pressure Level (SPL or L_p)	The sound pressure level is an expression of sound pressure using the decibel (dB) scale; the standard frequency pressures of which are 1 µPa for water and 20 µPa for air.
Sound Pressure Level Peak (SPL_{peak}, $L_{p,pk}$ or L_{z-p})	The highest (zero-peak) positive or negative sound pressure, in decibels.
Temporary Threshold Shift (TTS)	Onset threshold level for a temporary reduction of hearing acuity caused by exposure to sound over time.
Unweighted sound level	Sound levels which are “raw” or have not been adjusted in any way, for example to account for the hearing ability of a species.
Weighted sound level	A sound level which has been adjusted with respect to a “auditory weighting function” or “weighting envelope” in the frequency domain, typically to make an unweighted level relevant to a particular species.

Acronyms

Acronym	Definition
ABP	An Bord Pleanála
ABWP2	Arklow Bank Wind Park 2
ACP	An Coimisiún Pleanála
ADD	Acoustic Deterrent Device
BGS	British Geological Survey
BSH	Bundesamt für Seeschifffahrt und Hydrographie
Cefas	Centre for the Environment, Fisheries and Aquaculture Science
DAHG	Department of the Arts, Heritage and the Gaeltacht, now DHLGH (see below)
Defra	Department of Environment, Food and Rural Affairs
DHLGH	Department of Housing, Local Government and Heritage
EIAR	Environmental Impact Assessment Report
EMODnet	European Marine Observation and Data Network
EPS	European Protected Species
EU	European Union
FPSO	Floating Production Storage and Offloading (vessel)
GES	Good Environmental Status
GIS	Geographic Information System
GOMOREUS	Guidance on Managing Offshore Renewable Energy Underwater Sound
HE	High Explosive
HF	High-Frequency Cetaceans
INSPIRE	Impulsive Noise Sound Propagation and Impact Range Estimator
ISO	International Organisation for Standardisation
JNCC	Joint Nature Conservation Committee
LF	Low-Frequency Cetaceans
LOBE	Level of Onset of Biologically Significant Effect (MSFD)
MMO	Marine Management Organisation
MSFD	Marine Strategy Framework Directive
MTD	Marine Technology Directorate
NAS	Noise Abatement System
NE	Natural England
NEQ	Net Explosive Quantity
NMFS	National Marine Fisheries Service

NOAA	National Oceanic and Atmospheric Administration
NPL	National Physical Laboratory
NPWS	National Parks and Wildlife Service
OSP	Offshore Platform
OWF	Offshore Wind Farm
PCW	Phocid Carnivores in Water
PPV	Peak Particle Velocity
PTS	Permanent Threshold Shift
RMS	Root Mean Square
SE	Sound Exposure
SEL ($L_{E,p}$)	Sound Exposure Level
SEL$_{\text{cum}}$ ($L_{E,p,t}$)	Cumulative Sound Exposure Level
SEL$_{\text{ss}}$ ($L_{E,p,ss}$)	Single Strike Sound Exposure Level
SPL	Sound Pressure Level
SPL$_{\text{peak}}$ ($L_{p,pk}$)	Peak Sound Pressure Level
SPL$_{\text{RMS}}$ (L_{p})	Root Mean Square Sound Pressure Level
TNT	Trinitrotoluene (explosive)
TTS	Temporary Threshold Shift
UK	United Kingdom
UXO	Unexploded Ordnance
VHF	Very High-Frequency Cetaceans
WTG	Wind Turbine Generator

Units

Unit	Definition
bl/min	Blows per minute (piling strike rate)
dB	Decibel (sound pressure)
Hz	Hertz (frequency)
kg	Kilogram (mass)
kHz	Kilohertz (frequency)
kJ	Kilojoule (energy)
km	Kilometre (distance)
km^2	Square kilometres (area)
kn	Knot (speed)
kW	Kilowatt (power)
m	Metre (distance)
mms^{-1}	Millimetres per second (particle velocity)
ms^{-1}	Metres per second (speed)
MW	Megawatt (power)
Pa	Pascal (pressure)
Pa^2s	Pascal squared seconds (acoustic energy)
s	Seconds (duration)
µPa	Micropascal (pressure)

1 Introduction

Arklow Bank Wind Park 2 (ABWP2) is a planned offshore wind farm situated on and around Arklow Bank in the Irish Sea, approximately 6 to 15 km to the east of Arklow in County Wicklow, Ireland.

Subacoustech Environmental Ltd. has undertaken detailed modelling and analysis in relation to underwater noise from impact piling in order to install foundations for wind turbine generators (WTG) and offshore platforms (OSP).

Following from the initial underwater noise assessment undertaken as part of the EIAR (Appendix 11.1), this report is a revision of that assessment utilises the latest version of the modelling software along with updated input parameters in order to ascertain the potential effects of impact piling on marine mammals and fish during construction of ABWP2.

The array covers an area of 63.4 km^2 and has a proposed capacity of 800 MW, utilising either 47 or 53 wind turbine generators (WTG) depending on the final Design Option chosen. The location of ABWP2 is shown in Figure 1-1.

This technical report presents a detailed assessment of the potential underwater noise from impact piling activities during the construction of ABWP2, and includes the following:

- Background information covering the units for measuring and assessing underwater noise, and a review of the underwater noise metrics and criteria used to assess the possible environmental effects in marine receptors (section 2).
- Discussion of the approach, confidence, input parameters, and assumptions for the detailed impact piling 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, including the use of a noise attenuation system (NAS) (section 4).
- Modelling of other noise sources expected around the construction and operation of ABWP2 including cable laying, dredging, drilling, rock placement, vessel movements, operational WTG noise, and unexploded ordnance (UXO) clearance (section 5).
- Summary and conclusions (section 6).

Further modelling results covering the noise from the first pile strike and for non-impulsive thresholds (see sections 2.2.1 and 2.3.1) are presented in Appendix A.

This technical report is an update to the previous Arklow Bank Wind Park underwater noise report issued as part of the EIAR in 2024, including updated modelling and consideration of Further Information Requests from ACP.

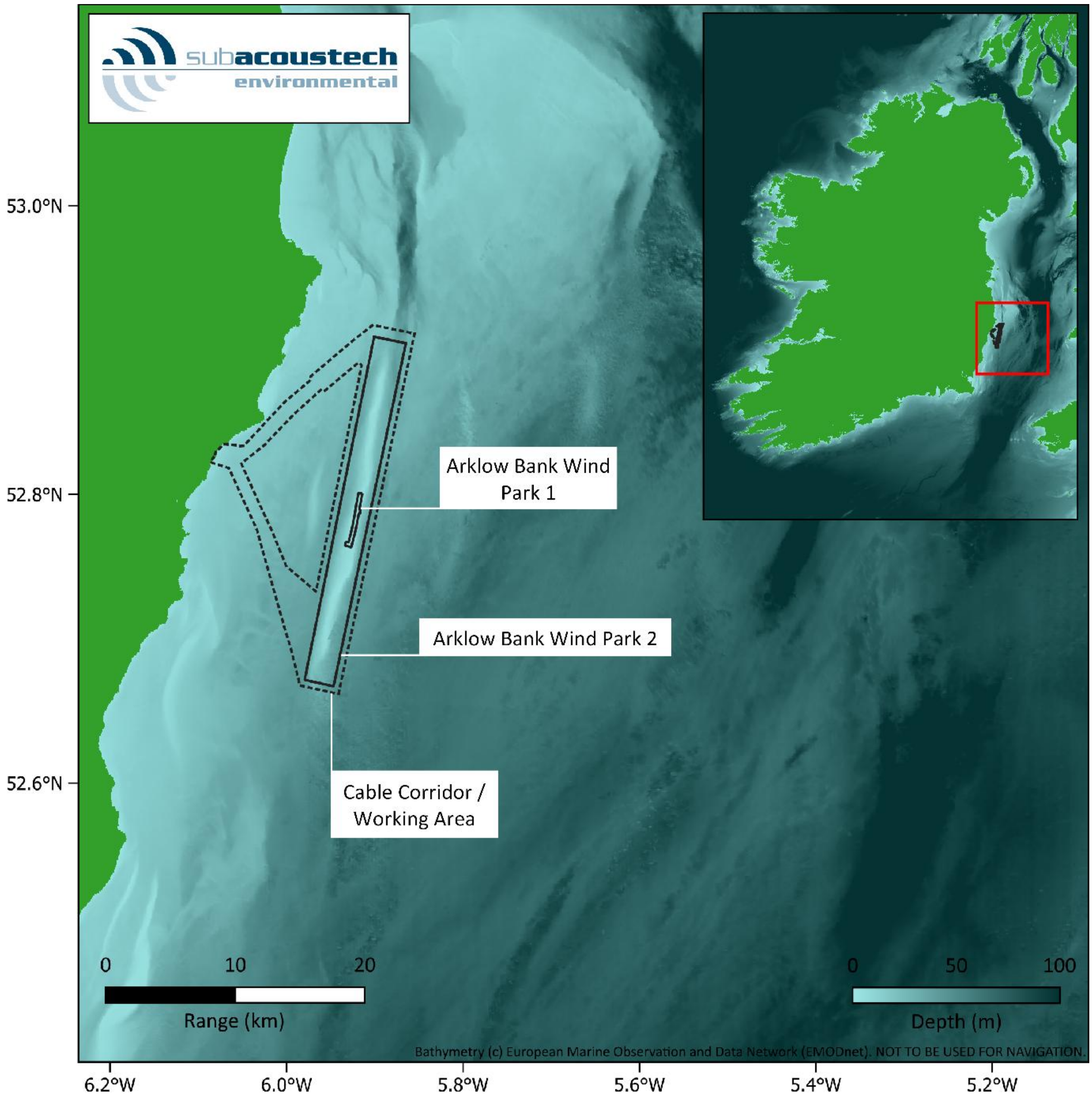

Figure 1-1: Overview map showing the ABWP2 boundary, its location next to the Irish coast, and the surrounding bathymetry.

2 Underwater noise concepts

Sound travels much faster in water (approximately 1,500 ms^{-1}) than in air (340 ms^{-1}) as water is relatively incompressible and has a higher density than air. This affects the way in which sound measurements are expressed between the two mediums, which means that underwater sound levels are not directly comparable to airborne sound levels. This is noted for context; this report does not contain or include any reference to airborne sound.

2.1 Units of measurement

Sound measurements underwater are usually expressed using the decibel (dB) scale, which is a logarithmic measure of sound. A logarithmic scale is used as this better reflects how sound is perceived. For example, equal increments of sound pressure do not have an equal increase in the perceived sound. Instead, a doubling of sound pressure will cause a roughly equal increase of perceived loudness each time. Any quantity expressed in this dB scale is termed a “level.” For example, if the unit is sound pressure, it will be termed a “sound pressure level” on the dB scale.

The fundamental definition of the dB scale is given by:

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

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

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

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

2.1.1 Sound pressure level

Sound Pressure Level (SPL or L_p) is a measure of the pressure variation caused by sound waves, expressed in decibels (dB), as seen in the equations above. Variations of L_p are used depending on the noise source being measured. Unless otherwise defined, all L_p noise levels in this report are referenced to 1 µPa.

2.1.1.1 Mean squared sound pressure

For continuous, non-impulsive noise sources such as drilling or vibropiling, an unweighted sound pressure level, averaged over a measurement period, known as a root mean squared (RMS) sound pressure level (SPL_{RMS} or $L_{p,RMS}$), can be used to represent the noise levels. The RMS period must be specified (e.g. $L_{p,RMS,125ms}$), as the mean level can vary significantly depending on the measurement duration.

2.1.1.2 Peak sound pressure

Transient, impulsive pressure waves such as generated from impact piling are usually expressed using the level of the peak sound pressure (SPL$_{\mathrm{peak}}$ or $L_{p,pk}$). This is calculated using the maximum pressure variation from positive to zero, representing the peak change in pressure as the transient wave propagates.

2.1.2 Sound exposure level

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 (1955) 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 (e.g., Popper *et al.,* 2014; Southall *et al.,* 2019; Southall *et al.,* 2007).

The $L_{E,p}$ sums the acoustic energy over a measurement period, and effectively takes account of both the L_p 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^{2}s).

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

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

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

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

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

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

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

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

Where $L_{E,p}$ is the sound exposure level of one impulse and X is the total number of impulses or strikes. Unless otherwise defined, all $L_{E,p}$ noise levels in this report are referenced to 1 µPa^{2}s.

2.2 Properties of sound

2.2.1 Impulsive and non-impulsive sound

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

These differences are important when considering the potential for auditory injury, as impulsive noise is more injurious than non-impulsive noise (Henderson and Hamernik, 1986; Hastie *et al*., 2019).

Due to the differences between impulsive and non-impulsive noise sources, different metrics are appropriate, for example:

- Impulsive noises: peak SPL ($L_{p,pk}$) and cumulative SEL ($L_{E,p,t}$).
- Non-impulsive noises: cumulative SEL ($L_{E,p,t}$) and SPL$_{\text{RMS}}$ ($L_{p,RMS}$).

Objective categorisation of a noise as impulsive or non-impulsive is not always clear. This is particularly the case if sound is travelling over large distances. For example, as an impulsive sound propagates through an environment, the energy within the sound wave will scatter and dissipate, and it will become less impulsive with distance. This is important to consider regarding auditory injury and impact range calculations, as noise will become less injurious if it becomes less impulsive.

Research to define a range-dependent transition from impulsive to non-impulsive noise has been a significant field of study (see, for example, Martin *et al*., 2020). Although the situation is complex, Hastie *et al*. (2019) concluded that an impulsive sound can be considered effectively non-impulsive at a range of 3.5 km from the source using some metrics. However, the recent study by Matei *et al*. (2024) concludes that there is still insufficient evidence to clearly define a transition point suitable for an assessment such as this. It is, however, reasonable to presume there is a fully impulsive region close to the source, and a fully non-impulsive region at some greater distance, and a transition region in between. The paper makes it clear that there is a substantial reduction in impulsiveness within the first 5 km. However, due to the uncertainty in identifying a transition point, no presumption of a change has been made in this report, although it is reasonable to assume that the sound can be considered not fully impulsive where PTS onset ranges (see section 2.3.1 for marine mammals) are calculated above 5 km. Results in respect of both impulsive and non-impulsive criteria have been presented for impact piling noise in this report.

2.2.2 Particle motion

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

It has been identified by several researchers that many fish species (e.g., Popper and Hawkins, 2019; Nedelec *et al*., 2016; Radford *et al.,* 2012), as well as marine invertebrates (see section 2.3.3) are sensitive to particle motion. However, sound pressure metrics are still preferred and more widely used than particle motion due to a lack of supporting data (Popper and Hawkins, 2018). There continue to be calls for additional research on the levels of and effects on marine receptors with respect to levels of particle motion.

2.3 Analysis of environmental effects: Assessment criteria

Over the last 20 years it has become increasingly evident that noise from human activities in and around underwater environments can have an impact on the marine species in the area. The extent to which intense underwater sound might cause adverse impacts in species is dependent upon the incident sound level, source frequency, duration of exposure, and/or repetition rate of an impulsive sound (see, for example, Hastings and Popper, 2005). As a result, scientific interest in the hearing abilities of aquatic species has increased. Studies are primarily based on evidence from high level sources of underwater noise such as seismic airguns, impact piling and blasting as these sources are likely to have the greatest immediate environmental impact and therefore the clearest observable effects, although interest in chronic noise exposure is increasing.

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

- Physical traumatic injury and fatality.
- Auditory injury (either permanent or temporary).
- Behavioural responses.

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

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.
- Popper *et al*. (2014) sound exposure guidelines for fishes and sea turtles.

2.3.1 Marine mammals

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

The Southall *et al*. (2019) guidance categorises marine mammals into groups of similar species and applies filters to the unweighted noise to approximate the hearing sensitivities of the receptor in question. The hearing groups given by Southall *et al*. (2019) are summarised in Table 2-1 and the relevant auditory weighting functions are shown in 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 our study area.

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

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

Hearing group	Generalised hearing range	Example species
Low-frequency cetaceans (LF)	7 Hz to 35 kHz	Baleen whales (including minke 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)

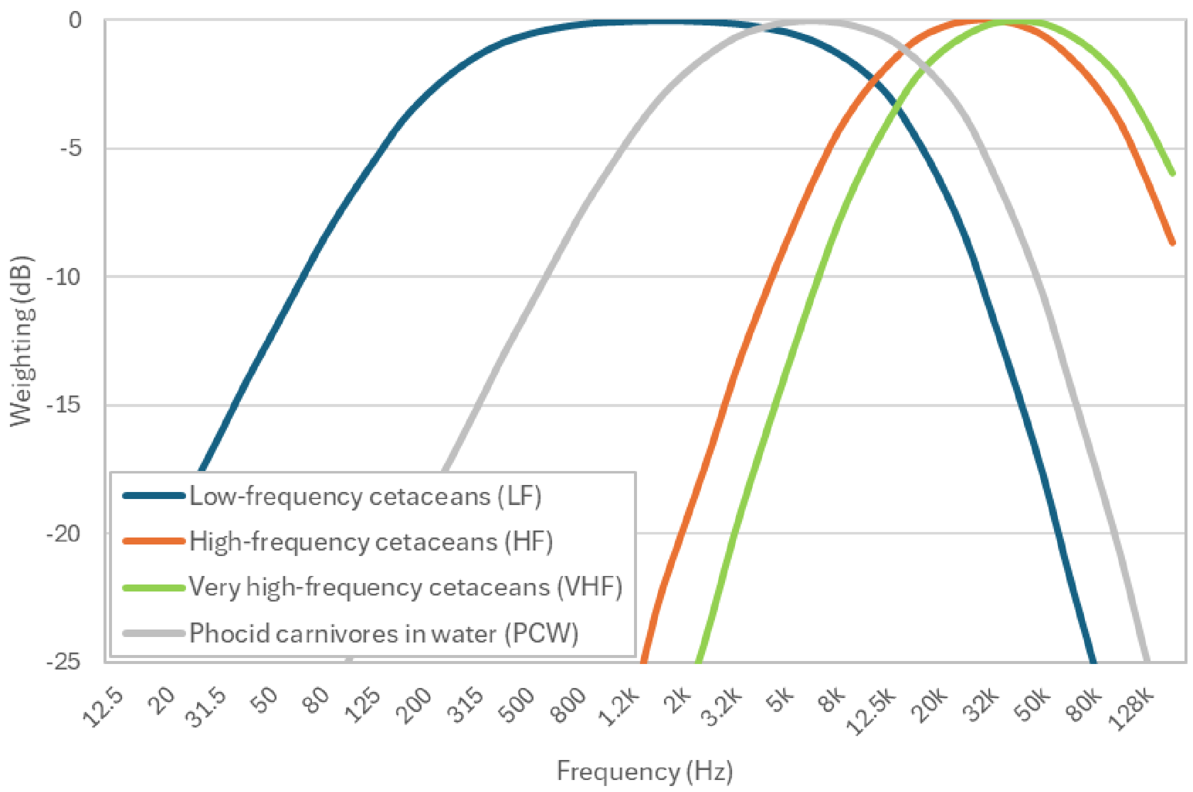

Figure 2-1: Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al., 2019).

Southall *et al*. (2019) considers the nature of the sound in the context of whether it is an impulsive or non-impulsive noise source (see section 2.2.1 for details). Although the use of impact ranges derived using the impulsive criteria are recommended for all but clearly defined non-impulsive sources, it should be recognised that where calculated ranges are beyond 5 km (see section 2.2.1; Matei *et al*., 2024), the sound is expected to be beyond the fully impulsive region and the real impact range is likely to be somewhere between the impulsive and non-impulsive impact criteria. Therefore, if the modelled impact range of an impulsive noise has been predicted to be greater than 5 km, the non-impulsive impact range should also be considered. Both impulsive and non-impulsive criteria have been presented in this study.

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

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

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

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

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$ (dB re 1 µPa²s)	**Impulsive**		**Non-impulsive**	
	PTS	**TTS**	**PTS**	**TTS**
Low-frequency cetaceans (LF)	183	168	199	179
High frequency cetaceans (HF)	185	170	198	178
Very high-frequency cetaceans (VHF)	155	140	173	153
Phocid carnivores in water (PCW)	185	170	201	181

Where $L_{E,p,t}$ thresholds are required for marine mammals, a fleeing animal model has been used. This assumes that a receptor, when exposed to high noise levels, will swim away from the noise source. A constant fleeing speed of 3.25 ms^{-1} has been assumed for the low-frequency cetaceans (LF) group (Blix and Folkow, 1995), based on data for minke whale, and for other receptors, a constant rate of 1.5 ms^{-1} has been assumed for fleeing, which is a cruising speed for a harbour porpoise (Otani *et al*., 2000). These are considered worst case assumptions as marine mammals are expected to be able to swim much faster under stress conditions (Kastelein *et al.* 2018), especially at the start of any noisy process when the receptor will be closest.

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

Limited data is available for behavioural disturbance on species of marine mammal. To take this into account, the National Oceanic and Atmospheric Administration (NOAA) (2005) Level B (behavioural disturbance) harassment criterion for impulsive noise on marine mammals has been included to cover disturbance effects. This criterion is 160 dB re 1 µPa ($L_{p,RMS}$) from a single strike.

In addition, the concept of r_{safe}, following the Danish regulations (Danish Energy Agency, 2023), has been utilised. This derives a distance from the pile that would represent a distance that, provided a marine mammal is beyond at the start of piling, it would be safe from the effects of PTS according to the Southall *et al.* (2019) guidance. This distance is known as "r_{safe}" and is effectively the distance that must be cleared before piling starts to avoid auditory injury for marine mammals. This is also one of the options presented in the Guidance On Managing Offshore Renewable Energy Underwater Sound (GOMOREUS) study for underwater sound in Irish waters (Tougaard *et al.*, 2025) and is used as the basis of this assessment. The Danish, and other EU, guidance currently in use is discussed further in section 2.4, in accordance with the Further Information Request from An Coimisiún Pleanála (ACP) (RFI 9a ii).

2.3.2 Fish

The Popper *et al*. (2014) guidelines are recognised as a suitable reference for underwater noise impacts on marine fauna (aside from marine mammals) in UK and Irish waters. Popper *et al*. (2014) provides a summary of research and guidelines for fish (and other marine fauna) exposure to sound and uses categories that a representative of the species present around ABWP2.

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

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

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

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

Where $\underline{L_{E,p,t}}$ thresholds are required for fish, both a stationary and a fleeing animal model has been used. Most species described by Popper *et al*. (2014) are likely to be able to move away from a sound that is loud enough to cause harm (Dahl *et al*., 2015; Popper *et al*., 2014). For those species that can swim away, a speed of 1.5 ms^{-1} (based on Hirata, 1999) has been considered as a conservative speed at which to base a fleeing animal model. However, considering the diversity of species described by Popper *et al*. (2014), whether an animal flees or remains stationary in response to a loud noise will differ between species. It is recognised that there is limited evidence for fish fleeing from high level noise sources in the wild (Hubert *et al*., 2024). The species that are likely to remain stationary are though more likely to be benthic species of species without a swim bladder, due to their reduced hearing capabilities making these species least sensitive to noise (Goertner *et al*., 1994; Goertner *et al*., 1978; Stephenson *et al*., 2010; Halvorsen *et al*., 2012).

Hubert *et al*. (2024) noted that pelagic fish did not clearly flee with exposure to sound, albeit at sound pressure levels far lower than piling noise, and did not rule out the possibility that a flee response could occur at higher levels. Despite this, only including results for a stationary animal as a worst-case scenario is likely to greatly overestimate the potential risk to fish species. As such, a combined approach is recommended, which considers impact ranges from both fleeing and stationary receptors.

The thresholds and relative risk descriptions given by Popper *et al*. (2014) used in this study are reproduced in Table 2-4 to Table 2-6. Similar to the Southall *et al*. (2019) criteria in section 2.3.1, the Popper *et al*. (2014) criteria use the SPL_{peak} and SEL_{cum} notation, and this report will present the ISO 18405:2017 notation ($L_{p,pk}$ and $L_{E,p,t}$ respectively) for consistency.

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

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

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

Receptor	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	229 – 234 dB $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) Moderate (F) Low
Fish: swim bladder not involved in hearing	229 – 234 dB $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) Low (F) Low
Fish: swim bladder involved in hearing	229 – 234 dB $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low
Sea turtles	229 – 234 dB $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low
Eggs and larvae	> 13 mms^{-1} peak velocity	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low

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

Receptor	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder not involved in hearing	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder involved in hearing	(N) Low (I) Low (F) Low	170 dB $L_{p,48h}$	158 dB $L_{p,12h}$	(N) High (I) High (F) high	(N) High (I) Moderate (F) Low
Sea turtles	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) High (I) Moderate (F) Low
Eggs and larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) Moderate (I) Moderate (F) Low

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

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

2.3.3 Marine invertebrates

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

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

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

In its current state, research on the effects of anthropogenic noise on marine invertebrates is emerging, but more slowly than for marine mammals and fish. At this time, this research is in too early a stage to be used to accurately generate impact thresholds which would be satisfactory to regulators. The data available could potentially be referenced for some species but with caution, as there are still considerable gaps in the knowledge that would enable reliable conclusions for the impact of noise for most species.

2.4 EU regulations in marine mammals

ACP requested, in their Further Information Request (RFI 9a ii and 9l), consideration of underwater noise thresholds in use in other EU jurisdictions. As a result, this section details the current status of these thresholds, alongside the United Kingdom (UK).

2.4.1 Ireland

In Ireland, the National Parks and Wildlife Service (NPWS), as part of Department of the Arts, Heritage and the Gaeltacht (DAHG, now Department of Housing, Local Government and Heritage), published guidance to manage the risk that anthropogenic sound sources pose to marine mammals in Irish waters (DAHG, 2014). This guidance presents a staged process towards managing risk but **does not enforce any specific process nor state explicit dB limits** to restrict noise impacts. Although it states that TTS “may constitute an injury” as it could “have negative effects on the ability to use natural sounds”, this is not a universally accepted definition (Tougaard *et al*., 2025) and other countries do not consider these short-term effects an injury. However, it offers suggestions for mitigation that can be applied to projects, including pre-piling monitoring for marine mammals and a soft start and ramp up process. In section 4 of the guidance various management options for regulatory authorities to consider are detailed while approving any marine licences.

The recent publication of Ireland’s Marine Strategy Part 1, Assessment of the Marine Environment (Annex III), Department of Housing, Local Government and Heritage (DHLGH, 2025) also notes a threshold for Level of Onset of Biologically Significant Effect (LOBE) in reference to the Marine Strategy Framework Directive (MSFD) Descriptor 11 (Underwater Noise) of 176 dB SEL. This was the lowest reported sound level at which bottlenosed dolphins begin to experience temporary hearing loss when exposed to impulsive noise as presented in NMFS, (2018). Bottlenosed Dolphin was selected as a receptor organism for assessment of impulsive underwater noise since it is found throughout the Irish maritime area and is sensitive to mid-frequency sounds such as those generated by impulsive noise sources. It is important to note that the value of 176 dB SEL appears to have been selected erroneously: the results were derived from a table in NMFS (2018) that explicitly references continuous exposure to steady-state, non-impulsive, and therefore we do not recommend use of this threshold.

Additionally, the recent GOMOREUS study (Tougaard *et al.*, 2025), prepared for the Marine Institute, concludes with an overarching recommendation towards the Danish requirements (see section 2.4.2) or a modified single figure SEL threshold, similar to the German requirements (see section 2.4.3).

2.4.2 Denmark

The Danish Energy Agency (2023) has published guidelines for managing underwater noise during the installation of impact or vibratory driven piles. They include a required prognosis scenario section which asks the developer to consider noise reduction methodologies during a planned construction case. The developer may choose to use NAS or not but must show that the planned activity complies with the relevant PTS thresholds highlighted in section 2 of their guidance. These thresholds follow those presented in Southall *et al.* (2019). Thresholds are species-specific, covering the six species of marine mammal common to Danish waters (grey and harbour seal, minke whale, pilot whale, white beaked dolphin, harbour porpoise, all of which are also found in Irish waters), and were derived from Southall *et al.* (2019) and reviewed in Tougaard (2021). The guidelines specify that **a radial distance from the piling, r_{safe}, should be presented over which there should be no animals of these species, and therefore no risk of PTS within this distance (i.e., modelled PTS range < r_{safe})**, and which can be mitigated through the use of an ADD (unless r_{safe} is low, < 200 m). In effect, the Danish guidelines use the same marine mammal thresholds as in the UK (Southall *et al.*, 2019) but use them to set a requirement for a PTS range that must be fully mitigated.

It is worth noting that although the Further Information Request from ACP states in section 9 a ii that PTS ranges of 200 m should not be exceeded to be compliant with Danish guidance, this is not strictly the case. In effect, the guidance requires that there is sufficient attenuation to reduce the PTS range enough that this range is mitigatable with an ADD. Indicative maximum ranges suitable for ADD effectiveness are 1 km (minimum) for minke whale (McGarry *et al.*, 2017) and 7.5 km for harbour porpoise (Brandt *et al.,* 2013).

2.4.3 Germany

Germany's regulation authority, Bundesamt für Seeschifffahrt und Hydrographie (BSH), was the first to establish a legal dB limit of **160 dB re 1 µPa²s ($L_{E,p,ss}$) or 190 dB re 1 µPa ($L_{p,pk}$)** which must be complied with at a distance of 750 m from the pile installation location (Koschinski and Lüdemann, 2013; Müller and Zerbs, 2013). The criteria are derived from research into noise impacts on harbour porpoise (Lucke *et al.*, 2009). Since 2013, licences for pile driving are only granted if the anticipated piling noise is below this legal limit (Merchant and Robinson, 2020). These limitations have been adopted in marine licences for some projects in other jurisdictions, such as Taiwan, where potential Offshore Wind Farm (OWF) installations are a concern for the critically endangered Taiwanese white dolphin (*Sousa chinensis taiwanensis*; Liu *et al.*, 2018).

Merchant (2019) reviewed the German approach and concluded that it was the most effective noise management model available at the time. However, as pile sizes and hammer energies are increasing, the German sound limit is becoming increasingly more difficult to achieve and is not always met even with the deployment of multiple noise abatement systems (NAS) (Tetra Tech RPS Energy Limited and Seiche, 2024). The German requirements are also criticised in the GOMOREUS (Tougaard *et al.* 2025) study for the Marine Institute as not accounting for cumulative effects or any consideration of the sensitivity to noise of any species. They would also be much harder to meet in Ireland due to the deeper water, larger piles and hammers currently proposed, and the fact that the most common NAS utilised in German waters, bubble curtains, will not be suitable for many locations in Irish waters due to high currents.

2.4.4 Belgium

Within the European MSFD, underwater noise is addressed as a priority for implementation where it considers that 'good environmental status (GES) is achieved when introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment' (European Commission, 2017). To implement this, Belgium adopted an 'interim' criterion for impulsive noise of a 'maximum zero to peak noise level (L_{z-p}) (equivalent to $L_{p,pk}$ or SPL_{peak}) of **185 dB re 1 µPa at 750 m** from the source' (Anonymous, 2012a, as cited in Rumes *et al.*, 2016). It is understood that an $L_{E,p,ss}$ (SEL_{ss}) threshold of **162 dB re 1 µPa²s at 750 m** is also proposed alongside the $L_{z\text{-}p}$ limit. However, noise mitigation is only implemented if this noise limit is exceeded (Rumes *et al.*, 2016). Belgium also has seasonal piling restrictions where there is no piling from 1st January to 30th April to protect sensitive life-history periods for key species such as harbour porpoise and seals (Rumes *et al.*, 2016; Verfuss *et al.* 2016).

2.4.5 Netherlands

The Netherlands requires mitigation for piling and geophysical survey activities on a **case-by-case basis** (Anonymous, 2012b, as cited in Rumes *et al.*, 2016). An example presented in Rumes *et al.* (2016) showed that they set a noise restriction at Borssele OWF at 160 to 172 dB re 1 µPa²s at 750 m from the source. This project set up continuous noise monitoring and had a seasonal piling restriction between 1st January and 31st May to protect sensitive life-history periods for key species such as harbour porpoise and seals (Rumes *et al.*, 2016; Verfuss *et al.*, 2016).

There is no standard set of thresholds or criteria in the Netherlands.

2.4.6 United Kingdom

No decibel limit currently exists in the UK, although underwater noise may be one factor considered within the UK marine licensing system (Convention on Biological Diversity, 2016). The Department of Environment, Food and Rural Affairs (Defra) commissioned a feasibility assessment and pilot programme titled “A noise limit for offshore wind pile driving,” aimed at evaluating the feasibility of a introducing a decibel-based noise limit for offshore wind pile driving in English and Welsh waters (Tetra Tech RPS Energy Limited and Seiche, 2024). As part of the study, modelling was conducted to assess the effectiveness of NAS. The findings concluded that whilst the German limit (160 dB re 1 µPa²s $L_{E,p,ss}$ at 750 m) is technically achievable, it is situation dependent and not expected to be universally attainable for future projects in the UK, Germany and probably Ireland due to the increasing scale of new turbine designs. Therefore, a variable decibel limit would need to be applied to English and Welsh waters to allow developments to continue. It is also emphasised that a combination of NAS solutions is likely essential, especially for large, deep-water piles.

In January 2025, the Joint Nature Conservation Committee (JNCC), Natural England (NE) and the Centre for the Environment, Fisheries and Aquaculture Science (Cefas) published a joint position statement on the use of quieter piling methods and noise abatement systems when installing offshore wind turbine foundations (JNCC, 2025). This joint position statement states that the use of NAS or quieter installation methods is necessary to meet Test 2 of the European Protected Species (EPS) Licence application process, which requires applicants to demonstrate that there are no satisfactory alternatives.

Furthermore, the Marine Management Organisation (MMO) has published its policy paper “Reducing Marine Noise”, which outlines that developers are now expected to demonstrate best endeavours to reduce underwater noise. This includes the use of primary and/or secondary noise reduction measures, such as NAS (MMO, 2025).

2.4.7 Conclusion

Bearing in mind all of the details above, and in the absence of the revised underwater noise guidance for Ireland, it is considered that the Danish guidelines would be most appropriate and relevant to consider for the purpose of this assessment and in response to the Further Information Request from ACP, which requested consideration of defined thresholds in other European jurisdictions. While the German, Belgian and Dutch regulations are relatively straightforward to interpret, in that they use single-figure criteria to define a simple acceptable/unacceptable threshold, they are also based on older and limited studies focused on harbour porpoise (primarily Lucke *et al.*, 2009) that does not take into account the variety of species in Irish waters, their sensitivity to sound frequencies, cumulative exposures or the latest research on PTS, TTS and auditory injury in marine mammals. Such factors are, however, incorporated into the Danish guidance, which has the advantage of being easily updatable in the event that better data for PTS and TTS becomes available. The variable bathymetry around Ireland is also similar to the conditions around Denmark. As a result, the concepts and principles in this guidance are recommended for further consideration as part of this assessment and in response to the RFI. This is also discussed in the recommendations in the Irish GOMOREUS report (Tougaard *et al.*, 2025), which discusses the applicability and consequences of the various noise thresholds in use in the different jurisdictions. The GOMOREUS study primarily investigates the balance between the use of German (or German-logic) thresholds and the Danish guidance, but criticises the lack of species-specific thresholds and weightings in the German framework.

Additionally, the TTS threshold for LOBE in Ireland’s Marine Strategy Part 1 (2025) is not recommended and should be reviewed.

3 Modelling methodology

To estimate the underwater noise levels likely to arise during impact piling operations at ABWP2, 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).

The modelling of impact piling has been undertaken using the INSPIRE underwater noise model, which has been widely used for wind farm assessments around the UK and Ireland. The INSPIRE model (currently version 6.0) is a semi-empirical underwater noise propagation model based around a combination of numerical modelling, a combined geometric energy flow/hysteresis loss method, and actual measured data. It is designed to calculate the propagation of noise in shallow (i.e., generally around 100 m or less), mixed water, typical of the conditions around the UK and Ireland and well-suited for use in the Irish Sea.

INSPIRE provides estimates of unweighted $L_{p,pk}$, $L_{E,p,ss}$, $L_{p,RMS}$ and $L_{E,p,t}$ noise levels, as well as other weighted noise metrics. Calculations are made along 180 equally-spaced 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 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 for the location and nature of the piling operation. It should also be noted that the results should be considered conservative as maximum design parameters and worst-case assumptions have been selected for:

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

This report presents results for remodelling of the underwater noise impacts from the previous (2024) version of Appendix 11.1 using the most up to date model and piling design parameters. More details are provided in this section.

Simpler modelling approaches have been used for noise sources other than impact piling that may be presented during the construction and operation of ABWP2; these are discussed in section 5.

3.1 Modelling confidence

The INSPIRE model is semi-empirical, and as such validation is inherently built into the development process. Whenever a new set of reliable impact piling measurement data is gathered through offshore surveys, either by Subacoustech or a published by a third party, it is compared against the outputted levels from INSPIRE and, if necessary, the model can be adjusted.

Currently, 120 separate impact piling noise datasets, primarily from the North and Irish Seas, have been used as part of the development for the latest version of INSPIRE. For $L_{E,p}$, an average, or slightly above the average, fit to the data is used, meaning that for a given dataset some points in the measured dataset will be louder than the predicted level. When cumulative noise is considered this is necessary to reduce conservatism due to the variations in level for individual pile strikes, which can be as much as 5 to 10 dB (Bailey *et al*., 2010). Calculating a cumulative SEL ($L_{E,p,t}$) based on every pulse being worst case would lead to an excessive prediction. For $L_{p,pk}$ however, a slightly more conservative fit to the data has been used to reduce the chance of underestimation. Designing a model to over-predict for all parameters would ultimately lead to an excessively precautionary and unrealistic model.

INSPIRE is designed to predict trends when increasing parameters beyond empirical data, and uses the measured data combined with standard acoustic theory to predict the effect of greater blow energies, larger piles and deeper water on the noise levels produced and propagated through the water.

The largest pile diameter included in the analysis for development of INSPIRE v6.0 was 9.5 m in diameter, and the highest measured blow energy was 3,000 kJ. The model has been validated by comparing the noise levels outputted from the model with measurements and modelling undertaken by third parties, for example in Thompson *et al*. (2013) and Thompson *et al*. (2025). In Thompson *et al*. (2025), piles up to 10 m in diameter and blow energies up to 4,400 kJ were modelled using INSPIRE v5.2 in blind testing against measured data, and a good agreement was found in general, although INSPIRE was found to over-estimate the impact ranges in this earlier software version, especially closer to the pile (< 7 km) where the exposures to noise would have the greatest effect.

The version of INSPIRE used to remodel the impacts of underwater noise for ABWP2 (v6.0) in this report is the product of reanalysing all the impact piling noise in Subacoustech Environmental's measurement database, in preparation for the NMFS (2024) guidance, and cross-referencing it with blow energy data from piling logs, and relevant parameters such as pile diameter, length and water depth. This gives a database of single strike noise levels referenced to a specific blow energy at a specific range and environmental conditions, primarily water depth.

Figure 3-1 and Figure 3-3 present a small selection of the measured impact piling noise data plotted against outputs from INSPIRE. The plots show data points from measured data (in blue) plotted alongside modelled data (in orange) from INSPIRE, matching the pile size, blow energy and position of the measured data. These show the fit to the data, with the modelled INSPIRE data points placed, more or less, in the middle (or slightly above, in the case of $L_{p,pk}$) of the measured noise levels at each range (this can also be seen in Figure 3-2 and Figure 3-4). When combined with the precautionary assumptions in parameter selection, modelled results will remain precautionary. The greatest deviations from the model tend to be at the greatest distances (> 10 km), where INSPIRE appears over-precautionary in many cases, but due to the lower relative levels the influence on the overall $L_{E,p,t}$ exposure will be small.

Statistical analysis has been carried out to compare measured and modelled data to show the confidence present in INSPIRE v6.0. Figure 3-2 and Figure 3-4 show the distribution of the predicted levels against measured data with R^2 values of 0.81 for unweighted $L_{p,pk}$ and 0.89 for unweighted $L_{E,p,ss}$.

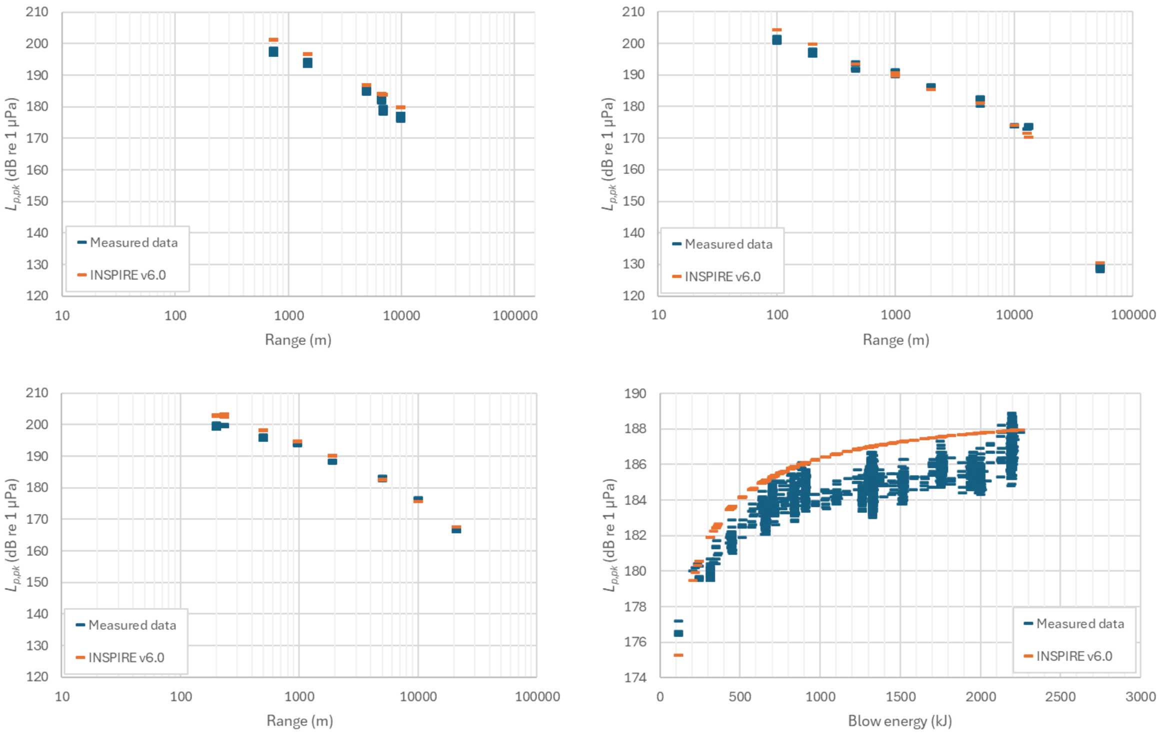

Figure 3-1: Comparison between example measured $L_{p,pk}$ impact piling data (blue) and modelled data using INSPIRE v6.0 (orange)[1].

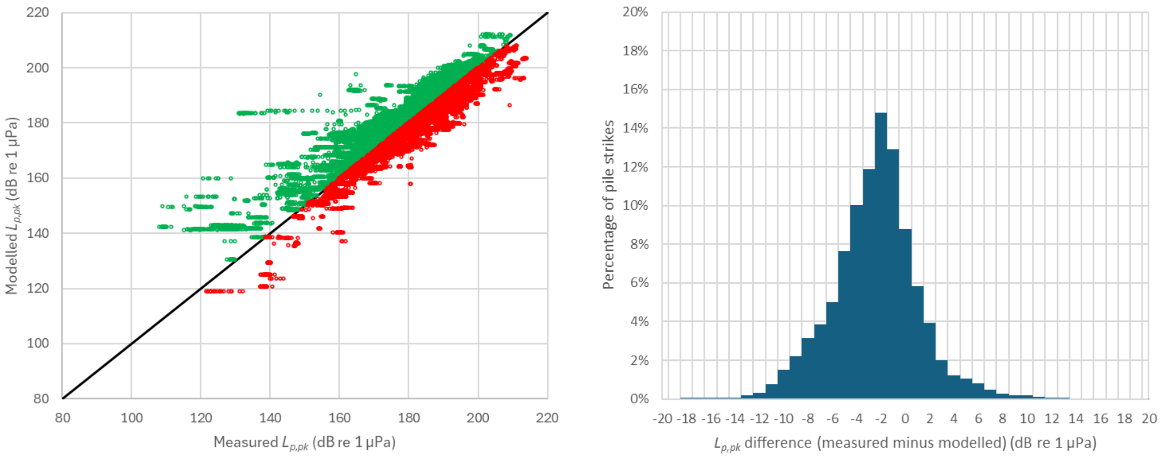

Figure 3-2: Distribution of measured impact piling data against modelled levels using INSPIRE v6.0 for unweighted $L_{p,pk}$ ($R^2 = 0.81$).

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[1] Top left: 8.6 m diameter pile, 2,500 kJ max hammer energy, North Sea, 2024; Top right: 6.0 m diameter pile, 890 kJ max hammer energy, Irish Sea, 2010; Bottom left: 6.0 m diameter pile, 1,010 kJ max hammer energy, Suffolk Coast, 2009; Bottom right: 8.6 m diameter pile, 3.0 km range, 2,250 kJ max hammer energy, North Sea, 2024.

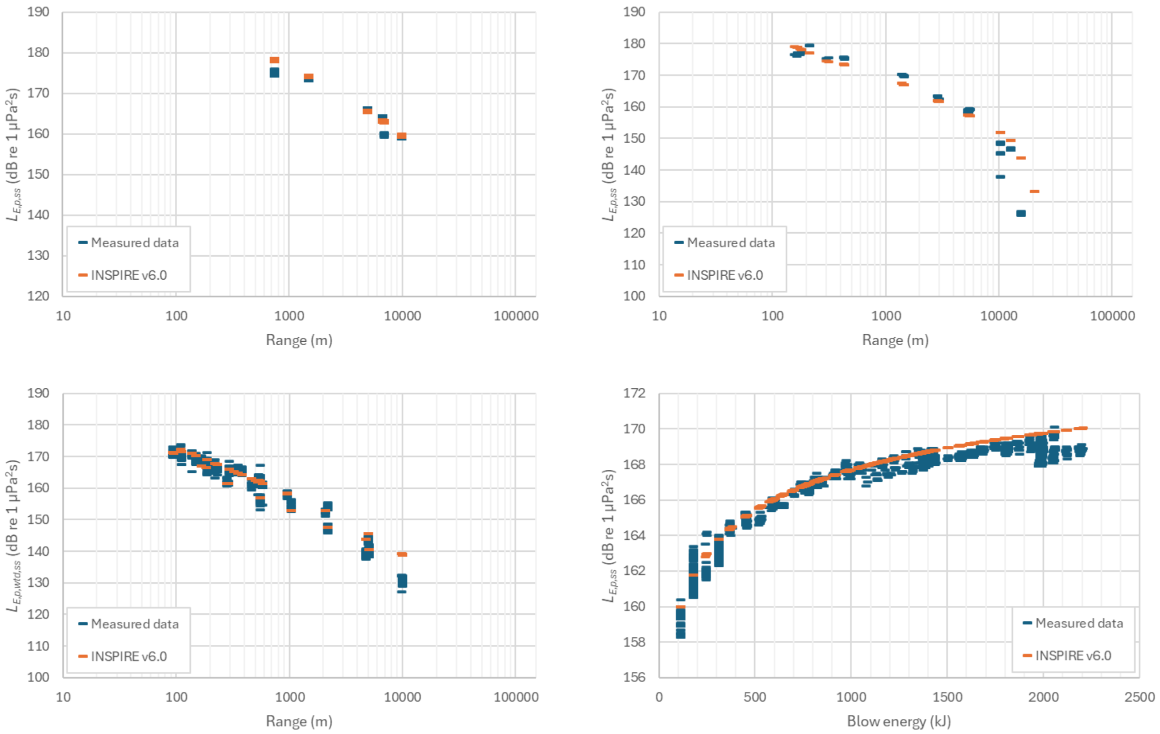

Figure 3-3: Comparison between example measured $L_{E,p,ss}$, impact piling data (blue) and modelled data using INSPIRE v6.0 (orange)[2].

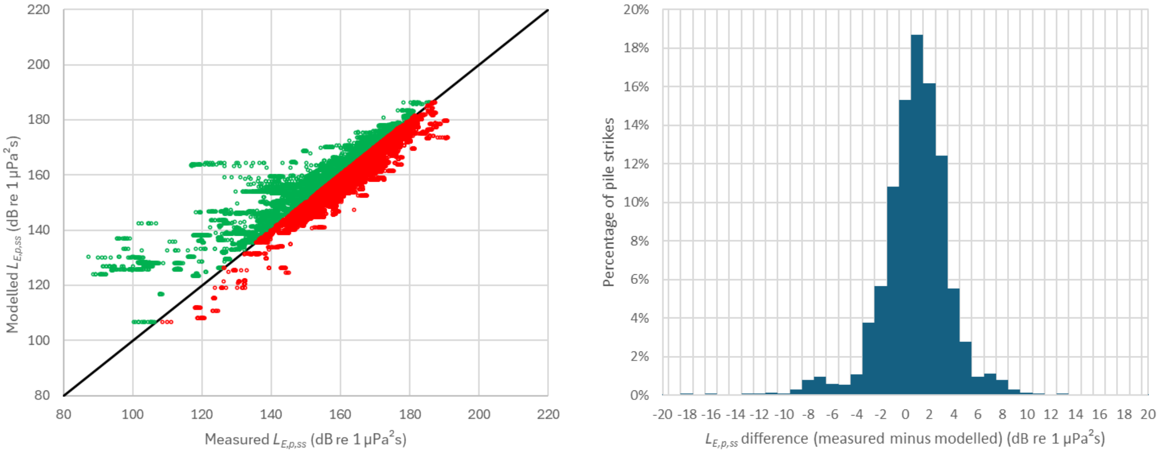

Figure 3-4: Distribution of measured impact piling data against modelled levels using INSPIRE v6.0 for unweighted $L_{E,p,ss}$ ($R^2 = 0.89$).

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[2] Top left: 8.6 m diameter pile, 2,500 kJ max hammer energy, North Sea, 2024; Top right: 4.7 m diameter pile, 1,340 kJ max hammer energy, North Wales Coast, 2012; Bottom left: 1.4 m diameter pile, 620 kJ max hammer energy, Lincolnshire Coast, 2011; Bottom right: 8.6 m diameter pile, 2.1 km range, 2,200 kJ max hammer energy, North Sea, 2024.

Additional validation has been undertaken using data presented by von Pein *et al*. (2022), which studied trends in noise level with changes in piling parameters using data primarily acquired in the North Sea and Baltic Sea. The data showed a strong correlation with blow energy, and a lower correlation with pile diameter, which Subacoustech agrees with, although the calculated correlation based on that data appears to have overestimated the trend. Figure 3-5 and Figure 3-6 are adapted from von Pein *et al*. (2022), replicating their results and overlaying with measured data from Subacoustech's measurement database (selecting samples taken at the same reference distance) and results at equivalent datapoints using INSPIRE v6.0.

This shows a very good agreement with Subacoustech's data (relating to blow energy). It should be noted that the upper and lower bounds for a correlation of noise level with pile diameter, based on the von Pein *et al*. (2022) data alone, could easily be close to horizontal; there is also no control for blow energy within the dataset, which is not constant. With the inclusion of Subacoustech's data, there is little correlation at greater pile diameters, and it can be seen that the variations at a single pile diameter are largely controlled by changes in blow energy.

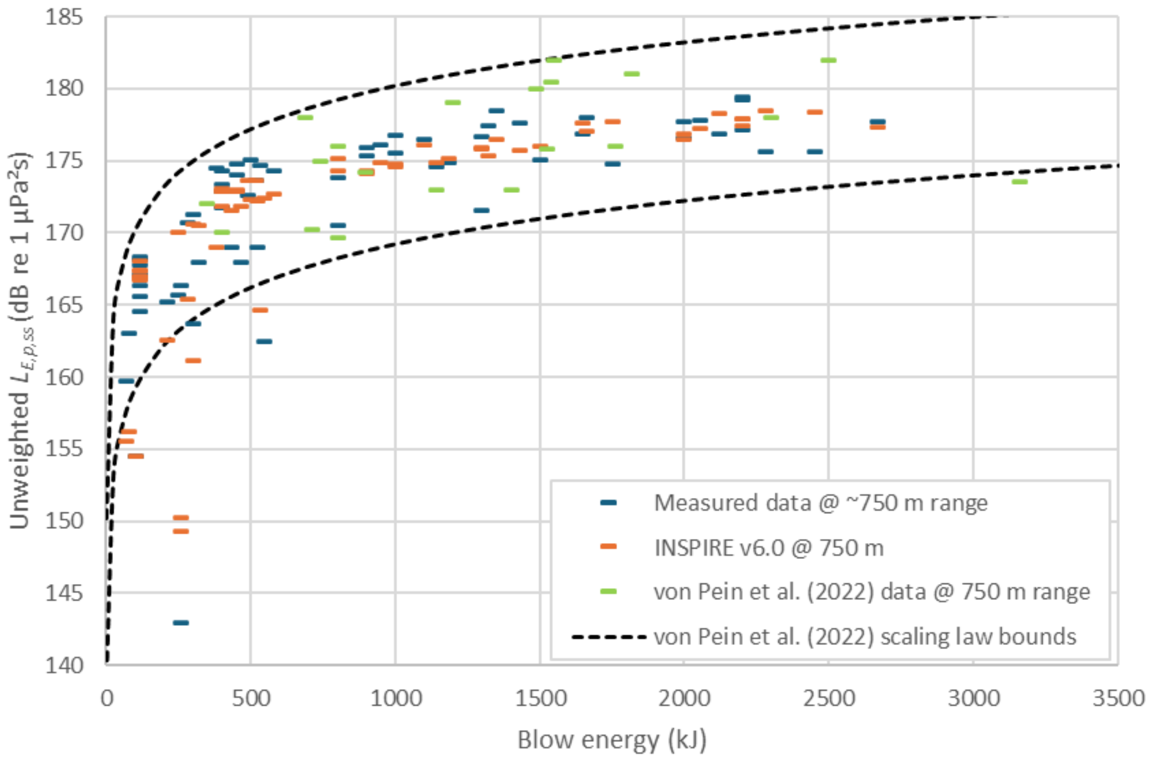

Figure 3-5: Data relating blow energy to noise level ($L_{E,p,ss}$) adapted from von Pein et al. (2022) (green) overlaid with Subacoustech measured data (blue) and INSPIRE v6.0 predictions (orange). Upper and lower scaling law bounds from von Pein (2022).

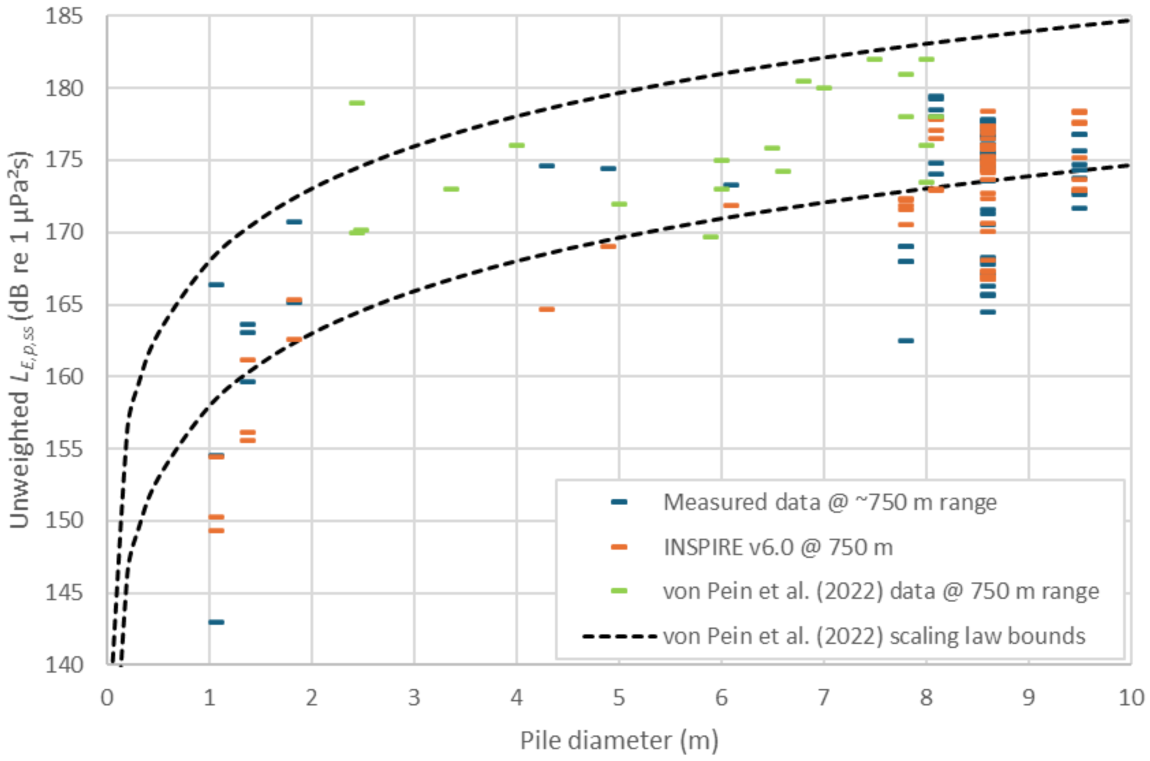

Figure 3-6: Data relating pile diameter to noise level ($L_{E,p,ss}$) adapted from von Pein (2022) (green) overlaid with Subacoustech measured data (blue) and INSPIRE v6.0 predictions (orange). Upper and lower scaling law bounds from von Pein (2022).

3.2 Input parameters

3.2.1 Modelling locations

Modelling for impact piling noise to install foundations for WTG and OSP foundations has been undertaken at five representative locations covering the extents of ABWP2, giving a spread of water depths, distances to shore, and bathymetry. Monopile foundations have been considered at three locations for WTG foundations and two locations for OSP foundations. These locations are summarised in Table 3-1 and illustrated in Figure 3-7, and have been selected from the Design Option 1 layout (53 WTG option).

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

Modelling locations	Latitude	Longitude	Water depth
North location (WT03)	52.91484°N	005.91770°W	26.2 m
Central location (WT28)	52.80250°N	005.93113°W	30.7 m
South west location (WT53)	52.68030°N	005.99125°W	26.4 m
North OSP location	52.90693°N	005.92530°W	22.0 m
South OSP location	52.68627°N	005.98945°W	21.1 m

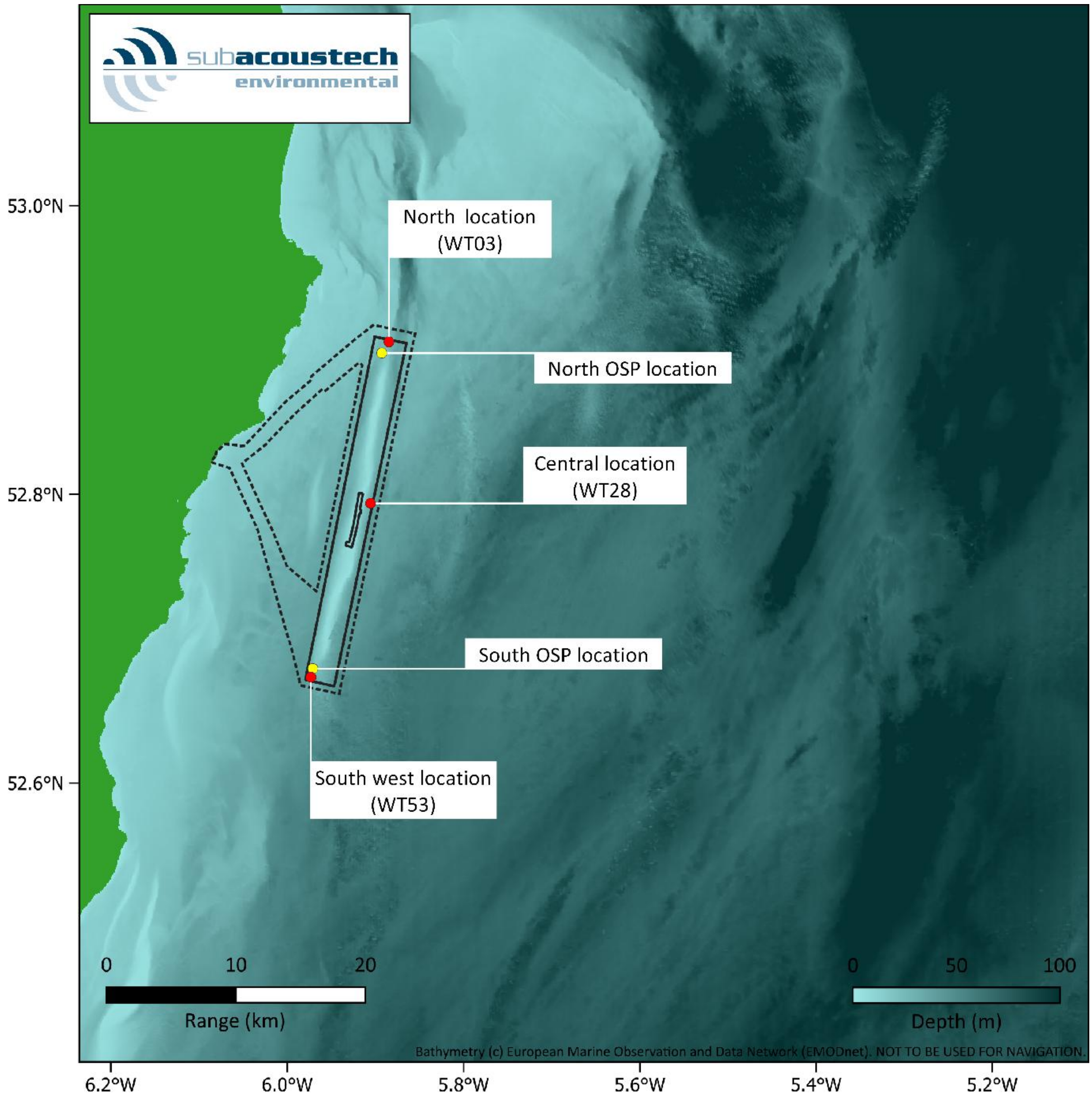

Figure 3-7: Approximate positions of the WTG and OSP modelling locations used at ABWP2.

3.2.2 Environmental conditions

With the inclusion of measured noise propagation data for similar offshore piling operations in UK and Irish 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 throughout the day or year, as well as the sediment type in and around the site. Data from the British Geological Survey (BGS) show that the seabed in and around ABWP2 is made up of various combinations of sand and gravel over a bedrock of mudstone and sandstone.

Digital bathymetry from the European Marine Observation and Data Network (EMODnet, 2024) has been used for this modelling.

3.2.3 Impact piling parameters

Four piling scenarios have been considered for this study, based on two monopile designs. The largest diameter piles were chosen, smaller monopiles would have lower noise impacts.

- 11 m diameter monopiles for WTG foundations, installed with a maximum blow energy of 3,500 kJ;
- 14 m diameter monopiles for OSP foundations, installed with a maximum blow energy of 3,500 kJ.

In each case, two ramp-up scenarios have been modelled for these foundations, a Precautionary scenario using the largest piling energies and parameters likely to lead to the maximum impact ranges, and an Alternative scenario utilising lower energies for longer periods and slower strike rates. This Alternative scenario is designed to reduce $L_{E,p,t}$ impacts without the need for physical mitigation (section 3.2.4), to represent a more gradual, realistic ramp-up that is more likely to occur on site.

For $\mathrm{L}_{\mathrm{E,p,t}}$ criteria, the soft start and ramp-up of blow energies, along with the total duration of piling and strike rate, must be considered. The assumptions used for this study are summarised in Table 3-2 to Table 3-5 for the WTG and OSP foundation scenarios. Each piling scenario considers a single monopile being installed in a 24-hour period, and the only difference between the WTG and OSP scenarios is the pile diameter.

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

WTG foundation (11 m diameter)	825 kJ		1,550 kJ	2,275 kJ	3,500 kJ
No of strikes	12	600	400	400	4,600
Duration (s)	1,200	1,200	800	800	9,200
Strike rate (bl/min)	0.6	30	30	30	30
6,012 strikes over 3 hours 40 minutes per pile					

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

Alternative WTG foundation (11 m diameter)	400 kJ		800 kJ	1,550 kJ	2,275 kJ	3,500 kJ
No of strikes	18	450	600	600	600	3,600
Duration (s)	1,800	1,800	1,200	1,200	1,200	7,200
Strike rate (bl/min)	0.6	15	30	30	30	30
5,868 strikes over 4 hours per pile						

Table 3-4: Summary of the soft start and ramp-up used for the Precautionary OSP foundation monopile scenario.

OSP foundation (14 m diameter)	825 kJ		1,550 kJ	2,275 kJ	3,500 kJ
No of strikes	12	600	400	400	4,600
Duration (s)	1,200	1,200	800	800	9,200
Strike rate (bl/min)	0.6	30	30	30	30
6,012 strikes over 3 hours 40 minutes per pile					

Table 3-5: Summary of the soft start and ramp-up used for the Alternative OSP foundation monopile scenario.

Alternative OSP foundation (14 m diameter)	400 kJ		800 kJ	1,550 kJ	2,275 kJ	3,500 kJ
No of strikes	18	450	600	600	600	3,600
Duration (s)	1,800	1,800	1,200	1,200	1,200	7,200
Strike rate (bl/min)	0.6	15	30	30	30	30
5,868 strikes over 4 hours per pile						

3.2.4 Mitigation

The effect of noise abatement systems (NAS) as mitigation for impact piling noise has also been investigated at ABWP2. For both the Precautionary WTG and OSP monopile foundation scenarios detailed in Table 3-2 and Table 3-4, an at-source reduction of 4 dB has been included alongside the unabated scenarios, representing the noise reduction from using a low-noise hammer.

No NAS has been considered for the Alternative ramp-up scenarios, as the ramp-up was designed to reduce impact ranges caused by the noise exposure.

3.2.5 Apparent source levels

Noise modelling requires knowledge of a source level, which is the theoretical noise level at one metre from the noise source. It is worth noting that the 'source level' technically does not exist in the context of many shallow water (around 100 m or less) noise sources (Heaney *et al*., 2020). The actual noise level one metre from the pile will be highly complex and vary up and down the water column by the pile, which is a long, extended noise source, rather than being one simple noise level. In practice, for underwater noise modelling such as this, it is effectively an 'apparent source level' that is used, essentially a value that can be used to produce correct noise levels at range (for a specific model), as required in impact assessments.

The INSPIRE model requires an apparent source level, which is estimated based on the pile diameter and the blow energy imparted on the pile by the hammer. This is adjusted depending on the water depth at the modelling location to allow for the length of the pile (and effective surface area) in contact with the water, which can affect the amount of noise that is transmitted from the pile into its surroundings. The unweighted and unmitigated single strike $L_{p,pk}$ and $L_{E,p,ss}$ apparent source levels estimated for this study are provided in Table 3-6 and Table 3-7 for the maximum hammer energy and first pile strike hammer energy respectively, with no mitigation considered. Both WTG foundation scenarios have the same maximum hammer energy.

These figures are presented in accordance with requests commonly made by regulatory authorities, although as indicated above, they are not necessarily compatible with any other model or predicted apparent source level. Due to the similar water depths at each modelling location, the differences in apparent source level are minimal.

Table 3-6: Summary of the unweighted and unmitigated apparent source levels used for modelling at maximum hammer energy.

Apparent source levels	Modelling location	$L_{p,pk}$ @ 1 m	$L_{E,p,ss}$ @ 1 m
WTG foundation (11 m diameter pile / 3,500 kJ maximum energy)	North location (WT03)	246.8 dB re 1 µPa	218.9 dB re 1 µPa²s
	Central location (WT28)	246.8 dB re 1 µPa	219.0 dB re 1 µPa²s
	South west location (WT53)	246.8 dB re 1 µPa	218.9 dB re 1 µPa²s
OSP foundation (14 m diameter pile / 3,500 kJ maximum energy)	North OSP location	246.9 dB re 1 µPa	219.1 dB re 1 µPa²s
	South OSP location	246.9 dB re 1 µPa	219.1 dB re 1 µPa²s

Table 3-7: Summary of the unweighted and unmitigated apparent source levels used for modelling of the first pile strike.

Apparent source levels	Modelling location	$L_{p,pk}$ @ 1 m	$L_{E,p,ss}$ @ 1 m
WTG foundation (11 m diameter pile / 825 kJ energy)	North location (WT03)	244.1 dB re 1 µPa	214.7 dB re 1 µPa^{2}s
	Central location (WT28)	244.2 dB re 1 µPa	214.8 dB re 1 µPa^{2}s
	South west location (WT53)	244.1 dB re 1 µPa	214.7 dB re 1 µPa^{2}s
Alternative WTG ramp-up (11 m diameter pile / 400 kJ energy)	North location (WT03)	241.4 dB re 1 µPa	212.3 dB re 1 µPa^{2}s
	Central location (WT28)	241.4 dB re 1 µPa	212.3 dB re 1 µPa^{2}s
	South west location (WT53)	241.4 dB re 1 µPa	212.3 dB re 1 µPa^{2}s
OSP foundation (14 m diameter pile / 825 kJ energy)	North OSP location	244.3 dB re 1 µPa	214.9 dB re 1 µPa^{2}s
	South OSP location	244.3 dB re 1 µPa	214.9 dB re 1 µPa^{2}s
Alternative OSS ramp-up (14 m diameter pile / 400 kJ energy)	North OSP location	241.5 dB re 1 µPa	212.5 dB re 1 µPa^{2}s
	South OSP location	241.5 dB re 1 µPa	212.5 dB re 1 µPa^{2}s

3.2.6 Predicted noise levels at 750 m from the noise source

In addition to the apparent source levels, it is useful to look at the potential noise levels at a range of 750 m from the noise source, which is a common feature of underwater noise studies where the primary consideration is impact piling.

These levels have the added advantage of being comparable with other modelling or measurements (as a valid measurement can be taken at this range; for example, von Pein *et al.*, 2022), where the source level (or apparent source level) may not. A summary of the modelled unweighted levels at a range of 750 m are given in Table 3-8 and Table 3-9, considering the transect with the greatest noise transmission at each location while piling at the maximum hammer energy and the hammer energy at first pile strike with no mitigation considered.

Table 3-8: Summary of the unweighted and unmitigated $L_{p,pk}$ and $L_{E,p,ss}$ (single strike) noise levels at a range of 750 m from the noise source when considering the maximum hammer energy.

Predicted levels	Modelling location	$L_{p,pk}$ @ 750 m	$L_{E,p,ss}$ @ 750 m
WTG foundation (11 m diameter pile / 3,500 kJ maximum energy)	North location (WT03)	200.2 dB re 1 µPa	178.8 dB re 1 µPa^{2}s
	Central location (WT28)	201.3 dB re 1 µPa	179.4 dB re 1 µPa^{2}s
	South west location (WT53)	200.2 dB re 1 µPa	178.8 dB re 1 µPa^{2}s
OSP foundation (14 m diameter pile / 3,500 kJ maximum energy)	North OSP location	199.2 dB re 1 µPa	178.4 dB re 1 µPa^{2}s
	South OSP location	197.2 dB re 1 µPa	177.0 dB re 1 µPa^{2}s

Table 3-9: Summary of the unweighted and unmitigated $L_{p,pk}$ and $L_{E,p,ss}$ (single strike) noise levels at a range of 750 m from the noise source when considering the hammer blow energy at the first pile strike.

Predicted levels	Modelling location	$L_{p,pk}$ @ 750 m	$L_{E,p,ss}$ @ 750 m
WTG foundation (11 m diameter pile / 825 kJ energy)	North location (WT03)	197.5 dB re 1 µPa	174.6 dB re 1 µPa^{2}s
	Central location (WT28)	198.6 dB re 1 µPa	175.2 dB re 1 µPa^{2}s
	South west location (WT53)	197.6 dB re 1 µPa	174.6 dB re 1 µPa^{2}s
Alternative WTG ramp-up (11 m diameter pile / 400 kJ energy)	North location (WT03)	194.8 dB re 1 µPa	172.2 dB re 1 µPa^{2}s
	Central location (WT28)	195.9 dB re 1 µPa	172.7 dB re 1 µPa^{2}s
	South west location (WT53)	194.8 dB re 1 µPa	172.2 dB re 1 µPa^{2}s
OSP foundation (14 m diameter pile / 825 kJ energy)	North OSP location	196.6 dB re 1 µPa	174.2 dB re 1 µPa^{2}s
	South OSP location	194.5 dB re 1 µPa	172.8 dB re 1 µPa^{2}s
Alternative WTG ramp-up (11 m diameter pile / 400 kJ energy)	North OSP location	193.8 dB re 1 µPa	171.8 dB re 1 µPa^{2}s
	South OSP location	191.8 dB re 1 µPa	170.4 dB re 1 µPa^{2}s

3.2.7 Predicted noise levels against range

Figure 3-8 has been provided in order to show the modelled noise transmission, which can be used as a basis to compare and validate the levels against future noise monitoring. This plot presents the predicted unweighted $L_{p,pk}$ and $L_{E,p,ss}$ noise levels against range over the longest calculated transect (130°; SE) from the Central (WT28) modelling location during installation of a WTG foundation monopile using the maximum hammer energy (3,500 kJ). It should not be assumed necessarily comparable to any other transect or blow energy, although it is expected to present a precautionary scenario.

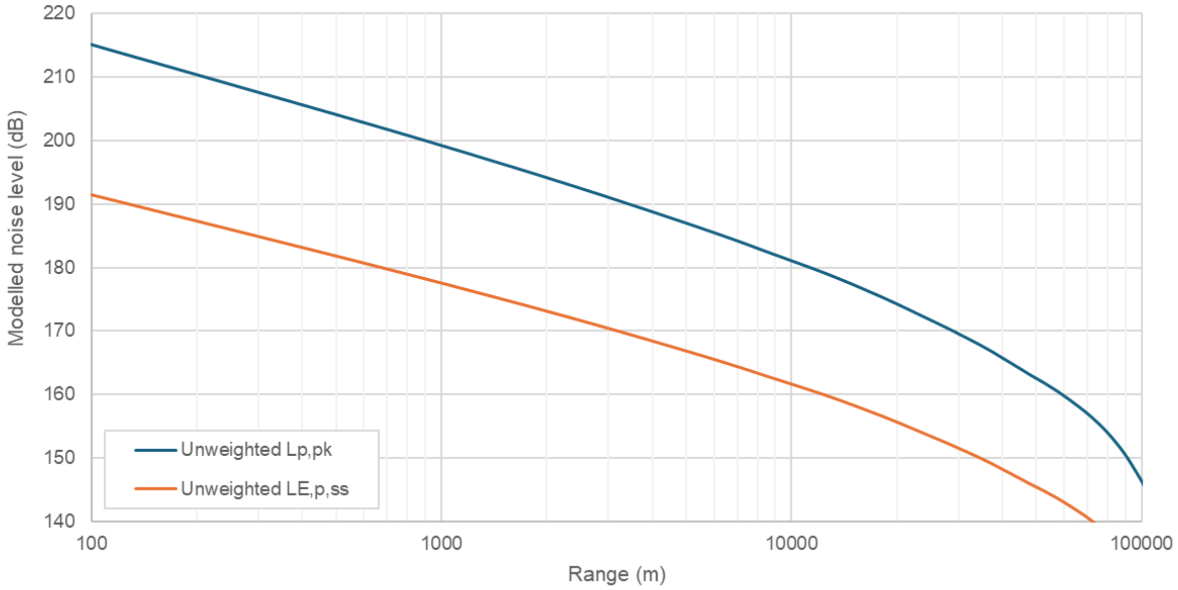

Figure 3-8: Modelled unweighted $L_{p,pk}$ and $L_{E,p,ss}$ noise levels with range for the monopile scenario assuming maximum blow energy along a SE transect (130°) from the Central (WT28) modelling location.

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

Expanding on the information in section 2.3 regarding $L_{E,p,t}$ and the fleeing animal assumptions used for modelling, this section lays out the methodology behind calculating these results to aid with interpretation.

When an $L_{E,p,t}$ impact range is presented for a fleeing animal, this range can be considered a starting position (at the commencement of piling) for the fleeing receptor. For example, if a receptor began to flee in a straight line from the noise source, starting at the position (distance from a pile) denoted by a modelled PTS contour, the receptor would receive exactly the noise exposure as per the PTS onset criterion under consideration (see Figure 3-11).

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

For a fleeing model, the varying distance from the noise source relative to the receptor is considered. To model this, a nominal starting point close to the source is chosen and the received noise level for each noise event (e.g., pile strike) is noted; the receptor moves away from the source at a defined speed through the piling operation. For example, if a noise (i.e., a pulse from a pile strike) occurs every six seconds, and an animal is fleeing at a rate of 1.5 ms^{-1}, it is 9 m further from the noise source after each noise pulse, resulting in a slightly reduced noise level each time. These values are then aggregated into a $L_{E,p,t}$ value over the entire operation. The faster an animal is fleeing, the greater the distance travelled between noise events. The impact range outputted by the model for this represents the location the receptor must be at the start of the operation to exactly meet the exposure threshold.

As an example, the graphs in Figure 3-9 and Figure 3-10 show the difference in the received $L_{E,p,ss}$ and $L_{E,p,t}$ from a stationary receptor and a fleeing receptor travelling at a constant speed of 1.5 ms^{-1} using the transect with the largest transmission (130°) for the worst-case WTG foundation installation at the Central (WT28) modelling location.

The received single strike $L_{E,p,ss}$ from the stationary receptor, as illustrated in Figure 3-9, shows the noise levels rising as the blow energy increases throughout the monopile installation. These step changes are also visible for the fleeing receptor, but as the fleeing receptor is further from the noise source by the time the levels increase, the total received exposure reduces, resulting in lower cumulative levels. As an example, for the first 20 minutes of piling, where the blow energy is 825 kJ, a receptor fleeing at a rate of 1.5 ms^{-1} has the potential to move 1.8 km away from the noise source. After the full installation of 3 hours and 40 minutes, a receptor has the potential to be almost 20 km from the noise source.

Figure 3-10 shows the effect that these differing single strike received levels have when calculating the $L_{E,p,t}$, clearly showing the difference in the cumulative levels between a receptor remaining still as opposed to fleeing. To use an extreme example, starting at a range of 1 m, the first strike results in a received level of 214.8 dB re 1 µPa²s. If the receptor were to remain stationary for the entire piling operation it would receive a cumulative noise exposure of 256.3 dB re 1 µPa²s, whereas when a receptor flees at a constant speed of 1.5 ms^{-1} over the same scenario, the cumulative received exposure is calculated to be just 214.9 dB re 1 µPa²s, only slightly higher than the first pile strike alone.

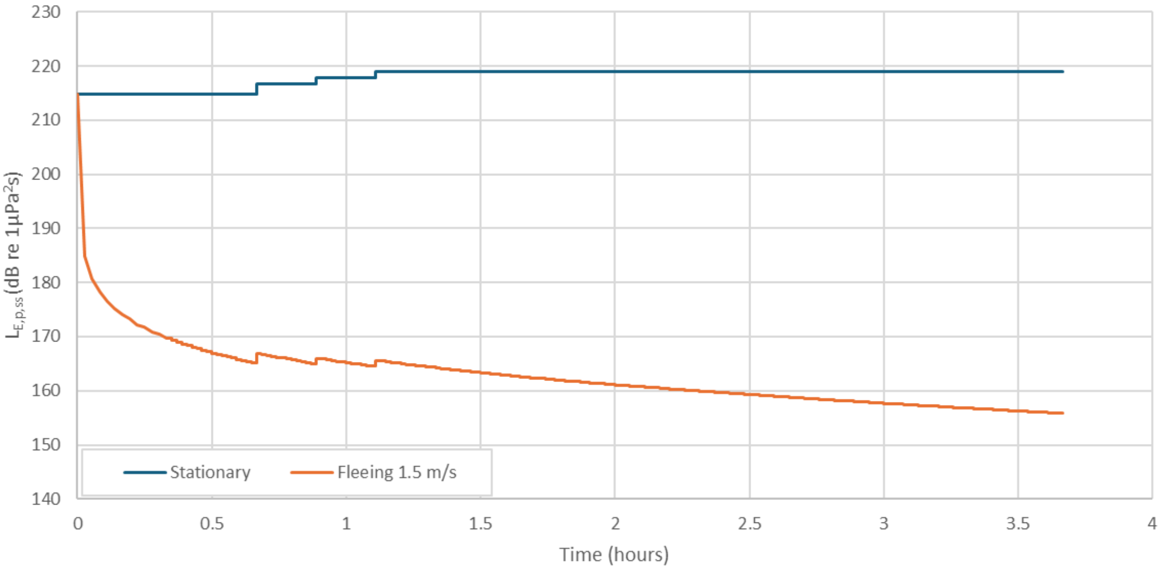

Figure 3-9: Received single strike noise levels ($L_{E,p,ss}$) for receptors during the worst-case WTG foundation installation at the Central (WT28) modelling location, assuming both stationary and fleeing receptors starting at a location 1 m from the noise source.

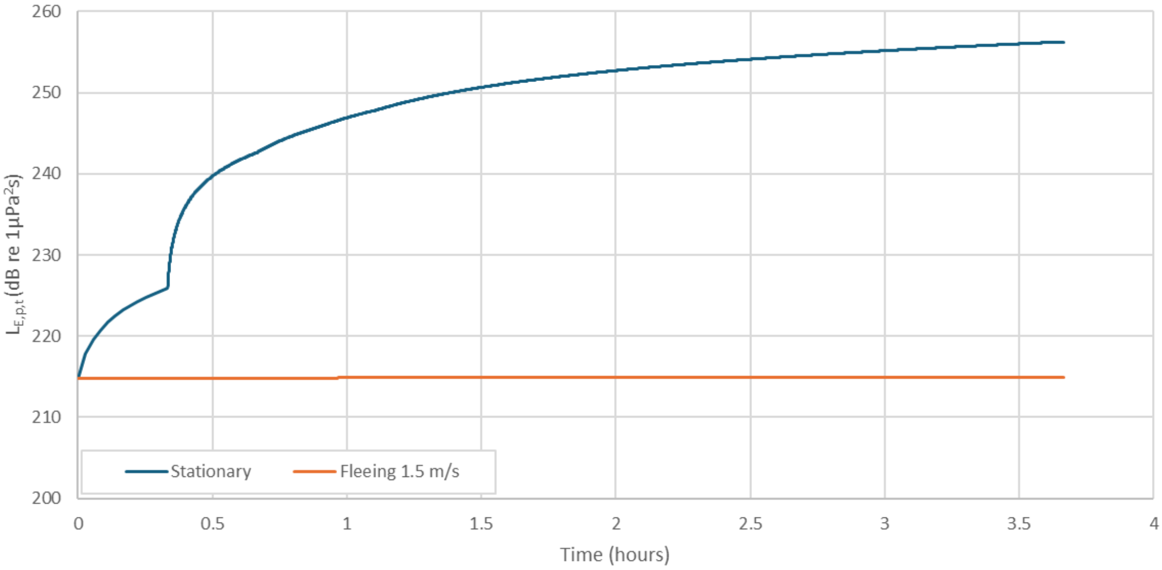

Figure 3-10: Cumulative received noise level ($L_{E,p,t}$) for receptors during the worst-case WTG foundation installation at the Central (WT28) modelling location, assuming both stationary and fleeing receptors starting at a location 1 m from the noise source.

To summarise, if a receptor were to start fleeing in a straight line away from the noise source starting at a range closer than the modelled impact range, it would receive a noise exposure in excess of the criterion, and if the receptor were to start fleeing from a range further than the modelled value, it would receive a noise exposure below the criterion. This is illustrated in Figure 3-11.

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. This is not recommended for inclusion in modelling, as there are many ADDs with different performances and species-specific reactions and effectiveness, and instead the efficacy requirement from an ADD can 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 ms^{-1}, it would travel 1.8 km before piling begins. If a calculated cumulative $L_{E,p,t}$ impact range was below 1.8 km, it can be assumed that the ADD will be effective in eliminating the risk of exceedance of the threshold. The noise from an ADD is of a much lower level than impact piling, and as such its overall effect on the total $L_{E,p,t}$ exposure would be minimal.

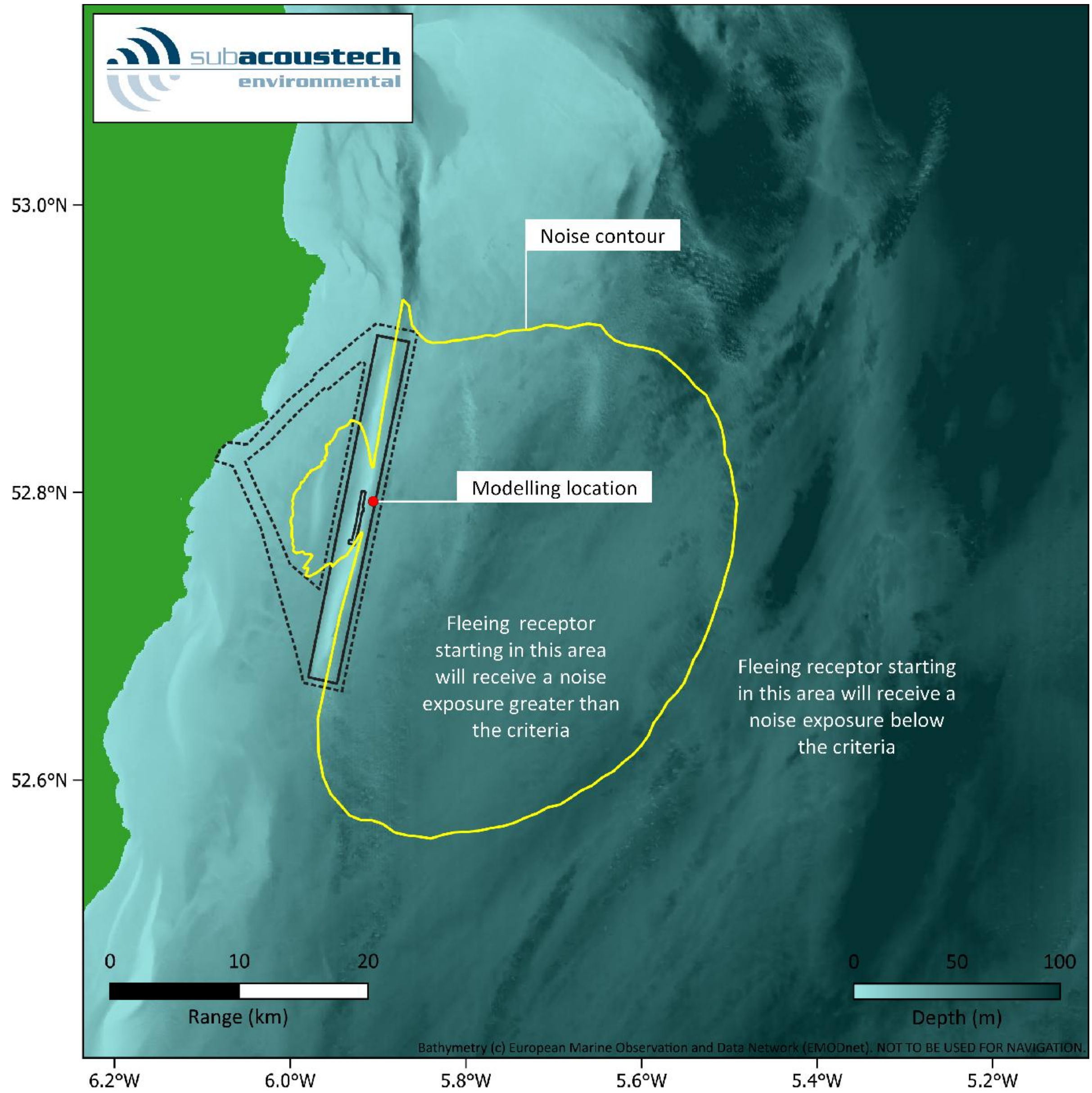

Figure 3-11: Example plot showing a fleeing animal $L_{E,p,t}$ criteria contour and the areas where the cumulative noise exposure will exceed a given impact.

3.3.1 The effect of parameters on cumulative levels and fleeing receptors

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

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

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

In general, the greatest contribution to the received exposure is found when a receptor is close to the noise source. If high blow energies or a fast strike rate are implemented at or close to the start of piling activities, it will tend to make impact ranges worse. This was one of the main considerations when creating the alternative ramp-up scenario in Table 3-3.

Another factor that can cause big differences in calculated impact ranges is the bathymetry, as deeper water results in less attenuation of noise (i.e., levels remain higher over greater distances). However, it is not feasible to limit piling activity in or near to deep water at ABWP2. This effect can be seen clearly in the example in Figure 3-11.

3.4 Precaution in underwater noise modelling

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

3.4.1 Source

The modelling locations were chosen to provide the greatest extents of the site, and specifically the locations likely to lead to underwater noise transmission over the greatest distances. The largest diameter for all types of pile has been used for the modelling scenarios. The maximum blow energies were used for a duration unlikely to occur in practice. The total piling duration is at the top of expectations and not expected to be exceeded on site.

3.4.2 Transmission path

Sound attenuates over distance from the source. The model considers fundamental noise spreading predictions adjusted to empirical data, accounting for frequency content, water depth, and other environmental factors, but fits to this data can still overestimate predicted levels (see section 3.1).

3.4.3 Receiver

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

Concerning the flee speeds used in the modelling, studies have shown that these are typical swimming speeds (Williams, 2009), however flee speeds would be expected to be much faster during high noise conditions (McGarry *et al*., 2017; Kastelein *et al*., 2018). Using a faster flee speed would lead to much smaller cumulative impact ranges and consequently fewer impacted individuals.

The risk of PTS will not remain constant throughout an entire modelled PTS area either, although the model cannot account for this. The further away from the noise source the lower the risk will be, and thus at the PTS contour, this is effectively the position of onset of the risk of PTS.

Modelling does not include any assessment of impulsiveness, as criteria do not yet exist to specify a transition (Matei *et al.*, 2024). This means that any injury (or PTS) or TTS onset thresholds beyond a distance of the order of 3.5 km to 5 km (Hastie *et al.*, 2019, Matei *et al*., 2024) are likely to over-estimate the risk to marine mammals, especially at greater distances.

All of these elements are not acting in isolation but will combine (i.e., at the greatest ranges there is a low risk of PTS, and reduced impulsivity, and are unlikely due to the slower-than-expected swim speeds), and contribute to the significant degree of precaution in the assessment.

4 Modelling results

This section presents the modelled results from impact piling noise to install monopile foundations at ABWP2 following the parameters detailed in section 3.2. The calculated impact ranges and areas cover the Southall *et al*. (2019) marine mammal criteria (section 2.3.1) and Popper *et al*. (2014) fish criteria (section 2.3.2). For completeness, Table 4-1 gives a list of the results tables presented in sections 4.1 and 4.2. The largest modelled ranges from impact piling at ABWP2 are predicted at the Central (WT28) location due to the deeper water at that location as well as proximity to the deeper water in the Irish Sea to the east of that location. The modelling results for the first pile strike and the Southall *et al*. (2019) non-impulsive criteria are presented in Appendix A.

Throughout this report, any predicted ranges smaller than 50 m have not been presented in detail. At ranges this close to the noise source, the modelling processes are unable to model to a sufficient level of accuracy due to complex acoustic effects present near the source. These ranges are given as “less than” this limit (e.g., < 50 m). Similarly, areas smaller than 0.01 km^2 have not been presented.

Table 4-1: List of the impact piling modelling results presented in this section.

Table (page)	Scenario	Location	Criteria	
Table 4-2 (p34)	WTG foundations (Precautionary) (4.1)	North location (WT03) (4.1.1)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)
Table 4-3 (p34)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)
Table 4-4 (p34)			NOAA (2005)	Unweighted $L_{p,RMS}$ (Level B)
Table 4-5 (p34)			Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)
Table 4-6 (p35)				Unweighted $L_{E,p,24h}$ (Pile driving)
Table 4-7 (p35)		Central location (WT28) (4.1.2)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)
Table 4-8 (p35)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)
Table 4-9 (p35)			NOAA (2005)	Unweighted $L_{p,RMS}$ (Level B)
Table 4-10 (p36)			Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)
Table 4-11 (p36)				Unweighted $L_{E,p,24h}$ (Pile driving)
Table 4-12 (p36)		South west location (WT53) (4.1.3)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)
Table 4-13 (p36)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)
Table 4-14 (p37)			NOAA (2005)	Unweighted $L_{p,RMS}$ (Level B)
Table 4-15 (p37)			Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)
Table 4-16 (p37)				Unweighted $L_{E,p,24h}$ (Pile driving)
Table 4-17 (p37)	WTG foundations (Alternative ramp-up) (4.1.4)	North location (WT03) (4.1.4.1)	Southall *et al.* (2019)	Weighted $L_{E,p,24h,wtd}$ (Impulsive)
Table 4-18 (p38)			Popper *et al.* (2014)	Unweighted $L_{E,p,24h}$ (Pile driving)
Table 4-19 (p38)		Central location (WT28) (4.1.4.2)	Southall *et al.* (2019)	Weighted $L_{E,p,24h,wtd}$ (Impulsive)
Table 4-20 (p38)			Popper *et al.* (2014)	Unweighted $L_{E,p,24h}$ (Pile driving)
Table 4-21 (p39)		South west location (WT53) (4.1.4.3)	Southall *et al.* (2019)	Weighted $L_{E,p,24h,wtd}$ (Impulsive)
Table 4-22 (p39)			Popper *et al.* (2014)	Unweighted $L_{E,p,24h}$ (Pile driving)
Table 4-23 (p39)	WTG foundations (Mitigated) (4.1.5)	North location (WT03) (4.1.5.1)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)
Table 4-24 (p40)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)
Table 4-25 (p40)			NOAA (2005)	Unweighted $L_{p,RMS}$ (Level B)
Table 4-26 (p40)			Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)
Table 4-27 (p40)				Unweighted $L_{E,p,24h}$ (Pile driving)
Table 4-28 (p41)		Central location (WT28) (4.1.5.2)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)
Table 4-29 (p41)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)
Table 4-30 (p41)			NOAA (2005)	Unweighted $L_{p,RMS}$ (Level B)
Table 4-31 (p41)			Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)
Table 4-32 (p42)				Unweighted $L_{E,p,24h}$ (Pile driving)

Table (page)	Scenario	Location	Criteria	
Table 4-33 (p42)	WTG foundations (Mitigated) (4.1.5)	South west location (WT53) (4.1.5.3)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)
Table 4-34 (p42)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)
Table 4-35 (p42)			NOAA (2005)	Unweighted $L_{p,RMS}$ (Level B)
Table 4-36 (p43)			Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)
Table 4-37 (p43)				Unweighted $L_{E,p,24h}$ (Pile driving)
Table 4-38 (p43)	OSP foundations (Precautionary) (4.2)	North OSP location (4.2.1)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)
Table 4-39 (p44)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)
Table 4-40 (p44)			NOAA (2005)	Unweighted $L_{p,RMS}$ (Level B)
Table 4-41 (p44)			Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)
Table 4-42 (p44)				Unweighted $L_{E,p,24h}$ (Pile driving)
Table 4-43 (p45)		South OSP location (4.2.2)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)
Table 4-44 (p45)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)
Table 4-45 (p45)			NOAA (2005)	Unweighted $L_{p,RMS}$ (Level B)
Table 4-46 (p45)			Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)
Table 4-47 (p46)				Unweighted $L_{E,p,24h}$ (Pile driving)
Table 4-48 (p46)	OSP foundations (Alternative ramp-up) (4.2.3)	North OSP location (4.2.3.1)	Southall *et al.* (2019)	Weighted $L_{E,p,24h,wtd}$ (Impulsive)
Table 4-49 (p46)			Popper *et al.* (2014)	Unweighted $L_{E,p,24h}$ (Pile driving)
Table 4-50 (p47)		South OSP location (4.2.3.2)	Southall *et al.* (2019)	Weighted $L_{E,p,24h,wtd}$ (Impulsive)
Table 4-51 (p47)			Popper *et al.* (2014)	Unweighted $L_{E,p,24h}$ (Pile driving)
Table 4-52 (p47)	OSP foundations (Mitigated) (4.2.4)	North OSP location (4.2.4.1)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)
Table 4-53 (p48)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)
Table 4-54 (p48)			NOAA (2005)	Unweighted $L_{p,RMS}$ (Level B)
Table 4-55 (p48)			Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)
Table 4-56 (p48)				Unweighted $L_{E,p,24h}$ (Pile driving)
Table 4-57 (p49)		South OSP location (4.2.4.2)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)
Table 4-58 (p49)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)
Table 4-59 (p49)			NOAA (2005)	Unweighted $L_{p,RMS}$ (Level B)
Table 4-60 (p49)			Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)
Table 4-61 (p50)				Unweighted $L_{E,p,24h}$ (Pile driving)

Table 4-2 to Table 4-61 present the impact piling modelling results for ABWP2, covering WTG and OSP foundations. For the WTG foundation scenarios, the largest predicted impact ranges were calculated for the LF cetaceans at the Central (WT28) modelling location, with maximum PTS ranges of 7.1 km. For fish, maximum recoverable injury (203 dB $L_{E,p,24h}$) ranges of up to 6.0 km were predicted for stationary receptors. When a fleeing receptor was considered, this range reduced to less than 50 m.

When considering the Alternative ramp-up scenario (Table 3-3) the maximum PTS ranges reduced to 870 m for LF cetacean and 5.5 km for recoverable injury in stationary fish. The use of mitigation (Mitigated scenarios) also reduced the maximum impact ranges down to 720 m for LF cetaceans PTS and 3.4 km for stationary fish. Note that the $L_{p,pk}$ impact ranges for the alternative ramp up have not been run as they use the same maximum blow energy to the worst case and thus would have identical impact ranges.

In accordance with the Danish requirements, an “r_{safe}” distance of 1 km was targeted for the marine mammal PTS impact ranges, which is mitigated using an ADD for key marine mammal species. As above, this is achieved using the WTG alternative ramp up, and also using the Precautionary scenario with a -4 dB noise reduction (the Mitigated scenario).

For the OSP foundation scenarios, maximum impact ranges were predicted at the deeper North OSP location, with maximum ranges for marine mammals calculated for LF cetaceans with PTS ranges of 3.0 km. For fish the maximum recoverable injury ranges for stationary fish were 4.9 km, reducing to less than 50 m when a fleeing receptor was considered.

4.1 WTG foundations

4.1.1 North location (WT03)

Table 4-2: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum expected hammer blow energy during the WTG foundation installation scenario at the North (WT03) modelling location.

Southall *et al.* (2019)		**WTG foundation (maximum energy)**			
Unweighted $L_{p,pk}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	50 m	50 m	50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.0 km²	580 m	550 m	560 m
	PCW (218 dB)	0.01 km²	60 m	60 m	60 m
TTS (Impulsive)	LF (213 dB)	0.05 km²	120 m	120 m	120 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	4.9 km²	1.4 km	1.2 km	1.3 km
	PCW (212 dB)	0.06 km²	140 m	140 m	140 m

Table 4-3: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the WTG foundation installation scenario at the North (WT03) modelling location assuming fleeing receptors.

Southall *et al.* (2019)		**WTG foundation**			
Weighted $L_{E,p,24h,wtd}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	16 km²	4.1 km	100 m	1.7 km
	HF (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	0.6 km²	820 m	< 50 m	330 m
	PCW (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	3,100 km²	53 km	2.4 km	25 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	1,000 km²	30 km	2.6 km	16 km
	PCW (170 dB)	200 km²	13 km	920 m	7.1 km

Table 4-4: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) Level B impulsive behavioural disturbance criteria for the maximum expected hammer blow energy during the WTG foundation installation scenario at the North (WT03) modelling location.

NOAA (2005)		**WTG foundation (maximum energy)**			
Unweighted $L_{p,RMS}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	760 km²	22 km	6.3 km	15 km

Table 4-5: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum expected hammer blow energy during the WTG foundation installation scenario at the North (WT03) modelling location.

Popper *et al.* (2014)		**WTG foundation (maximum energy)**			
Unweighted $L_{p,pk}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	0.05 km²	120 m	120 m	120 m
	207 dB	0.25 km²	290 m	280 m	280 m

Table 4-6: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the WTG foundation installation scenario at the North (WT03) modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		**WTG foundation**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	186 dB	580 km^2	22 km	1.9 km	12 km
Stationary (0 ms^{-1})	219 dB	0.68 km^2	470 m	460 m	470 m
	216 dB	1.8 km^2	770 m	730 m	750 m
	210 dB	11 km^2	2.0 km	1.7 km	1.9 km
	207 dB	25 km^2	3.1 km	2.4 km	2.9 km
	203 dB	68 km^2	5.5 km	3.3 km	4.8 km
	186 dB	1,500 km^2	32 km	7.5 km	24 km

4.1.2 Central location (WT28)

Table 4-7: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum expected hammer blow energy during the WTG foundation installation scenario at the Central (WT28) modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		**WTG foundation (maximum energy)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	60 m	60 m	60 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.3 km^2	680 m	570 m	630 m
	PCW (218 dB)	0.01 km^2	70 m	70 m	70 m
TTS (Impulsive)	LF (213 dB)	0.06 km^2	140 m	130 m	130 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	5.8 km^2	1.6 km	960 m	1.3 km
	PCW (212 dB)	0.07 km^2	160 m	150 m	150 m

Table 4-8: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the WTG foundation installation scenario at the Central (WT28) modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**WTG foundation**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	57 km^2	7.1 km	110 m	3.0 km
	HF (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	3.3 km^2	1.7 km	< 50 m	720 m
	PCW (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	4,500 km^2	60 km	2.7 km	30 km
	HF (170 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	1,600 km^2	35 km	2.9 km	19 km
	PCW (170 dB)	340 km^2	16 km	820 m	8.7 km

Table 4-9: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) Level B impulsive behavioural disturbance criteria for the maximum expected hammer blow energy during the WTG foundation installation scenario at the Central (WT28) modelling location.

NOAA (2005) Unweighted $L_{p,RMS}$		**WTG foundation (maximum energy)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	1,100 km^2	26 km	6.6 km	18 km

Table 4-10: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum expected hammer blow energy during the WTG foundation installation scenario at the Central (WT28) modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		**WTG foundation (maximum energy)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	0.06 km^2	140 m	130 m	130 m
	207 dB	0.31 km^2	330 m	300 m	320 m

Table 4-11: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the WTG foundation installation scenario at the Central (WT28) modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		**WTG foundation**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	186 dB	1,000 km^2	28 km	2.5 km	15 km
Stationary (0 ms^{-1})	219 dB	0.79 km^2	520 m	480 m	500 m
	216 dB	2.0 km^2	840 m	710 m	810 m
	210 dB	11 km^2	2.2 km	1.3 km	2.0 km
	207 dB	26 km^2	3.4 km	1.7 km	3.0 km
	203 dB	73 km^2	6.0 km	2.4 km	4.9 km
	186 dB	2,300 km^2	39 km	7.3 km	27 km

4.1.3 South west location (WT53)

Table 4-12: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum expected hammer blow energy during the WTG foundation installation scenario at the South west (WT53) modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		**WTG foundation (maximum energy)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	50 m	< 50 m	50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.9 km^2	580 m	480 m	530 m
	PCW (218 dB)	0.01 km^2	60 m	60 m	60 m
TTS (Impulsive)	LF (213 dB)	0.04 km^2	120 m	110 m	120 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	4.6 km^2	1.4 km	1.0 km	1.2 km
	PCW (212 dB)	0.06 km^2	140 m	130 m	130 m

Table 4-13: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the WTG foundation installation scenario at the South west (WT53) modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**WTG foundation**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	37 km^2	5.8 km	90 m	2.8 km
	HF (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	2.8 km^2	1.5 km	< 50 m	800 m
	PCW (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	4,100 km^2	59 km	1.5 km	30 km
	HF (170 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	1,600 km^2	34 km	1.7 km	20 km
	PCW (170 dB)	370 km^2	16 km	570 m	9.9 km

Table 4-14: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) Level B impulsive behavioural disturbance criteria for the maximum expected hammer blow energy during the WTG foundation installation scenario at the South west (WT53) modelling location.

NOAA (2005) Unweighted $L_{p,RMS}$		WTG foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
Level B	160 dB	1,100 km^2	24 km	4.9 km	18 km

Table 4-15: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum expected hammer blow energy during the WTG foundation installation scenario at the South west (WT53) modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		WTG foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.04 km^2	120 m	110 m	120 m
	207 dB	0.22 km^2	280 m	250 m	270 m

Table 4-16: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the WTG foundation installation scenario at the South west (WT53) modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		WTG foundation			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 ms^{-1})	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	186 dB	890 km^2	25 km	1.3 km	15 km
Stationary (0 ms^{-1})	219 dB	0.63 km^2	470 m	420 m	450 m
	216 dB	1.6 km^2	770 m	660 m	720 m
	210 dB	11 km^2	2.0 km	1.6 km	1.8 km
	207 dB	26 km^2	3.1 km	2.1 km	2.8 km
	203 dB	78 km^2	5.4 km	2.7 km	4.9 km
	186 dB	2,100 km^2	36 km	5.4 km	26 km

4.1.4 Alternative ramp-up

4.1.4.1 North location (WT03)

Table 4-17: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the WTG foundation installation (alternative ramp-up) scenario at the North (WT03) modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		WTG foundation (alternative ramp-up)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	0.04 km^2	170 m	60 m	100 m
	HF (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	2,100 km^2	44 km	1.3 km	19 km
	HF (170 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	690 km^2	25 km	620 m	12 km
	PCW (170 dB)	78 km^2	8.8 km	70 m	3.9 km

Table 4-18: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the WTG foundation installation (alternative ramp-up) scenario at the North (WT03) modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		WTG foundation (alternative ramp-up)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 ms^{-1})	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	186 dB	340 km^2	18 km	320 m	8.5 km
Stationary (0 ms^{-1})	219 dB	0.57 km^2	430 m	420 m	430 m
	216 dB	1.5 km^2	710 m	670 m	690 m
	210 dB	9.6 km^2	1.9 km	1.6 km	1.8 km
	207 dB	22 km^2	2.9 km	2.3 km	2.7 km
	203 dB	59 km^2	5.1 km	3.1 km	4.5 km
	186 dB	1,400 km^2	31 km	7.5 km	23 km

4.1.4.2 Central location (WT28)

Table 4-19: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the WTG foundation installation (alternative ramp-up) scenario at the Central (WT28) modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		WTG foundation (alternative ramp-up)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	0.58 km^2	870 m	70 m	300 m
	HF (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	3,200 km^2	51 km	1.7 km	24 km
	HF (170 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	1,100 km^2	30 km	870 m	15 km
	PCW (170 dB)	170 km^2	12 km	80 m	5.5 km

Table 4-20: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the WTG foundation installation (alternative ramp-up) scenario at the Central (WT28) modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		WTG foundation (alternative ramp-up)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 ms^{-1})	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	186 dB	690 km^2	24 km	620 m	12 km
Stationary (0 ms^{-1})	219 dB	0.66 km^2	470 m	440 m	460 m
	216 dB	1.7 km^2	770 m	670 m	750 m
	210 dB	9.7 km^2	2.0 km	1.2 km	1.8 km
	207 dB	22 km^2	3.2 km	1.6 km	2.7 km
	203 dB	64 km^2	5.5 km	2.3 km	4.6 km
	186 dB	2,100 km^2	37 km	7.3 km	26 km

4.1.4.3 South west location (WT53)

Table 4-21: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the WTG foundation installation (alternative ramp-up) scenario at the South west (WT53) modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		WTG foundation (alternative ramp-up)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	0.08 km^2	330 m	60 m	140 m
	HF (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	2,900 km^2	50 km	1.0 km	24 km
	HF (170 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	1,100 km^2	29 km	340 m	16 km
	PCW (170 dB)	180 km^2	12 km	60 m	6.5 km

Table 4-22: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the WTG foundation installation (alternative ramp-up) scenario at the South west (WT53) modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		WTG foundation (alternative ramp-up)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 ms^{-1})	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	186 dB	560 km^2	21 km	180 m	12 km
Stationary (0 ms^{-1})	219 dB	0.53 km^2	430 m	390 m	410 m
	216 dB	1.4 km^2	710 m	610 m	650 m
	210 dB	9.5 km^2	1.9 km	1.5 km	1.7 km
	207 dB	23 km^2	2.9 km	2.0 km	2.6 km
	203 dB	68 km^2	5.1 km	2.7 km	4.6 km
	186 dB	1,900 km^2	34 km	5.5 km	25 km

4.1.5 Mitigation

4.1.5.1 North location (WT03)

Table 4-23: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum expected hammer blow energy during the mitigated WTG foundation installation scenario at the North (WT03) modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		WTG foundation (maximum energy), mitigated			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.3 km^2	330 m	320 m	320 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km^2	70 m	70 m	70 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	1.7 km^2	770 m	710 m	740 m
	PCW (212 dB)	0.02 km^2	80 m	80 m	80 m

Table 4-24: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the mitigated WTG foundation installation scenario at the North (WT03) modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		WTG foundation, mitigated			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	0.03 km²	150 m	50 m	90 m
	HF (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	PCW (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	1,400 km²	36 km	1.4 km	17 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	410 km²	18 km	1.6 km	10 km
	PCW (170 dB)	43 km²	5.7 km	170 m	3.3 km

Table 4-25: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) Level B impulsive behavioural disturbance criteria for the maximum expected hammer blow energy during the mitigated WTG foundation installation scenario at the North (WT03) modelling location.

NOAA (2005) Unweighted $L_{p,RMS}$		WTG foundation (maximum energy), mitigated			
		Area	Maximum range	Minimum range	Mean range
Level B	160 dB	390 km²	14 km	5.2 km	11 km

Table 4-26: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum expected hammer blow energy during the mitigated WTG foundation installation scenario at the North (WT03) modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		WTG foundation (maximum energy) , mitigated			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.02 km²	70 m	70 m	70 m
	207 dB	0.08 km²	160 m	160 m	160 m

Table 4-27: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the mitigated WTG foundation installation scenario at the North (WT03) modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		WTG foundation, mitigated			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 ms^{-1})	219 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	216 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	210 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	203 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	186 dB	180 km²	12 km	930 m	6.8 km
Stationary (0 ms^{-1})	219 dB	0.2 km²	250 m	250 m	250 m
	216 dB	0.5 km²	400 m	390 m	400 m
	210 dB	3.5 km²	1.1 km	980 m	1.1 km
	207 dB	8.5 km²	1.8 km	1.5 km	1.7 km
	203 dB	25 km²	3.1 km	2.4 km	2.9 km
	186 dB	800 km²	22 km	6.4 km	17 km

4.1.5.2 Central location (WT28)

Table 4-28: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum expected hammer blow energy during the mitigated WTG foundation installation scenario at the Central (WT28) modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		**WTG foundation (maximum energy) , mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.4 km^2	380 m	350 m	360 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km^2	80 m	80 m	80 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	2.1 km^2	900 m	690 m	820 m
	PCW (212 dB)	0.02 km^2	90 m	90 m	90 m

Table 4-29: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the mitigated WTG foundation installation scenario at the Central (WT28) modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**WTG foundation, mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	0.42 km^2	720 m	50 m	260 m
	HF (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	2,300 km^2	43 km	1.8 km	21 km
	HF (170 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	680 km^2	23 km	1.9 km	12 km
	PCW (170 dB)	84 km^2	8.2 km	100 m	4.1 km

Table 4-30: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) Level B impulsive behavioural disturbance criteria for the maximum expected hammer blow energy during the mitigated WTG foundation installation scenario at the Central (WT28) modelling location.

NOAA (2005) Unweighted $L_{p,RMS}$		**WTG foundation (maximum energy), mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	540 km^2	17 km	5.1 km	12 km

Table 4-31: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum expected hammer blow energy during the mitigated WTG foundation installation scenario at the Central (WT28) modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		**WTG foundation (maximum energy) , mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	0.02 km^2	80 m	80 m	80 m
	207 dB	0.1 km^2	180 m	170 m	180 m

Table 4-32: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the mitigated WTG foundation installation scenario at the Central (WT28) modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014)		**WTG foundation, mitigated**			
Unweighted $L_{E,p,24h}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	186 dB	360 km^2	17 km	1.1 km	9.0 km
Stationary (0 ms^{-1})	219 dB	0.22 km^2	270 m	260 m	260 m
	216 dB	0.57 km^2	440 m	410 m	430 m
	210 dB	3.8 km^2	1.2 km	830 m	1.1 km
	207 dB	8.7 km^2	1.9 km	1.2 km	1.7 km
	203 dB	26 km^2	3.4 km	1.7 km	2.8 km
	186 dB	1,200 km^2	27 km	6.7 km	19 km

4.1.5.3 South west location (WT53)

Table 4-33: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum expected hammer blow energy during the mitigated WTG foundation installation scenario at the South west (WT53) modelling location.

Southall *et al.* (2019)		**WTG foundation (maximum energy) , mitigated**			
Unweighted $L_{p,pk}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.3 km^2	330 m	280 m	300 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.01 km^2	70 m	60 m	70 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	1.5 km^2	770 m	620 m	700 m
	PCW (212 dB)	0.02 km^2	80 m	70 m	80 m

Table 4-34: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the mitigated WTG foundation installation scenario at the South west (WT53) modelling location assuming fleeing receptors.

Southall *et al.* (2019)		**WTG foundation, mitigated**			
Weighted $L_{E,p,24h,wtd}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	0.06 km^2	260 m	50 m	130 m
	HF (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	2,000 km^2	40 km	820 m	21 km
	HF (170 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	710 km^2	22 km	990 m	13 km
	PCW (170 dB)	95 km^2	7.9 km	80 m	5.1 km

Table 4-35: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) Level B impulsive behavioural disturbance criteria for the maximum expected hammer blow energy during the mitigated WTG foundation installation scenario at the South west (WT53) modelling location.

NOAA (2005)		**WTG foundation (maximum energy), mitigated**			
Unweighted $L_{p,RMS}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	530 km^2	16 km	4.2 km	13 km

Table 4-36: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum expected hammer blow energy during the mitigated WTG foundation installation scenario at the South west (WT53) modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		**WTG foundation (maximum energy) , mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	0.01 km²	70 m	60 m	70 m
	207 dB	0.07 km²	160 m	150 m	150 m

Table 4-37: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the mitigated WTG foundation installation scenario at the South west (WT53) modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		**WTG foundation, mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	216 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	210 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	203 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	186 dB	310 km²	14 km	530 m	9.1 km
Stationary (0 ms^{-1})	219 dB	0.18 km²	250 m	230 m	240 m
	216 dB	0.46 km²	400 m	360 m	380 m
	210 dB	3.2 km²	1.1 km	880 m	1.0 km
	207 dB	8.0 km²	1.7 km	1.4 km	1.6 km
	203 dB	26 km²	3.1 km	2.1 km	2.9 km
	186 dB	1,100 km²	25 km	5.0 km	18 km

4.2 OSP foundations

4.2.1 North OSP location

Table 4-38: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum expected hammer blow energy during the OSP foundation installation scenario at the North OSP modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		**OSP foundation (maximum energy)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	50 m	50 m	50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.8 km²	520 m	480 m	500 m
	PCW (218 dB)	< 0.01 km²	60 m	60 m	60 m
TTS (Impulsive)	LF (213 dB)	0.04 km²	110 m	110 m	110 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	3.8 km²	1.2 km	1.0 km	1.1 km
	PCW (212 dB)	0.05 km²	130 m	130 m	130 m

Table 4-39: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the OSP foundation installation scenario at the North OSP modelling location assuming fleeing receptors.

Southall *et al.* (2019)		**OSP foundation**			
Weighted $L_{E,p,24h,wtd}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	7.1 km^2	3.0 km	100 m	1.1 km
	HF (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	0.23 km^2	520 m	< 50 m	200 m
	PCW (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	2,500 km^2	49 km	2.2 km	22 km
	HF (170 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	900 km^2	29 km	2.3 km	14 km
	PCW (170 dB)	160 km^2	12 km	850 m	6.4 km

Table 4-40: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) Level B impulsive behavioural disturbance criteria for the maximum expected hammer blow energy during the OSP foundation installation scenario at the North OSP modelling location.

NOAA (2005)		**OSP foundation (maximum energy)**			
Unweighted $L_{p,RMS}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	650 km^2	20 km	5.8 km	14 km

Table 4-41: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum expected hammer blow energy during the OSP foundation installation scenario at the North OSP modelling location.

Popper *et al.* (2014)		**OSP foundation (maximum energy)**			
Unweighted $L_{p,pk}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	0.04 km^2	110 m	110 m	110 m
	207 dB	0.21 km^2	260 m	250 m	260 m

Table 4-42: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the OSP foundation installation scenario at the North OSP modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014)		**OSP foundation**			
Unweighted $L_{E,p,24h}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	186 dB	450 km^2	20 km	1.7 km	10 km
Stationary (0 ms^{-1})	219 dB	0.62 km^2	450 m	430 m	440 m
	216 dB	1.6 km^2	720 m	680 m	700 m
	210 dB	9.9 km^2	1.9 km	1.6 km	1.8 km
	207 dB	22 km^2	2.9 km	2.1 km	2.7 km
	203 dB	59 km^2	4.9 km	2.8 km	4.4 km
	186 dB	1,300 km^2	30 km	6.9 km	22 km

4.2.2 South OSP location

Table 4-43: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum expected hammer blow energy during the OSP foundation installation scenario at the South OSP modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		**OSP foundation (maximum energy)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.4 km^2	380 m	310 m	340 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km^2	80 m	80 m	80 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	1.7 km^2	880 m	620 m	730 m
	PCW (212 dB)	0.03 km^2	100 m	90 m	90 m

Table 4-44: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the OSP foundation installation scenario at the South OSP modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**OSP foundation**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	0.28 km^2	790 m	70 m	240 m
	HF (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	0.09 km^2	370 m	< 50 m	130 m
	PCW (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	1,900 km^2	41 km	590 m	19 km
	HF (170 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	1,000 km^2	28 km	250 m	15 km
	PCW (170 dB)	180 km^2	11 km	60 m	6.7 km

Table 4-45: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) Level B impulsive behavioural disturbance criteria for the maximum expected hammer blow energy during the OSP foundation installation scenario at the South OSP modelling location.

NOAA (2005) Unweighted $L_{p,RMS}$		**OSP foundation (maximum energy)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	560 km^2	17 km	1.4 km	13 km

Table 4-46: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum expected hammer blow energy during the OSP foundation installation scenario at the South OSP modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		**OSP foundation (maximum energy)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	0.02 km^2	80 m	80 m	80 m
	207 dB	0.1 km^2	190 m	170 m	180 m

Table 4-47: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the OSP foundation installation scenario at the South OSP modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014)		**OSP foundation**			
Unweighted $L_{E,p,24h}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	186 dB	350 km^2	16 km	120 m	9.3 km
Stationary (0 ms^{-1})	219 dB	0.33 km^2	350 m	300 m	320 m
	216 dB	0.81 km^2	570 m	450 m	500 m
	210 dB	5.3 km^2	1.5 km	980 m	1.3 km
	207 dB	13 km^2	2.4 km	1.3 km	2.0 km
	203 dB	37 km^2	4.1 km	1.6 km	3.4 km
	186 dB	1,100 km^2	26 km	5.0 km	20 km

4.2.3 Alternative ramp-up

4.2.3.1 North OSP location

Table 4-48: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the OSP foundation installation (alternative ramp-up) scenario at the North OSP modelling location assuming fleeing receptors.

Southall *et al.* (2019)		**OSP foundation (alternative ramp-up)**			
Weighted $L_{E,p,24h,wtd}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	0.02 km^2	120 m	60 m	80 m
	HF (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	1,600 km^2	41 km	1.2 km	17 km
	HF (170 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	570 km^2	24 km	520 m	11 km
	PCW (170 dB)	58 km^2	7.9 km	60 m	3.3 km

Table 4-49: Unweighted $L_{E,p,24h}$ impact areas and ranges for marine mammals using the Popper et al. (2014) pile driving criteria for the OSP foundation installation (alternative ramp-up) scenario at the North OSP modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014)		**OSP foundation (alternative ramp-up)**			
Unweighted $L_{E,p,24h}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	186 dB	250 km^2	16 km	270 m	7.2 km
Stationary (0 ms^{-1})	219 dB	0.52 km^2	420 m	400 m	410 m
	216 dB	1.3 km^2	660 m	630 m	650 m
	210 dB	8.5 km^2	1.7 km	1.5 km	1.6 km
	207 dB	19 km^2	2.7 km	2.0 km	2.5 km
	203 dB	52 km^2	4.5 km	2.7 km	4.1 km
	186 dB	1,200 km^2	29 km	6.8 km	21 km

4.2.3.2 South OSP location

Table 4-50: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the OSP foundation installation (alternative ramp-up) scenario at the South OSP modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		OSP foundation (alternative ramp-up)			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	< 0.01 km^2	70 m	50 m	60 m
	HF (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	1,100 km^2	33 km	430 m	14 km
	HF (170 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	670 km^2	24 km	130 m	12 km
	PCW (170 dB)	61 km^2	7.4 km	< 50 m	3.5 km

Table 4-51: Unweighted $L_{E,p,24h}$ impact areas and ranges for marine mammals using the Popper et al. (2014) pile driving criteria for the OSP foundation installation (alternative ramp-up) scenario at the South OSP modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		OSP foundation (alternative ramp-up)			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	186 dB	170 km^2	12 km	80 m	6.1 km
Stationary (0 ms^{-1})	219 dB	0.27 km^2	320 m	280 m	290 m
	216 dB	0.68 km^2	520 m	420 m	460 m
	210 dB	4.5 km^2	1.4 km	920 m	1.2 km
	207 dB	11 km^2	2.2 km	1.3 km	1.8 km
	203 dB	32 km^2	3.8 km	1.6 km	3.2 km
	186 dB	1,000 km^2	25 km	4.9 km	19 km

4.2.4 Mitigation

4.2.4.1 North OSP location

Table 4-52: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum expected hammer blow energy during the mitigated OSP foundation installation scenario at the North OSP modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		OSP foundation (maximum energy), mitigated			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.27 km^2	300 m	290 m	300 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.01 km^2	60 m	60 m	60 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	1.3 km^2	680 m	620 m	650 m
	PCW (212 dB)	0.01 km^2	70 m	70 m	70 m

Table 4-53: Weighted $L_{E,p,24h,wtd}$ *impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the mitigated OSP foundation installation scenario at the North OSP modelling location assuming fleeing receptors.*

Southall *et al.* (2019)		**OSP foundation, mitigated**			
Weighted $L_{E,p,24h,wtd}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	0.02 km^2	100 m	50 m	70 m
	HF (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	1,100 km^2	33 km	1.2 km	15 km
	HF (170 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	340 km^2	17 km	1.4 km	9.1 km
	PCW (170 dB)	33 km^2	5.2 km	120 m	2.9 km

Table 4-54: Unweighted $L_{p,RMS}$ *impact areas and ranges for marine mammals using the NOAA (2005) Level B impulsive behavioural disturbance criteria for the maximum expected hammer blow energy during the mitigated OSP foundation installation scenario at the North OSP modelling location.*

NOAA (2005)		**OSP foundation (maximum energy), mitigated**			
Unweighted $L_{p,RMS}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	330 km^2	13 km	4.8 km	10 km

Table 4-55: Unweighted $L_{p,pk}$ *impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum expected hammer blow energy during the mitigated OSP foundation installation scenario at the North OSP modelling location.*

Popper *et al.* (2014)		**OSP foundation (maximum energy) , mitigated**			
Unweighted $L_{p,pk}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	0.01 km^2	60 m	60 m	60 m
	207 dB	0.07 km^2	150 m	150 m	150 m

Table 4-56: Unweighted $L_{E,p,24h}$ *impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the mitigated OSP foundation installation scenario at the North OSP modelling location assuming both fleeing and stationary receptors.*

Popper *et al.* (2014)		**OSP foundation, mitigated**			
Unweighted $L_{E,p,24h}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	186 dB	130 km^2	11 km	840 m	5.8 km
Stationary (0 ms^{-1})	219 dB	0.18 km^2	240 m	230 m	240 m
	216 dB	0.45 km^2	390 m	370 m	380 m
	210 dB	2.9 km^2	990 m	900 m	950 m
	207 dB	7.4 km^2	1.6 km	1.4 km	1.5 km
	203 dB	22 km^2	2.9 km	2.1 km	2.7 km
	186 dB	680 km^2	21 km	5.9 km	16 km

4.2.4.2 South OSP location

Table 4-57: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the maximum expected hammer blow energy during the mitigated OSP foundation installation scenario at the South OSP modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		**OSP foundation (maximum energy) , mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.13 km^2	220 m	190 m	200 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	0.6 km^2	500 m	390 m	440 m
	PCW (212 dB)	< 0.01 km^2	60 m	50 m	60 m

Table 4-58: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the mitigated OSP foundation installation scenario at the South OSP modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**OSP foundation, mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	< 0.01 km^2	50 m	< 50 m	< 50 m
	HF (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (185 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	740 km^2	26 km	340 m	12 km
	HF (170 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	420 km^2	18 km	100 m	10 km
	PCW (170 dB)	32 km^2	4.9 km	< 50 m	2.9 km

Table 4-59: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) Level B impulsive behavioural disturbance criteria for the maximum expected hammer blow energy during the mitigated OSP foundation installation scenario at the South OSP modelling location.

NOAA (2005) Unweighted $L_{p,RMS}$		**OSP foundation (maximum energy), mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	280 km^2	11 km	1.4 km	9.1 km

Table 4-60: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the maximum expected hammer blow energy during the mitigated OSP foundation installation scenario at the South OSP modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		**OSP foundation (maximum energy) , mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	0.04 km^2	110 m	100 m	110 m

Table 4-61: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the mitigated OSP foundation installation scenario at the South OSP modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		**OSP foundation, mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing ($1.5\ ms^{-1}$)	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	186 dB	90 km^2	8.0 km	60 m	4.8 km
Stationary ($0\ ms^{-1}$)	219 dB	0.1 km^2	190 m	170 m	180 m
	216 dB	0.24 km^2	300 m	260 m	280 m
	210 dB	1.5 km^2	790 m	590 m	680 m
	207 dB	3.9 km^2	1.3 km	870 m	1.1 km
	203 dB	13 km^2	2.4 km	1.3 km	2.0 km
	186 dB	590 km^2	18 km	4.4 km	14 km

5 Other noise sources

Although impact piling is expected to generate the greatest overall noise levels during construction and development (Bailey *et al.*, 2014), several other anthropogenic underwater noise sources have the potential to be associated with the Proposed Development and need to be considered. These noise sources have been presented alongside relevant biological criteria (see section 2.3) in this section.

The list below shows the various noise producing sources, aside from impact piling, that are expected to occur during the construction and operation of ABWP2.

- Cable laying
- Dredging
- Drilling (including trenchless techniques)
- Rock placement
- Trenching
- Vessel activities
- Operational WTGs
- UXO clearance

The NPL Good Practice Guide 133 for underwater noise measurements (Robinson *et al.*, 2014) indicates that under certain circumstances, a simple modelling approach is considered appropriate. Such an approach has been used for these noise sources, which are variously either quiet compared to impact piling (e.g., cable laying and dredging), or where detailed modelling would imply unjustified accuracy (e.g., where data is limited such as with UXO detonation). As such, the modelling that has been presented here is considered sufficient for the purpose of understanding and describing the likely significant effects. The limitations of this approach are noted, including the lack of frequency or bathymetric dependence.

The majority 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 (construction)

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 5-1 along with a summary of the number of datasets used in each case. As previously, all $L_{E,p,t}$ criteria use the same assumptions as presented in section 2.3, and ranges smaller than 50 m have not been presented. It should be reiterated that this modelling approach does not take bathymetry or any other environmental conditions into account, and as such can be applied to any location at, or surrounding, ABWP2.

Table 5-1: Summary of the estimated unweighted source levels and transmission losses for the considered construction activities, based on directly measured data

Activity	Estimated L_p source level @ 1 m	Transmission loss coefficients	Comments
Cable laying	171 dB re 1 µPa	N: 13, α: 0.0 (no absorption)	Based on 11 datasets from a pipe laying vessel measuring 300 m in length, this is considered a precautionary noise source for cable laying operations.
Dredging (backhoe)	165 dB re 1 µPa	N: 19, α: 0.0009	Based on three datasets from backhoe dredgers.
Dredging (suction)	186 dB re 1 µPa	N: 19, α: 0.0009	Based on five datasets from suction and cutter-suction dredgers.
Drilling (including trenchless techniques)	169 dB re 1 µPa	N: 16, α: 0.0006	Based on six datasets from various drilling operations covering ground investigations and pile installation. A 200 kW drill has been assumed for modelling.
Rock placement	166 dB re 1 µPa	N: 9, α: 0.0025	Based on four datasets from rock placement vessel *Rollingstone*.
Trenching	172 dB re 1 µPa	N: 13, α: 0.0004	Based on three datasets from trenching vessels more than 100 m in length.
Vessel noise (large)	168 dB re 1 µPa	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 kn.
Vessel noise (medium)	161 dB re 1 µPa	N: 12, α: 0.0021	Based on three datasets of moderate sized vessels below 100 m in length. Vessel speed assumed as 10 kn.

All values of N and α are empirically derived and will be linked to the size and shape of the machinery, the transect on which the measurements were taken and the local environment at the time. It is noted that the depths at ABWP2 are deep relative to the locations where the original data here was derived, although the noise levels relative to the thresholds under consideration will mean that the relatively low impact ranges predicted are unlikely to be significantly affected.

For $L_{E,p,t}$ calculations in this section, the duration the noise is present also needs to be considered, with all sources assumed to operate constantly for 24 hours to give a precautionary assessment of noise. Due to the relatively low level of noise from these sources, both moving and stationary receptors have been included for all $L_{E,p,t}$ criteria; the same swim speeds as presented in section 2.3 have been assumed here.

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

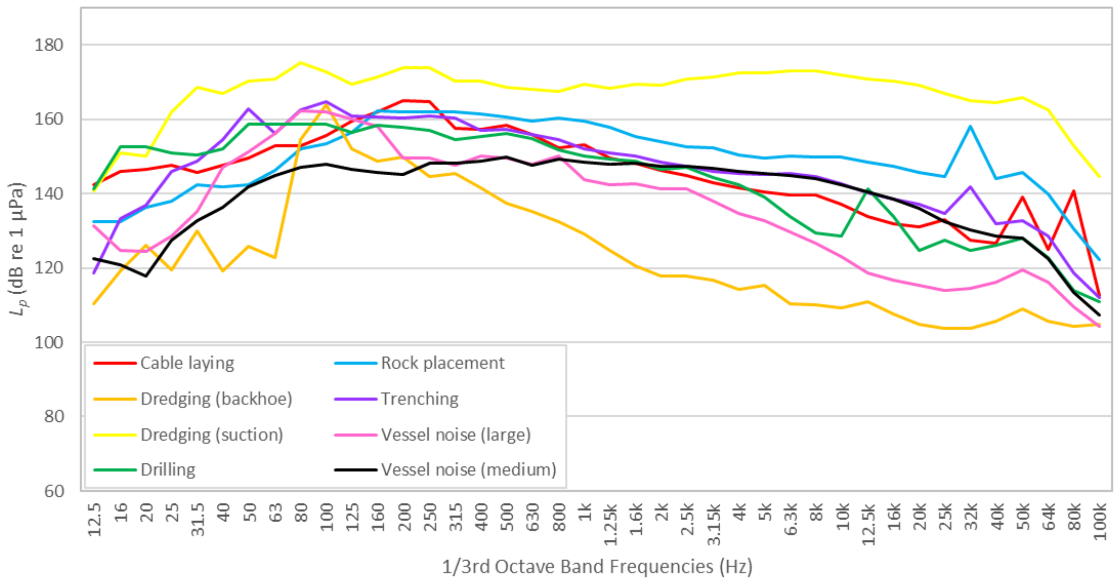

Figure 5-1: Summary of the unweighted 1/3rd octave frequency bands to which the weightings from Southall et al. (2019) have been applied.

Table 5-2: Reductions in source level for the different construction activities considered when the weightings from Southall et al. (2019) are applied.

Activity	**Reduction in L_p source level from the unweighted level (Southall *et al.*, 2019)**			
	LF	**HF**	**VHF**	**PCW**
Cable laying	2.5 dB re 1 µPa	25.6 dB re 1 µPa	26.6 dB re 1 µPa	13.8 dB re 1 µPa
Dredging (backhoe)	6.3 dB re 1 µPa	46.7 dB re 1 µPa	48.7 dB re 1 µPa	23.1 dB re 1 µPa
Dredging (suction)	2.5 dB re 1 µPa	7.9 dB re 1 µPa	9.6 dB re 1 µPa	4.1 dB re 1 µPa
Drilling	4.0 dB re 1 µPa	25.8 dB re 1 µPa	28.4 dB re 1 µPa	13.2 dB re 1 µPa
Rock placement	1.6 dB re 1 µPa	11.9 dB re 1 µPa	12.5 dB re 1 µPa	8.2 dB re 1 µPa
Trenching	4.1 dB re 1 µPa	23.0 dB re 1 µPa	25.0 dB re 1 µPa	13.6 dB re 1 µPa
Vessel noise (large)	5.6 dB re 1 µPa	34.4 dB re 1 µPa	38.7 dB re 1 µPa	17.4 dB re 1 µPa
Vessel noise (medium)	1.3 dB re 1 µPa	13.2 dB re 1 µPa	16.1 dB re 1 µPa	5.1 dB re 1 µPa

Table 5-3 to Table 5-5 summarise the predicted impact ranges for these noise sources. All the sources in this section are considered non-impulsive or continuous.

Given the modelled impact ranges, almost all marine mammals would have to be closer than 50 m from the noise sources at the start of the activity to acquire the necessary exposure for PTS onset as per Southall *et al*. (2019), with the possible exception of suction dredging and rock placement for stationary receptors. As previously iterated, these ranges only represent a range where the receptor reaches the ‘onset’ stage, 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 this only represents a minimal risk, especially bearing in mind that many sources above are mobile. For fish, there is only a minimal risk of any injury or TTS, using the L_p guidance for shipping and continuous noise sources in Popper *et al*. (2014), with all impact ranges predicted to be smaller than 50 m.

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

Table 5-3: Weighted $L_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the various noise-making activities assuming a fleeing receptor.

Southall *et al.* (2019) $L_{E,p,24h,wtd}$ (Fleeing)	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	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
Dredging (backhoe)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
Dredging (suction)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	250 m	< 50 m
Drilling	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
Rock placement	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
Trenching	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	820 m	< 50 m
Vessel noise (large)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
Vessel noise (medium)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m

Table 5-4: Weighted $L_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the various noise-making activities assuming a stationary receptor.

Southall *et al.* (2019) $L_{E,p,24h,wtd}$ (Stationary)	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	< 50 m	< 50 m	< 50 m	< 50 m	970 m	< 50 m	1.3 km	90 m
Dredging (backhoe)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
Dredging (suction)	60 m	< 50 m	560 m	< 50 m	630 m	380 m	4.2 km	420 m
Drilling	< 50 m	< 50 m	< 50 m	< 50 m	160 m	< 50 m	200 m	< 50 m
Rock placement	< 50 m	< 50 m	1.0 km	< 50 m	2.0 km	490 m	6.2 km	560 m
Trenching	< 50 m	< 50 m	60 m	< 50 m	820 m	< 50 m	1.8 km	110 m
Vessel noise (large)	< 50 m	< 50 m	< 50 m	< 50 m	440 m	< 50 m	130 m	< 50 m
Vessel noise (medium)	< 50 m	< 50 m	60 m	< 50 m	280 m	< 50 m	1.5 km	100 m

It should also be noted that that ranges for stationary animals are theoretical only and are expected to be over-conservative as the assumption is for the receptor to remain stationary in respect to the noise source for the entire assessment period (24 hours), when in a number of these instances, the noise source moves.

Table 5-5: Unweighted L_p impact ranges for fish using the Popper et al (2014) shipping and continuous noise criteria for the various noise-making activities.

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

5.2 Operational WTG noise

When considering the noise from operational WTG, the primary noise source is a consequence of mechanically generated vibration from the rotating machinery in the WTG transmitted into the water through the structure of the WTG tower and foundations (Nedwell *et al*., 2003; Tougaard *et al*,. 2020). For a fixed-bottom foundation, this is the surface area of the cylindrical pile in the water column (or piles for multi-leg designs). The complexities of the acoustics in large structures such as these make it difficult to predict their effect on the resulting noise output (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 noise data from 17 operational WTGs in Europe and the United States, from 0.2 MW to 6.15 MW nominal power output. The paper identified the nominal power output and wind speed as the 2 primary driving factors for underwater noise generation. Although the datasets were acquired under different conditions, the authors devised a formula based on the published data for the operational wind farms, allowing a broadband noise level to be estimated based on the application of wind speed, turbine size (by nominal power output) and distance from the turbine:

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

where C is a fixed constant and the coefficients α, β, and γ are derived from the 17 empirical datasets.

Indicative power outputs have been used assumed based on turbine size to calculate the impacts here. For ABWP2, WTGs with rotor diameters of between 236 and 250 m have been considered.

The WTG sizes under consideration at ABWP2 are much larger than those used to develop the estimation above, so caution must be taken when considering the results presented in this section; no empirical data is available for large wind turbines close to the specification proposed here. Research from Bellmann *et al*. (2024) using more up-to-date operational noise data from larger turbines currently installed (up to 8 MW) found that the predictions using the equation from Tougaard *et al*. (2020) are likely to overestimate the noise produced from the turbines, giving an extra level of conservatism for the estimations.

Figure 5-2 presents a level against range plot for the WTG sizes at ABWP2 using the Tougaard *et al*. (2020) equation, assuming an average wind speed of 6 ms^{-1}. Although wind speeds (and thus operational noise levels) may be greater than this, meaning this will not represent the typical condition. It is also worth noting that the background noise level will also naturally increase, due primarily to rougher seas, somewhat offsetting any additional impact this may have.

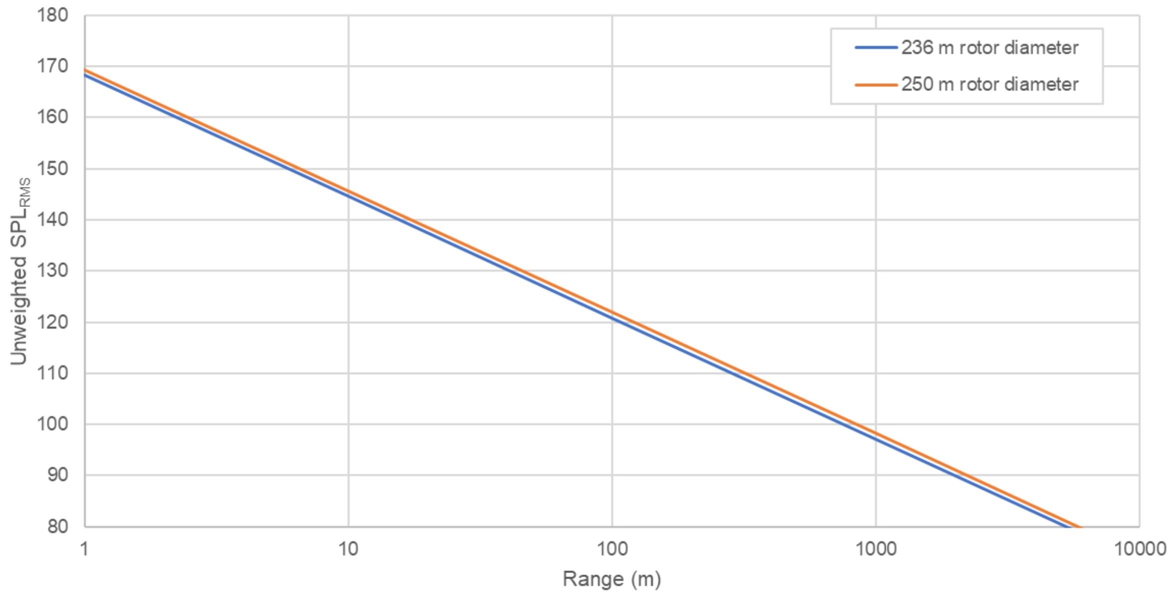

Figure 5-2: Predicted unweighted L_p from operational WTGs with rotor diameters of between 236 and 250 m using the calculation from Tougaard et al. (2020).

Using this data, a summary of the predicted impact ranges for operational WTG noise has been produced, presented in Table 5-6 and Table 5-7. The operational WTG source is considered non-impulsive or continuous. For $L_{E,p,t}$ calculations, a precautionary stationary animal has been used, and it is assumed that the operational WTG noise is present 24 hours a day.

Table 5-6: Weighted $L_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for operational WTG noise assuming a stationary receptor.

Southall *et al.* (2019) $L_{E,p,24h,wtd}$ (Stationary)	**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)**
236 m rotor diameter	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
250 m rotor diameter	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m

Based on the Southall *et al.* (2019) non-impulsive criteria, a marine mammal would need to remain within 50 m of the operational WTG for 12 hours to exceed threshold.

Table 5-7: Unweighted L_p impact ranges for fish using the Popper et al (2014) shipping and continuous noise criteria for the various noise-making activities.

Popper *et al.* (2014) L_p	**Recoverable injury 170 dB re 1 µPa (48 hours)**	**TTS 158 dB re 1 µPa (12 hours)**
236 m rotor diameter	< 50 m	< 50 m
250 m rotor diameter	< 50 m	< 50 m

The results show that, for operational WTGs, injury risk is minimal. Increasing the wind speed does not lead to significant increases in the impact ranges.

Stöber and Thomsen (2021) produced a similar study of operational WTG noise datasets and raised the potential for behavioural disturbance caused by larger WTGs. While prospective WTG sizes are increasing, Stöber and Thomsen (2021) concluded that these might only have limited impacts related to behavioural responses in marine mammals and fish, although there is considerable uncertainty in the criteria available to assess this. Based on the highly precautionary NOAA Level B behavioural threshold (120 dB re 1 µPa (L_p) for non-impulsive noise; see NOAA, 2005) that the study utilises. For ABWP2, it is estimated that larger WTG may only achieve the Level B behavioural threshold at ranges of 120 m using the Tougaard *et al*. (2020) equation (Figure 5-2). As the distance between turbines at ABWP2 is expected to be greater than this, any array effect from the turbines is not expected. Bellman *et al*. (2024) takes this further and shows that the predictions of underwater noise during the operational phase in Stöber and Thomsen (2021) represent significant over-estimations of the actual levels seen on site.

5.3 UXO clearance

It is possible, although highly unlikely, that UXO devices with a range of charge weights (or quantity of contained explosive), are present within in and around the ABWP2 site. These would need to be cleared before any construction can begin. When modelling potential noise from UXO clearance, a variety of explosive types need to be considered, with the potential that many have been subject to degradation and burying over time. Two otherwise identical explosive devices are likely to produce different blasts in the case where one has spent an extended period on the seabed or sits in a different topographical situation.

A selection of explosive sizes has been considered based on what might be present and, in each case, it has been assumed that the maximum explosive charge in each device is present and either detonates with the clearance (high-order) or a clearance method, such as deflagration (low-order), can be used. It is likely that a low-order technique will be the primary method of UXO clearance, with high-order clearance only to occur in exceptional circumstances.

5.3.1 Estimation of underwater noise levels

The noise produced by the detonation of explosives is affected by several different elements, only one of which can be easily 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 level of uncertainty in the estimation of noise levels. A precautionary estimation has therefore been used for calculations in this study, assuming the UXO to be detonated is not buried, degraded or subject to any other significant attenuation from its 'as-new' condition. A 'high-order' clearance technique, using an external 'donor charge' initiator to detonate the explosive material in the UXO, theoretically produces a blast wave equivalent to the full detonation of the device.

The consequence of this is that the noise produced, particularly by the larger explosives under consideration, are likely to be over-estimated as some degree of attenuation (i.e., from topography, burying, degradation, orientation) would be expected.

5.3.2 Low-order clearance

The primary choice for any UXO clearance at ABWP2 will be a low-order technique, in order to reduce the consequences of noise caused by detonation of the main charge of the UXO. Deflagration is one such 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 material.

Where the technique proceeds as intended, it is still not without noise impact. The process requires an initial shaped explosive donor charge, typically less than 0.5 kg, 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 UXO. Deflagration may not destroy all of the HE, which would necessitate further low-order clearance events or collection of the remnants. There is also the possibility (although rare) that the deflagration could produce an unintentional high-order event.

For calculation of the deflagration scenario, resulting in total destruction of the HE material, 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 a net explosive quantity (NEQ) determined according to the size of UXO on which it is placed. The prediction of this impact is based on a charge weight of 0.5 kg. The most precautionary scenario would, of course, be a high-order detonation with maximum pressures from complete detonation of the UXO.

5.3.3 High-order clearance

High-order clearance technique is not a proposed UXO clearance methodology, although for completeness has been included in this assessment. The only reason for a high-order clearance at ABWP2 would be as a last resort if the use of a less intrusive or quieter technique is not possible, or if the low-order technique accidentally results in a high-order detonation. A high-order clearance would involve detonating the UXO including all the HE material contained within.

The maximum equivalent charge weight for the potential UXO devices that could be present at ABWP2 has been estimated as 800 kg. This has been modelled alongside a range of smaller devices, at charge weights of 25, 55, 120, 240, 525 and 700 kg. In each case, an additional donor weight of 0.5 kg has been included to initiate detonation. No mitigation has been considered for this modelling.

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). This is covered in more detail in section 5.3.4.

5.3.4 Estimation of underwater noise propagation

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

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

and for $L_{E,p}$:

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

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

These equations give a relatively simple calculation which can be used to give an indication of the range of effect. The equation does not consider variable bathymetry or seabed type, and thus the 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 typical sound frequencies associated with UXO clearance. This uses standard frequency-based absorption coefficients for the seawater conditions expected in the region.

Despite this attenuation correction, the resulting noise levels still need to be considered carefully, for example, $L_{p,pk}$ noise levels over larger distances are difficult to predict accurately (von Benda-Beckmann *et al.*, 2015). Soloway and Dahl (2014) only verify results from the equation above for small charges at ranges of less than 1 km, although the long range and high charge weight results are similar to the measurements presented by von Benda-Beckamann *et al.* (2015). At longer ranges, greater confidence is expected with the $L_{E,p}$ calculations. However, Ocean Winds (2024) indicates that, based on measurements of deflagration noise in the Moray Firth, these calculations are likely to produce a higher, and therefore precautionary, prediction of noise levels than are seen in practice.

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

Additionally, an impulsive wave tends to be smoothed (i.e., the pulse becomes longer) over distance (Cudahy and Parvin, 2001), meaning that 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 $L_{E,p}$ is considered preferential at long range as it considers the overall energy, and the degree of smoothing of the peak with increasing distance is critical.

In light of this, the selection of assessment criteria needs careful consideration. As discussed in section 2.2.1, the smoothing of the pulse at range means that a pulse may be considered non-impulsive at distance, suggesting that, at greater ranges, it may be more appropriate to use the non-impulsive criteria. Based on impulsive noise from piling, this consideration may begin at ranges of 3.5 km (Hastie *et al.*, 2019) to 5 km (Matei *et al.*, 2024), although, as blast noise is inherently more impulsive than piling, the transition from full impulsivity may occur at a greater distance from the UXO source location.

A summary of the unweighted UXO clearance source levels, calculated using the equations above, are given in Table 5-8.

Table 5-8: List of the $L_{p,pk}$ and $L_{E,p}$ source levels used for UXO clearance modelling.

Charge weight	$L_{p,pk}$ @ 1 m	$L_{E,p}$ @ 1 m
Low order (0.5 kg)	272.1 dB re 1 µPa	217.1 dB re 1 μPa^2s
25 kg (+ donor)	284.9 dB re 1 µPa	228.0 dB re 1 μPa^2s
55 kg (+ donor)	287.5 dB re 1 µPa	230.1 dB re 1 μPa^2s
120 kg (+ donor)	290.0 dB re 1 µPa	232.3 dB re 1 μPa^2s
240 kg (+ donor)	292.3 dB re 1 µPa	234.2 dB re 1 μPa^2s
525 kg (+ donor)	294.8 dB re 1 µPa	236.4 dB re 1 μPa^2s
700 kg (+ donor)	295.8 dB re 1 µPa	237.2 dB re 1 μPa^2s
800 kg (+ donor)	296.2 dB re 1 µPa	237.5 dB re 1 μPa^2s

5.3.5 Impact ranges

Table 5-9 to Table 5-12 present the impact ranges for UXO clearance, considering various charge weights and impact criteria. It should be noted that Popper *et al*. (2014) gives specific impact criteria for explosions (Table 2-5). A UXO detonation source is defined as a single pulse, as such the $L_{E,p,wtd}$ criteria from Southall *et al*. (2019) have been given as single pulse values in the following tables, and fleeing animal assumptions do not apply.

Although the impact ranges in Table 5-9 to Table 5-12 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 5-9: Unweighted $L_{p,pk}$ impact ranges for marine mammals using the Southall et al (2019) impulsive criteria for UXO clearance noise.

Southall *et al.* (2019) $L_{p,pk}$	PTS (Impulsive)				TTS (Impulsive)			
	LF (219 dB)	HF (230 dB)	VHF (202 dB)	PCW (218 dB)	LF (213 dB)	HF (224 dB)	VHF (196 dB)	PCW (212 dB)
Low order (0.5 kg)	220 m	70 m	1.2 km	240 m	410 m	130 m	2.3 km	450 m
25 kg (+ donor)	820 m	260 m	4.6 km	910 m	1.5 km	490 m	8.5 km	1.6 km
55 kg (+ donor)	1.0 km	340 m	6.0 km	1.1 km	1.9 km	640 m	11 km	2.1 km
120 kg (+ donor)	1.3 km	450 m	7.8 km	1.5 km	2.5 km	830 m	14 km	2.8 km
240 kg (+ donor)	1.7 km	560 m	9.8 km	1.9 km	3.2 km	1.0 km	18 km	3.5 km
525 kg (+ donor)	2.2 km	730 m	12 km	2.5 km	4.1 km	1.3 km	23 km	4.6 km
700 kg (+ donor)	2.4 km	810 m	14 km	2.7 km	4.5 km	1.4 km	25 km	5.0 km
800 kg (+ donor)	2.6 km	840 m	14 km	2.8 km	4.7 km	1.5 km	26 km	5.3 km

Table 5-10: Weighted $L_{E,p,wtd}$ (single pulse) impact ranges for marine mammals using the Southall et al (2019) impulsive criteria for UXO clearance noise.

Southall *et al.* (2019) $L_{E,p,wtd}$ (Single pulse)	PTS (Impulsive)				TTS (Impulsive)			
	LF (183 dB)	HF (185 dB)	VHF (155 dB)	PCW (185 dB)	LF (168 dB)	HF (170 dB)	VHF (140 dB)	PCW (170 dB)
Low order (0.5 kg)	320 m	< 50 m	110 m	60 m	4.5 km	< 50 m	930m	800 m
25 kg (+ donor)	2.2 km	< 50 m	570 m	390 m	29 km	150 m	2.4 km	5.2 km
55 kg (+ donor)	3.2 km	< 50 m	740 m	570 m	41 km	210 m	2.8 km	7.5 km
120 kg (+ donor)	4.7 km	< 50 m	950 m	830 m	57 km	300 m	3.2 km	10 km
240 kg (+ donor)	6.5 km	< 50 m	1.1 km	1.1 km	76 km	390 m	3.5 km	14 km
525 kg (+ donor)	9.5 km	50 m	1.4 km	1.6 km	100 km	530 m	4.0 km	19 km
700 kg (+ donor)	10 km	60 m	1.5 km	1.9 km	110 km	590 m	4.1 km	22 km
800 kg (+ donor)	11 km	60 m	1.6 km	2.0 km	120 km	620 m	4.2 km	23 km

Table 5-11: Weighted $L_{E,p,wtd}$ (single pulse) impact ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for UXO clearance noise.

Southall *et al.* (2019)	**PTS (Non-impulsive)**				**TTS (Non-impulsive)**			
$L_{E,p,wtd}$ (Single pulse)	**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 (0.5 kg)	< 50 m	< 50 m	< 50 m	< 50 m	650 m	< 50 m	150 m	110 m
25 kg (+ donor)	130 m	< 50 m	< 50 m	< 50 m	4.4 km	< 50 m	730 m	790 m
55 kg (+ donor)	190 m	< 50 m	< 50 m	< 50 m	6.4 km	60 m	940 m	1.1 km
120 kg (+ donor)	280 m	< 50 m	70 m	< 50 m	9.4 km	80 m	1.1 km	1.6 km
240 kg (+ donor)	390 m	< 50 m	100 m	70 m	13 km	110 m	1.4 km	2.3 km
525 kg (+ donor)	570 m	< 50 m	130 m	100 m	18 km	160 m	1.7 km	3.3 km
700 kg (+ donor)	660 m	< 50 m	150 m	110 m	21 km	180 m	1.8 km	3.8 km
800 kg (+ donor)	700 m	< 50 m	160 m	120 m	22 km	190 m	1.8 km	4.1 km

Table 5-12: Unweighted $L_{p,pl}$ impact ranges for fish using the Popper et al. (2014) explosions criteria for UXO clearance noise.

Popper *et al.* (2014)	**Mortality and potential mortal injury**	
$L_{p,pk}$	**234 dB**	**229 dB**
Low order (0.5 kg)	< 50 m	80 m
25 kg (+ donor)	170 m	290 m
55 kg (+ donor)	230 m	380 m
120 kg (+ donor)	300 m	490 m
240 kg (+ donor)	370 m	620 m
525 kg (+ donor)	490 m	810 m
700 kg (+ donor)	530 m	890 m
800 kg (+ donor)	560 m	930 m

5.3.6 Summary

The maximum PTS onset ranges calculated for the largest high-order UXO clearance is 14 km for the VHF cetacean category when considering the $L_{p,pk}$ criteria. For $L_{E,p,wtd}$ criteria, the largest PTS onset range is calculated for LF cetaceans with a predicted impact range of 11 km using the impulsive noise criteria. As previously mentioned, this assumes no degradation of the UXO and no smoothing of the pulse over distance, which is a very precautionary approach. Although using the non-impulsive criteria could underestimate the potential impact (Martin *et al*., 2020) (the equivalent non-impulsive criteria range for LF cetaceans is 700 m), it is likely that the long-range smoothing of the pulse peak would reduce its potential harm, making the impulsive range is precautionary.

A low-order clearance would produce a maximum PTS onset impact range of 1.2 km for VHF cetaceans using the $L_{p,pk}$ criteria, with all other species groups lower than this. A low-order methodology is expected to be used for any potential UXO clearance at ABWP2, with high-order being a last resort.

6 Summary and conclusions

Subacoustech Environmental has undertaken a study on behalf of GoBe Consultants to model the impact ranges caused by underwater noise from impact piling and its effects on marine fauna during construction of ABWP2, an offshore wind farm in the Irish Sea.

The level of underwater noise from the installation of monopile foundations using impact piling during construction has been modelled using the INSPIRE semi-empirical underwater noise model. This industry standard approach considers a wide variety of input parameters including bathymetry, and precautionary values for pile diameter, hammer blow energy, strike rate and flee speed of the receptor.

Five modelling locations, three for WTG installations and two for OSP, were chosen to give spatial variation across ABWP2 as well as accounting for changes in water depth. The WTG foundation scenarios considered 11 m diameter piles installed with a maximum hammer energy of 3,500 kJ. The OSP foundation scenario considers the same maximum hammer energy, but with a larger pile diameter of 14 m.

For marine mammals, the largest predicted impact ranges were calculated for the LF cetaceans at the Central (WT28) modelling location, with maximum PTS ranges of 7.1 km. For fish, maximum recoverable injury (203 dB $L_{E,p,24h}$) ranges of up to 6.0 km were predicted for stationary receptors. When a fleeing receptor was considered, this range reduced to less than 50 m.

An alternative ramp-up scenario was considered, to reduce the energy during the earlier stages of the piling (Table 3-3 and Table 3-5), and using this the maximum PTS impact ranges reduced to 870 m for LF cetaceans and 5.5 km for recoverable injury in stationary fish. The use of a low-noise hammer as mitigation also reduced the maximum impact ranges down to 720 m for LF cetaceans PTS and 3.4 km for stationary fish.

A review was undertaken of various underwater noise thresholds or limits for offshore wind farm installation in use in the EU as requested in the Further Information Request from ACP. The Danish requirements offer a combination of consideration of the varying sensitivities of different species groups expected to be present in Irish waters, site specific characteristics, and the total noise produced by an impact piling event. The Danish guidance uses the r_{safe} concept, effectively the PTS impact range, a distance which must be made clear of any marine mammals at the start of piling. Targeting an r_{safe} distance of 1 km, this target can be achieved using either the Mitigated (4 dB noise reduction) or the Alternative ramp up scenarios, without additional noise abatement.

Noise sources other than impact piling have been considered, which include noise from cable laying, dredging, drilling, rock placement, trenching, vessel noise, and operational WTGs. 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.

Potential noise from UXO clearance was also considered across the ABWP2 site. There is a risk of PTS onset up to 1.2 km for VHF cetaceans (unweighted $L_{p,pk}$ criteria) with the use of the expected technique of low-order clearance. In the event that a high-order detonation does occur, the maximum PTS onset range is up to 14 km from the largest UXO device considered (800 kg + donor charge), using the unweighted $L_{p,pk}$ criteria for VHF cetaceans. However, this is likely to be highly precautionary as the impact range is based on a 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.

By its nature, numerical modelling will produce results that indicate a precise range at which a criterion will be reached, but this does not reflect the inherent uncertainty in the physical processes, including many that change constantly under real world conditions. While the results present specific ranges at which each impact threshold is met based on the modelling results, the ranges should be taken as indicative in determining where environmental effects may occur in receptors during the proposed operations.

The outputs of this modelling have been used to inform assessments of the underwater noise impacts on marine mammals and fish at ABWP2 within the EIAR and NIS.

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Appendix A Additional modelling results

A.1 First pile strike

Table A-1 to Table A-45 present the single strike ($L_{p,pk}$ and $L_{p,RMS}$) impact ranges when considering the first pile strike of the WTG and OSP foundation modelling scenarios.

A.1.1 WTG foundations

Worst Case scenario

Table A-1: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the first hammer strike during the WTG foundation installation scenario at the North (WT03) modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		WTG foundation (first strike)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.48 km²	400 m	380 m	390 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km²	80 m	80 m	80 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	2.4 km²	930 m	840 m	880 m
	PCW (212 dB)	0.03 km²	100 m	100 m	100 m

Table A-2: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) impulsive behavioural disturbance criteria for the first hammer strike during the WTG foundation installation scenario at the North (WT03) modelling location.

NOAA (2005) Unweighted $L_{p,RMS}$		WTG foundation (first strike)			
		Area	Maximum range	Minimum range	Mean range
Level B	160 dB	370 km²	14 km	5.1 km	11 km

Table A-3: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the first hammer strike during the WTG foundation installation scenario at the North (WT03) modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		WTG foundation (first strike)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.02 km²	80 m	80 m	80 m
	207 dB	0.12 km²	200 m	190 m	190 m

Table A-4: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the first hammer strike during the WTG foundation installation scenario at the Central (WT28) modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		WTG foundation (first strike)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.6 km²	460 m	410 m	440 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.03 km²	90 m	90 m	90 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	3.0 km²	1.1 km	770 m	970 m
	PCW (212 dB)	0.03 km²	110 m	100 m	110 m

Table A-5: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) impulsive behavioural disturbance criteria for the first hammer strike during the WTG foundation installation scenario at the Central (WT28) modelling location.

NOAA (2005) Unweighted $L_{p,RMS}$		**WTG foundation (first strike)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	510 km²	17 km	5.0 km	12 km

Table A-6: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the first hammer strike during the WTG foundation installation scenario at the Central (WT28) modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		**WTG foundation (first strike)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	0.03 km²	90 m	90 m	90 m
	207 dB	0.15 km²	220 m	210 m	220 m

Table A-7: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the first hammer strike during the WTG foundation installation scenario at the South west (WT53) modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		**WTG foundation (first strike)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.42 km²	400 m	340 m	370 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km²	80 m	80 m	80 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	2.2 km²	930 m	730 m	840 m
	PCW (212 dB)	0.03 km²	90 m	90 m	90 m

Table A-8: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) impulsive behavioural disturbance criteria for the first hammer strike during the WTG foundation installation scenario at the South west (WT53) modelling location.

NOAA (2005) Unweighted $L_{p,RMS}$		**WTG foundation (first strike)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	510 km²	15 km	4.1 km	12 km

Table A-9: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the first hammer strike during the WTG foundation installation scenario at the South west (WT53) modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		**WTG foundation (first strike)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	0.02 km²	80 m	80 m	80 m
	207 dB	0.11 km²	190 m	170 m	180 m

Alternative ramp-up

Table A-10: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the first hammer strike during the WTG foundation installation (alternative ramp-up) scenario at the North (WT03) modelling location.

Southall *et al.* (2019)		**WTG foundation (first strike), alternative ramp-up**			
Unweighted $L_{p,pk}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.22 km^2	270 m	260 m	270 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.01 km^2	60 m	60 m	60 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	1.2 km^2	630 m	590 m	610 m
	PCW (212 dB)	0.01 km^2	70 m	70 m	70 m

Table A-11: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) impulsive behavioural disturbance criteria for the first hammer strike during the WTG foundation installation (alternative ramp-up) scenario at the North (WT03) modelling location.

NOAA (2005)		**WTG foundation (first strike), alternative ramp-up**			
Unweighted $L_{p,RMS}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	240 km^2	10 km	4.7 km	8.6 km

Table A-12: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the first hammer strike during the WTG foundation installation (alternative ramp-up) scenario at the North (WT03) modelling location.

Popper *et al.* (2014)		**WTG foundation (first strike), alternative ramp-up**			
Unweighted $L_{p,pk}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	0.01 km^2	60 m	60 m	60 m
	207 dB	0.06 km^2	130 m	130 m	130 m

Table A-13: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the first hammer strike during the WTG foundation installation (alternative ramp-up) scenario at the Central (WT28) modelling location.

Southall *et al.* (2019)		**WTG foundation (first strike), alternative ramp-up**			
Unweighted $L_{p,pk}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.28 km^2	310 m	290 m	300 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.01 km^2	60 m	60 m	60 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	1.5 km^2	740 m	600 m	680 m
	PCW (212 dB)	0.02 km^2	70 m	70 m	70 m

Table A-14: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) impulsive behavioural disturbance criteria for the first hammer strike during the WTG foundation installation (alternative ramp-up) scenario at the Central (WT28) modelling location.

NOAA (2005)		**WTG foundation (first strike), alternative ramp-up**			
Unweighted $L_{p,RMS}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	310 km^2	13 km	4.2 km	9.5 km

Table A-15: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the first hammer strike during the WTG foundation installation (alternative ramp-up) scenario at the Central (WT28) modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		**WTG foundation (first strike) , alternative ramp-up**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	0.01 km²	60 m	60 m	60 m
	207 dB	0.07 km²	150 m	140 m	150 m

Table A-16: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the first hammer strike during the WTG foundation installation (alternative ramp-up) scenario at the South west (WT53) modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		**WTG foundation (first strike) , alternative ramp-up**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.2 km²	270 m	240 m	250 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	< 0.01 km²	50 m	50 m	50 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	1.1 km²	630 m	520 m	580 m
	PCW (212 dB)	0.01 km²	60 m	60 m	60 m

Table A-17: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) impulsive behavioural disturbance criteria for the first hammer strike during the WTG foundation installation (alternative ramp-up) scenario at the South west (WT53) modelling location.

NOAA (2005) Unweighted $L_{p,RMS}$		**WTG foundation (first strike), alternative ramp-up**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	320 km²	11 km	3.7 km	9.9 km

Table A-18: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the first hammer strike during the WTG foundation installation (alternative ramp-up) scenario at the South west (WT53) modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		**WTG foundation (first strike) , alternative ramp-up**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	< 0.01 km²	50 m	50 m	50 m
	207 dB	0.05 km²	130 m	120 m	130 m

Mitigation

Table A-19: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the first hammer strike during the mitigated WTG foundation installation scenario at the North (WT03) modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		**WTG foundation (first strike), mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.16 km²	230 m	220 m	220 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	< 0.01 km²	50 m	50 m	50 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	0.83 km²	530 m	500 m	510 m
	PCW (212 dB)	< 0.01 km²	50 m	50 m	50 m

Table A-20: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) impulsive behavioural disturbance criteria for the first hammer strike during the mitigated WTG foundation installation scenario at the North (WT03) modelling location.

NOAA (2005)		**WTG foundation (first strike), mitigated**			
Unweighted $L_{p,RMS}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	180 km^2	9.1 km	4.3 km	7.4 km

Table A-21: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the first hammer strike during the mitigated WTG foundation installation scenario at the North (WT03) modelling location.

Popper *et al.* (2014)		**WTG foundation (first strike), mitigated**			
Unweighted $L_{p,pk}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	< 0.01 km^2	50 m	50 m	50 m
	207 dB	0.04 km^2	110 m	110 m	110 m

Table A-22: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the first hammer strike during the mitigated WTG foundation installation scenario at the Central (WT28) modelling location.

Southall *et al.* (2019)		**WTG foundation (first strike), mitigated**			
Unweighted $L_{p,pk}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.19 km^2	260 m	240 m	250 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	< 0.01 km^2	50 m	50 m	50 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	1.0 km^2	610 m	530 m	580 m
	PCW (212 dB)	0.01 km^2	60 m	60 m	60 m

Table A-23: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) impulsive behavioural disturbance criteria for the first hammer strike during the mitigated WTG foundation installation scenario at the Central (WT28) modelling location.

NOAA (2005)		**WTG foundation (first strike), mitigated**			
Unweighted $L_{p,RMS}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	210 km^2	11 km	3.8 km	7.9 km

Table A-24: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the first hammer strike during the mitigated WTG foundation installation scenario at the Central (WT28) modelling location.

Popper *et al.* (2014)		**WTG foundation (first strike), mitigated**			
Unweighted $L_{p,pk}$		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	< 0.01 km^2	50 m	50 m	50 m
	207 dB	0.05 km^2	120 m	120 m	120 m

Table A-25: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the first hammer strike during the mitigated WTG foundation installation scenario at the South west (WT53) modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		**WTG foundation (first strike), mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.14 km^2	220 m	200 m	210 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	< 0.01 km^2	50 m	< 50 m	50 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	0.74 km^2	530 m	440 m	480 m
	PCW (212 dB)	< 0.01 km^2	50 m	50 m	50 m

Table A-26: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) impulsive behavioural disturbance criteria for the first hammer strike during the mitigated WTG foundation installation scenario at the South west (WT53) modelling location.

NOAA (2005) Unweighted $L_{p,RMS}$		**WTG foundation (first strike), mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	230 km^2	9.4 km	3.4 km	8.4 km

Table A-27: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the first hammer strike during the mitigated WTG foundation installation scenario at the South west (WT53) modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		**WTG foundation (first strike), mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	< 0.01 km^2	50 m	< 50 m	50 m
	207 dB	0.03 km^2	110 m	100 m	100 m

A.1.2 OSP foundations

Table A-28: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the first hammer strike during the OSP foundation installation scenario at the North OSP modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		**OSP foundation (first strike)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.39 km^2	360 m	340 m	350 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km^2	80 m	80 m	80 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	1.9 km^2	810 m	730 m	780 m
	PCW (212 dB)	0.02 km^2	90 m	90 m	90 m

Table A-29: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) impulsive behavioural disturbance criteria for the first hammer strike during the OSP foundation installation scenario at the North OSP modelling location.

NOAA (2005) Unweighted $L_{p,RMS}$		**OSP foundation (first strike)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	320 km^2	12 km	4.8 km	9.9 km

Table A-30: Unweighted $L_{p,pk}$ *impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the first hammer strike during the WTG foundation installation scenario at the North OSP modelling location.*

Popper *et al.* (2014) Unweighted $L_{p,pk}$		**OSP foundation (first strike)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	0.02 km²	80 m	80 m	80 m
	207 dB	0.1 km²	180 m	170 m	180 m

Table A-31: Unweighted $L_{p,pk}$ *impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the first hammer strike during the WTG foundation installation scenario at the South OSP modelling location.*

Southall *et al.* (2019) Unweighted $L_{p,pk}$		**OSP foundation (first strike)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.18 km²	260 m	220 m	240 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.01 km²	60 m	60 m	60 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	0.85 km²	610 m	460 m	520 m
	PCW (212 dB)	0.01 km²	70 m	60 m	70 m

Table A-32: Unweighted $L_{p,RMS}$ *impact areas and ranges for marine mammals using the NOAA (2005) impulsive behavioural disturbance criteria for the first hammer strike during the OSP foundation installation scenario at the South OSP modelling location.*

NOAA (2005) Unweighted $L_{p,RMS}$		**OSP foundation (first strike)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B	160 dB	260 km²	11 km	1.4 km	8.9 km

Table A-33: Unweighted $L_{p,pk}$ *impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the first hammer strike during the OSP foundation installation scenario at the South OSP modelling location.*

Popper *et al.* (2014) Unweighted $L_{p,pk}$		**OSP foundation (first strike)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	0.01 km²	60 m	60 m	60 m
	207 dB	0.05 km²	130 m	120 m	130 m

Alternative ramp-up

Table A-34: Unweighted $L_{p,pk}$ *impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the first hammer strike during the OSP foundation installation (alternative ramp-up) scenario at the North OSP modelling location.*

Southall *et al.* (2019) Unweighted $L_{p,pk}$		**OSP foundation (first strike), alternative ramp-up**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.18 km²	250 m	240 m	240 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	< 0.01 km²	50 m	50 m	50 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	0.93 km²	560 m	520 m	540 m
	PCW (212 dB)	0.01 km²	60 m	60 m	60 m

Table A-35: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) impulsive behavioural disturbance criteria for the first hammer strike during the OSP foundation installation (alternative ramp-up) scenario at the North OSP modelling location.

NOAA (2005) Unweighted $L_{p,RMS}$		OSP foundation (first strike), alternative ramp-up			
		Area	Maximum range	Minimum range	Mean range
Level B	160 dB	210 km²	9.6 km	4.1 km	8.0 km

Table A-36: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the first hammer strike during the OSP foundation installation (alternative ramp-up) scenario at the North OSP modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		OSP foundation (first strike) , alternative ramp-up			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	< 0.01 km²	50 m	50 m	50 m
	207 dB	0.05 km²	120 m	120 m	120 m

Table A-37: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the first hammer strike during the OSP foundation installation (alternative ramp-up) scenario at the South OSP modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		OSP foundation (first strike) , alternative ramp-up			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.09 km²	180 m	160 m	170 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	0.42 km²	410 m	330 m	360 m
	PCW (212 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m

Table A-38: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) impulsive behavioural disturbance criteria for the first hammer strike during the OSP foundation installation (alternative ramp-up) scenario at the South OSP modelling location.

NOAA (2005) Unweighted $L_{p,RMS}$		OSP foundation (first strike), alternative ramp-up			
		Area	Maximum range	Minimum range	Mean range
Level B	160 dB	160 km²	8.0 km	1.4 km	7.0 km

Table A-39: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the first hammer strike during the OSP foundation installation (alternative ramp-up) scenario at the South OSP modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		OSP foundation (first strike) , alternative ramp-up			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	207 dB	0.02 km²	90 m	90 m	90 m

Mitigation

Table A-40: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the first hammer strike during the mitigated OSP foundation installation scenario at the North OSP modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		OSP foundation (first strike), mitigated			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.13 km²	210 m	200 m	200 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	0.66 km²	470 m	440 m	460 m
	PCW (212 dB)	< 0.01 km²	50 m	50 m	50 m

Table A-41: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) impulsive behavioural disturbance criteria for the first hammer strike during the mitigated OSP foundation installation scenario at the North OSP modelling location.

NOAA (2005) Unweighted $L_{p,RMS}$		OSP foundation (first strike), mitigated			
		Area	Maximum range	Minimum range	Mean range
Level B	160 dB	150 km²	8.3 km	3.7 km	6.9 km

Table A-42: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the first hammer strike during the mitigated OSP foundation installation scenario at the North OSP modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		OSP foundation (first strike), mitigated			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	207 dB	0.03 km²	100 m	100 m	100 m

Table A-43: Unweighted $L_{p,pk}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the first hammer strike during the mitigated OSP foundation installation scenario at the South OSP modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		OSP foundation (first strike), mitigated			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.06 km²	150 m	140 m	140 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	0.3 km²	350 m	290 m	310 m
	PCW (212 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m

Table A-44: Unweighted $L_{p,RMS}$ impact areas and ranges for marine mammals using the NOAA (2005) impulsive behavioural disturbance criteria for the first hammer strike during the mitigated OSP foundation installation scenario at the South OSP modelling location.

NOAA (2005) Unweighted $L_{p,RMS}$		OSP foundation (first strike), mitigated			
		Area	Maximum range	Minimum range	Mean range
Level B	160 dB	110 km²	6.7 km	1.4 km	5.9 km

Table A-45: Unweighted $L_{p,pk}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the first hammer strike during the mitigated OSP foundation installation scenario at the South OSP modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		**OSP foundation (first strike), mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Pile driving	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	0.02 km^2	80 m	70 m	70 m

A.2 Non-impulsive criteria

Following sections 2.2.1 and 2.3.1 where the principles of impulsive and non-impulsive noise are explained, Table A-46 to Table A-60 present the modelled impact piling noise in terms of the non-impulsive $L_{E,p,t}$ criteria from Southall *et al*. (2019). $L_{p,pk}$ criteria are not suitable for non-impulsive consideration so are not included. Note that although the impact ranges below have been calculated to the non-impulsive thresholds, in practice they should only be considered where the impact range is in excess of 5 km.

A.2.1 WTG foundations

Table A-46: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the WTG installation scenario at the North (WT03) modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**WTG foundation**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (173 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (201 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	LF (179 dB)	160 km^2	13 km	260 m	5.7 km
	HF (178 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	8.1 km^2	2.5 km	< 50 m	1.3 km
	PCW (181 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A-47: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the WTG installation scenario at the Central (WT28) modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**WTG foundation**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (173 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (201 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	LF (179 dB)	350 km^2	17 km	330 m	7.9 km
	HF (178 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	20 km^2	4.1 km	< 50 m	1.9 km
	PCW (181 dB)	< 0.01 km^2	70 m	< 50 m	< 50 m

Table A-48: Weighted $L_{E,p,24h,wtd}$ *impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the WTG installation scenario at the South west (WT53) modelling location assuming fleeing receptors.*

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**WTG foundation**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (173 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (201 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	LF (179 dB)	290 km^2	15 km	200 m	8.1 km
	HF (178 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	22 km^2	3.8 km	< 50 m	2.4 km
	PCW (181 dB)	< 0.01 km^2	50 m	< 50 m	< 50 m

Alternative ramp-up

Table A-49: Weighted $L_{E,p,24h,wtd}$ *impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the WTG installation (alternative ramp-up) scenario at the North (WT03) modelling location assuming fleeing receptors.*

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**WTG foundation (alternative ramp-up)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (173 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (201 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	LF (179 dB)	22 km^2	5.4 km	130 m	1.7 km
	HF (178 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (181 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A-50: Weighted $L_{E,p,24h,wtd}$ *impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the WTG installation scenario (alternative ramp-up) at the Central (WT28) modelling location assuming fleeing receptors.*

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**WTG foundation (alternative ramp-up)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (173 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (201 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	LF (179 dB)	97 km^2	9.7 km	140 m	3.8 km
	HF (178 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	0.21 km^2	570 m	< 50 m	160 m
	PCW (181 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A-51: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the WTG installation scenario (alternative ramp-up) at the South west (WT53) modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**WTG foundation (alternative ramp-up)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (198 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (173 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	PCW (201 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	LF (179 dB)	60 km²	8.0 km	120 m	3.1 km
	HF (178 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	0.06 km²	340 m	< 50 m	100 m
	PCW (181 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m

Mitigation

Table A-52: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the mitigated WTG installation scenario at the North (WT03) modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**WTG foundation, mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (198 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (173 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	PCW (201 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	LF (179 dB)	16 km²	4.1 km	100 m	1.7 km
	HF (178 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	PCW (181 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m

Table A-53: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the mitigated WTG installation scenario at the Central (WT28) modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**WTG foundation, mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (198 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (173 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	PCW (201 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	LF (179 dB)	57 km²	7.1 km	110 m	3.0 km
	HF (178 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	0.01 km²	120 m	< 50 m	50 m
	PCW (181 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m

Table A-54: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the mitigated WTG installation scenario at the South west (WT53) modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**WTG foundation, mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (173 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (201 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	LF (179 dB)	37 km^2	5.8 km	90 m	2.8 km
	HF (178 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	< 0.01 km^2	70 m	< 50 m	< 50 m
	PCW (181 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m

A.2.2 OSP foundations

Table A-55: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the OSP installation scenario at the North OSP modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**OSP foundation**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (173 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (201 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	LF (179 dB)	110 km^2	11 km	230 m	4.6 km
	HF (178 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	5.5 km^2	2.2 km	< 50 m	1.1 km
	PCW (181 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A-56: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the OSP installation scenario at the South OSP modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**OSP foundation**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (173 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (201 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	LF (179 dB)	47 km^2	7.0 km	120 m	3.1 km
	HF (178 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	5.6 km^2	2.2 km	< 50 m	1.2 km
	PCW (181 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Alternative ramp-up

Table A-57: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the OSP installation (alternative ramp-up) scenario at the North OSP modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**OSP foundation (alternative ramp-up)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (173 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (201 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	LF (179 dB)	8.6 km^2	3.8 km	120 m	1.0 km
	HF (178 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (181 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A-58: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the OSP installation scenario (alternative ramp-up) at the South OSP modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**OSP foundation (alternative ramp-up)**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (173 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (201 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	LF (179 dB)	0.29 km^2	840 m	80 m	240 m
	HF (178 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (181 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Mitigation

Table A-59: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the mitigated OSP installation scenario at the North OSP modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**OSP foundation, mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (173 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (201 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	LF (179 dB)	7.0 km^2	3.0 km	100 m	1.1 km
	HF (178 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (181 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A-60: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the mitigated OSP installation scenario at the South OSP modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**OSP foundation, mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (173 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (201 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	LF (179 dB)	0.28 km^2	790 m	70 m	240 m
	HF (178 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (181 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m