MachairWind Offshore Windfarm

Appendix 10.1 Underwater Noise Modelling Report

MachairWind Offshore Development: Underwater Noise Modelling Assessment

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Executive Summary

Subacoustech Environmental, on behalf of Haskoning, has undertaken a study in order to assess the potential underwater noise and its effects during construction and operation of the MachairWind Offshore Development (MachairWind).

The primary noise source considered as part of the assessment has been identified as impact piling to install foundations for wind turbine generators (WTGs) and offshore substation platforms (OSPs). Modelling of underwater noise generated by impact piling was undertaken at four representative locations, with the loudest levels predicted at the western corner due primarily to the deeper water to the north and west of the site.

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 injury (permanent threshold shift (PTS)) onset ranges from impact piling were predicted for receptors in the low-frequency (LF) cetacean hearing category, which includes minke whale, with maximum impact ranges out to 27 km. For fish, the largest recoverable injury ranges were predicted to be 14 km for a stationary receptor, or 1.6 km when considering a moving receptor.

When considering noise reduction from mitigation, a nominal 10 dB reduction was included as an achievable figure, although specific systems to be implemented are not yet determined. With this reduction included, the maximum PTS range for LF cetaceans reduced to 2.1 km and the maximum recoverable injury ranges for stationary fish reduced to 3.5 km.

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 ($L_{p,pk}$) 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 (750 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 worst-case criterion and calculation methodology that does not account for any smoothing of the pulse over long ranges, which would reduce the pulse peak and other characteristics of the sound that cause injury. High-order detonation has been included in this assessment as a worst case scenario, however is not the preferred 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 assessments.

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Terminology

Decibel (dB)	A customary scale commonly used (in various ways) for reporting levels of sound. The dB represents a ratio/comparison of a sound measurement (e.g., sound pressure) over a fixed reference level. The dB symbol is followed by a reference value (e.g., re 1 µPa).
Peak pressure	The highest pressure above or below ambient that is associated with a sound wave.
Peak-to-peak pressure	The sum of the highest positive and negative pressures that are associated with a sound wave.
Permanent Threshold Shift (PTS)	Noise threshold that represents the onset level of a permanent impairment hearing caused by acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the ear, and thus a permanent reduction of hearing acuity.
Root Mean Square (RMS)	The square root of the arithmetic average of a set of squared instantaneous values. Used for presentation of an average sound pressure level.
Sound Exposure Level (SEL or $L_{E,p}$)	The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.
Sound Exposure Level, cumulative (SEL_{cum} or $L_{E,p,t}$)	Single value for the collected, combined total of sound exposure over a specified time or multiple instances of a noise source.
Sound Exposure Level, single strike (SEL_{ss} 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} or $L_{p,pk}$)	The highest (zero-peak) positive or negative sound pressure, in decibels.
Temporary Threshold Shift (TTS)	Onset threshold level for a temporary reduction of hearing acuity caused by exposure to sound.
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

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

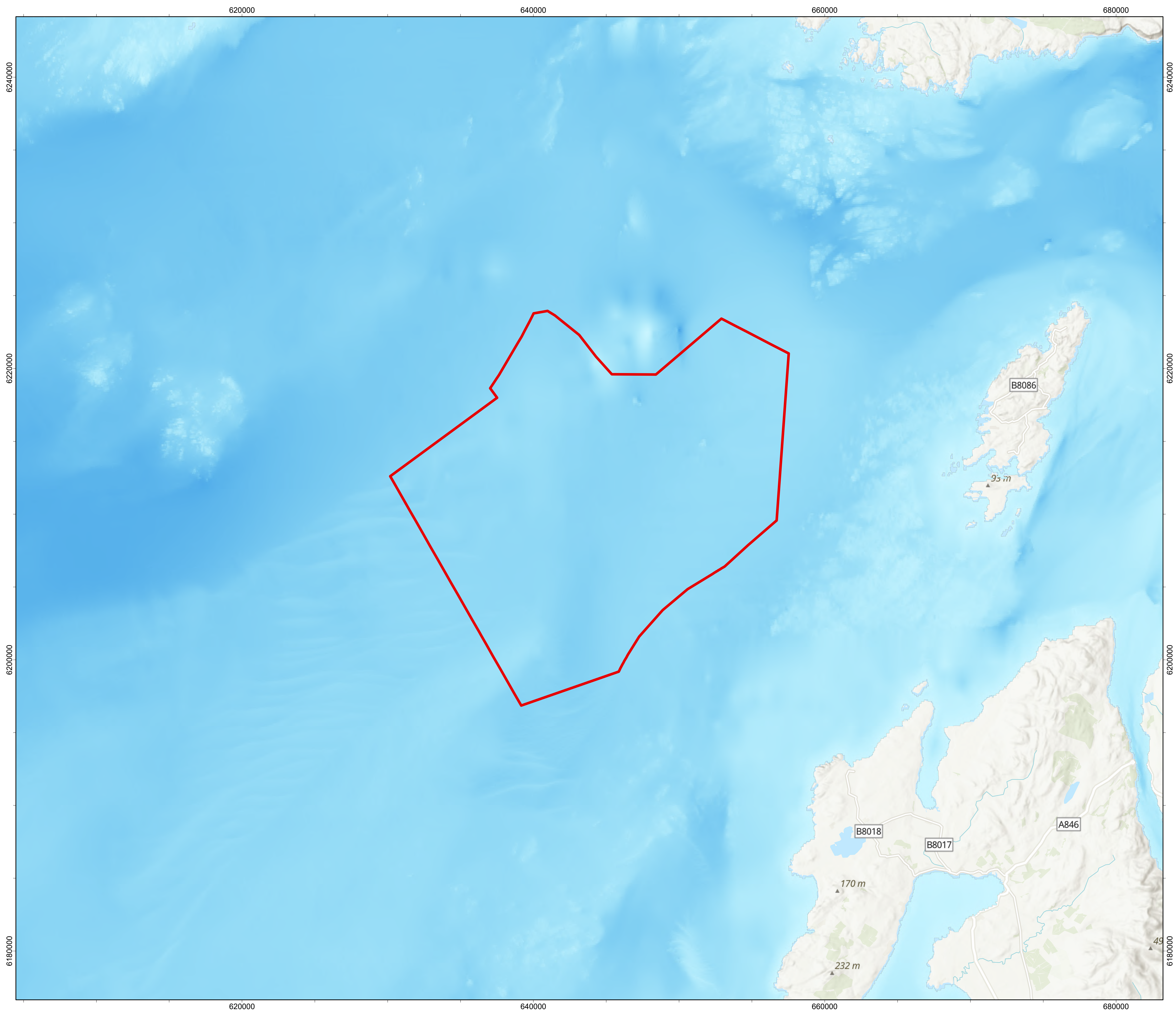
Units

dB	Decibel (sound pressure)
GW	Gigawatt (power)
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)
mm/s	Millimetres per second (particle velocity)
m/s	Metres per second (speed)
MW	Megawatt (power)
Pa	Pascal (pressure)
Pa^2s	Pascal squared seconds (acoustic energy)
µPa	Micropascal (pressure)

1 Introduction

MachairWind is a proposed offshore windfarm development located Northwest of Islay and West of Colonsay off the west coast of Scotland. As part of the Environmental Impact Assessment (EIA) process, Subacoustech Environmental Ltd has undertaken detailed modelling and analysis in relation to underwater noise and its effect on marine mammals and fish during the construction and operation of MachairWind.

The array has a proposed capacity of up to 2 GW and covers an area of 448 km^2 and is situated approximately 12.4 km west of Colonsay and 15 km off Islay. The location of MachairWind is shown in Figure 1.1.



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2	13/11/2025	AB	GC	SB	PM

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Figure 1.1: Overview map showing the MachairWind WDA, its location next to the Scottish coast, and the surrounding bathymetry

Service Layer Credits: World Ocean Reference: Sources: Esri, TomTom, Garmin, GEBCO, National Geographic, NOAA, and the GIS User Community
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This report presents a detailed assessment of the potential underwater noise during the construction and operation of MachairWind, 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 noise attenuation systems (section 4).
- Modelling of the other noise sources expected around construction and operation of MachairWind, including cable laying, dredging, drilling, rock placement, trenching, vessel noise, operational WTG noise and UXO clearance (section 5).
- Summary and conclusions (section 6).

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

2 Background to underwater noise metrics

Sound travels much faster in water (approximately 1,500 m/s) than in air (340 m/s). Since water is a relatively incompressible, dense medium, the pressure associated with underwater sound tends to be much higher than in air. Therefore, it should be noted that underwater noise levels stated in this report are different to those commonly stated for airborne noise levels, as a different scale is used between in water and in air measurements. Therefore, noise levels measured in air should not be compared to noise levels measured underwater.

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 Q_{ref} is the reference quantity.

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

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

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

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 (SPL, L_p)

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

Where SPL is used to characterise transient pressure waves, such as that from impact piling, seismic airgun or underwater explosions, it is critical that the period over which the RMS level is calculated is quoted (e.g., $L_{p,125ms}$) For instance, in the case of a pile strike lasting a tenth of a second, the mean taken over a tenth of a second will be ten times higher than the mean averaged over one second. Often, transient sounds such as these are quantified using "peak" SPLs ($L_{p,pk}$) or Sound Exposure Levels (SEL or $L_{E,p}$).

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

2.1.2 Peak sound pressure level (peak SPL, $L_{p,pk}$)

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

2.1.3 Sound exposure level (SEL, $L_{E,p}$)

When considering the noise from transient sources, the issue of the duration of the pressure wave is often addressed by measuring the total acoustic energy (energy flux density) of the wave. This form of analysis was used by Bebb and Wright (1953, 1954a, 1954b, 1955), and later by Rawlins (1987), to explain the apparent discrepancies in the biological effect of short and long-range blast waves on human divers. More recently, this form of analysis has been used to develop criteria for assessing injury ranges for fish and marine mammals from various noise sources (Popper *et al.,* 2014; Southall *et al.,* 2019; 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^2s).

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

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

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 µPa²s.

2.2 Properties of sound

2.2.1 Impulsive and non-impulsive noise

Sound can be generally categorised into two types: impulsive noise and non-impulsive noise. Non-impulsive noise is defined as a steady-state noise which does not necessarily have a long duration (e.g., vibropiling, drilling). Impulsive noise is 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 (e.g., 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_{RMS} (L_p).

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, when 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) are calculated above 5 km. Results in respect of both impulsive and non-impulsive criteria (see section 2.3.1 for marine mammals) have been presented for impact piling noise and UXO clearance.

2.2.2 Particle motion

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

It has been identified by several researchers that many fish species (e.g., Popper and Hawkins, 2019; Nedelec *et al*., 2016; Radford *et al.,* 2012), as well as marine invertebrates (see 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 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.

At the time of writing, these include the most up-to-date and authoritative criteria for assessing environmental effects for use in impact assessments. Although it is noted that other papers have been published recently with new guidance (e.g., NMFS, 2024), these have not yet been accepted by Scottish regulators.

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 of this report. It provides identical thresholds to those from the National Marine Fisheries Service (NMFS) (2018) guidance for marine mammals. It should be noted that, despite the identical thresholds, the marine mammal hearing groups are described slightly differently in the Southall *et al.* (2019) paper to the NMFS (2018) guidance. Therefore, care should be taken 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 the 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 $L_{p,pk}$ and $L_{E,p,t}$ respectively 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, bottle nose 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)

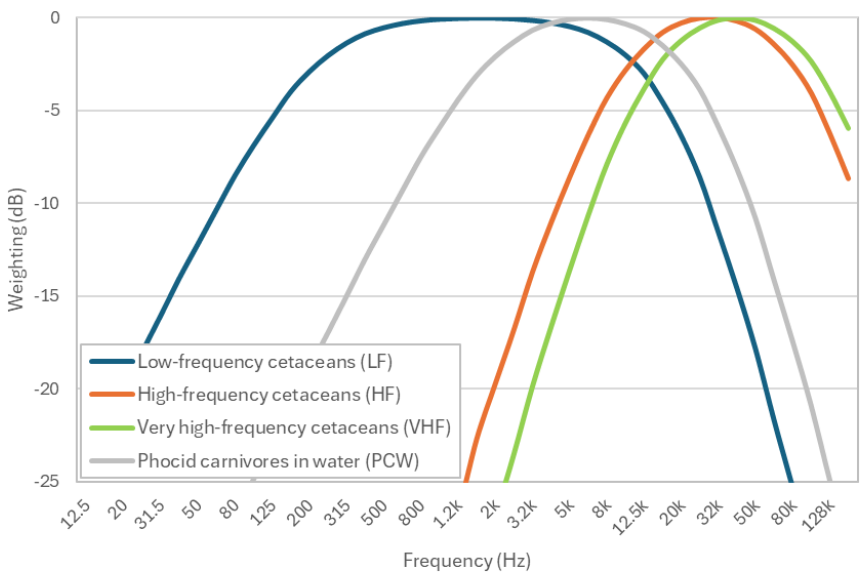


Figure 2.1: Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al., 2019)

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

- 2.1 m/s for low-frequency cetaceans (LF) (Scottish Natural Heritage; SNH, 2016).
- 1.52 m/s for high-frequency cetaceans (HF) (Bailey and Thompson, 2006).
- 1.4 m/s for very high-frequency cetaceans (VHF) (SNH, 2016).
- 1.8 m/s for phocid carnivores in water (PCW) (SNH, 2016).

These are considered worst-case assumptions as marine mammals are expected to be able to swim much faster under stress conditions (Kastelein *et al*., 2018), especially at the start of any noisy process when the receptor will be at its closest.

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

2.3.2 Fish (including sharks)

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

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

For each sound source, the marine fauna 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.

Elasmobranchs, in particular the basking shark, are a key consideration at MachairWind but very little data in respect of shark hearing sensitivity is available. In general, sharks are perceived as having a relatively low sensitivity to sound compared to teleost fish (Hart and Collin, 2015), with an auditory range of 20-1500 Hz and peak sensitivity of 200-600 Hz (Chapuis *et al.,* 2019). Although this is for sharks in general rather than basking sharks, this indicates they may be closer to flatfish (fish: no swim bladder, as per Popper *et al.* 2014), and far below the sensitivity of marine mammals. As Popper *et al.* (2014) (and reiterated in Popper *et al.* 2019), includes sharks in the 'fish without a swim bladder' category, this is unlikely to underestimate the sensitivity of basking sharks.

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 $L_{E,p,t}$ thresholds are required for fish (including basking sharks), 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 m/s (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 far more likely to be benthic species or 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, covering pile driving, explosions, and shipping and continuous noise sources. Similar to the Southall *et al*. (2019) criteria in section 2.3.1, the Popper *et al*. (2014) criteria use the SPL_{peak}, SEL_{cum}, and SPL_{RMS} notation, and this report will present the ISO 18405:2017 notation ($L_{p,pk}$, $L_{E,p,t}$, and L_p, 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 mm/s peak velocity	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low

Table 2.6: Recommended guidelines for shipping and continuous 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 in regarding the ability to predict the consequences of the particle motion of a noise source, and the sensitivity of fish to a specific particle motion value. Therefore, as stated by Popper and Hawkins (2019): "since there is an immediate need for updated criteria and guidelines on potential effects of anthropogenic sound on fishes, we recommend, as do our colleagues in Sweden (Andersson *et al*., 2017), that the criteria proposed by Popper *et al*. (2014) should be used."

2.3.3 Marine invertebrates

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

Comparatively, the studies described by Solé *et al.* (2023) show a general inconsistency in the way noise impacts have been quantified for marine invertebrates. For example, Hubert *et al*. (2021) notes behavioural changes in blue mussels to 150 and 300 Hz tones, whereas Spiga *et al.* (2016) describes behavioural changes in the same species at $L_{E,p}$ (single pulse) 153.47 dB re 1 µPa. These inconsistencies make it difficult to generate accurate thresholds for the onset of any impact for 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. However, due to the degree of uncertainty, benthic species will not be considered further.

3 Modelling methodology

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

Of those considered, the noise source of most importance is impact piling to install foundations, due to the potential noise levels and duration it will be present (Bailey *et al*., 2014). As such, the noise related to impact piling activity is the primary focus of this study.

The modelling of impact piling has been undertaken using the INSPIRE underwater noise model, which has been widely used for windfarm assessments around the UK. 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 well-suited for use at MachairWind.

INSPIRE provides estimates of unweighted $L_{p,pk}$, $L_{E,p,ss}$, and $L_{E,p,t}$ noise levels, as well as other weighted noise metrics. Calculations are made along 180 equally-spaced 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.

Simpler modelling approaches have been used for noise sources other than impact piling. These are covered 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 based on every pulse being the 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 any 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 this earlier version of INSPIRE was found to over-estimate some impact ranges, especially closer to the pile (< 7 km) where the exposures to noise would have the greatest effect.

The version of INSPIRE used for MachairWind (v6.0) 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 worst-case 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 of the fits between 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 $L_{E,p,ss}$.

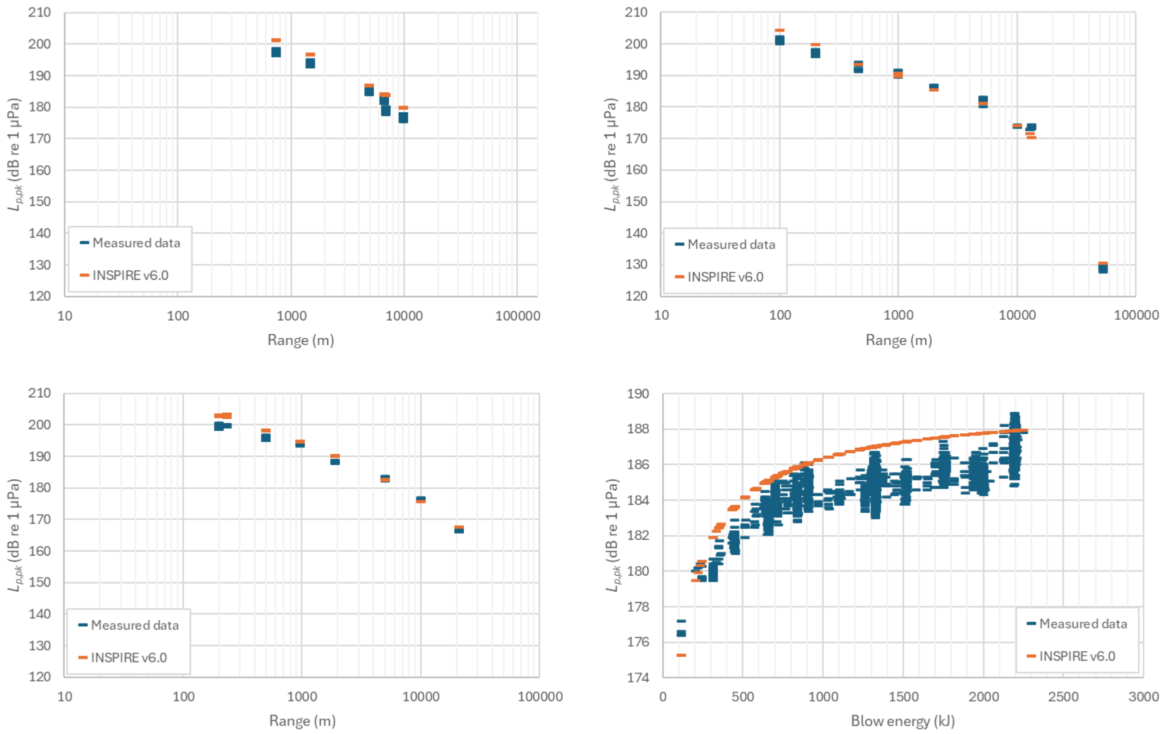


Figure 3.1: Comparison between example measured $L_{p,pk}$ impact piling data (blue) and modelled data using INSPIRE v6.0 (orange)[1]

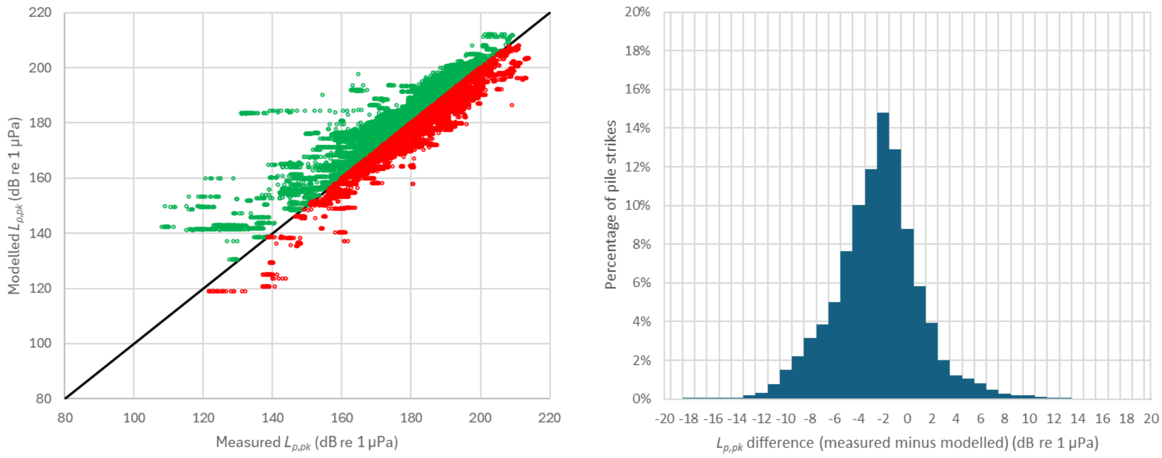


Figure 3.2: Distribution of measured impact piling data against modelled levels using INSPIRE v6.0 for unweighted $L_{p,pk}$ (R^2 = 0.81)

[1] Top left: 8.6 m diameter pile, 2,500 kJ max hammer energy, North Sea, 2024; Top right: 5.2 m diameter pile, 1,700 kJ max hammer energy, Lincolnshire Coast, 2011; 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.

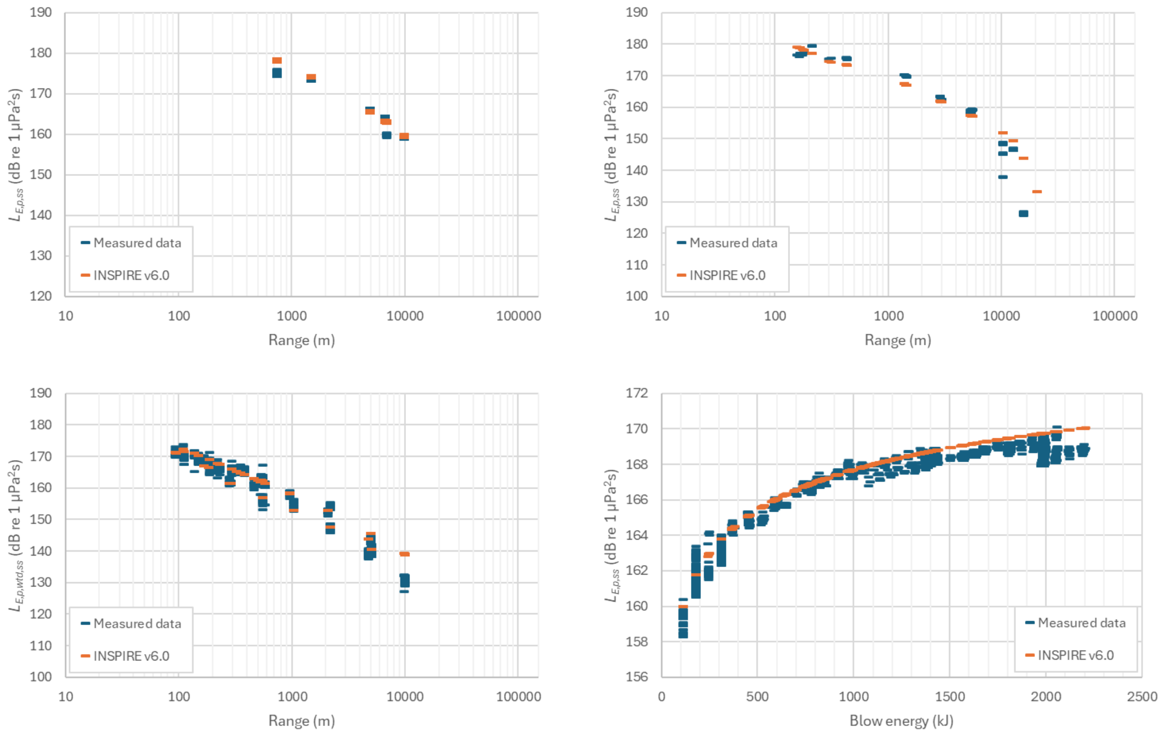


Figure 3.3: Comparison between example measured $L_{E,p,ss}$, impact piling data (blue) and modelled data using INSPIRE v6.0 (orange)[2]

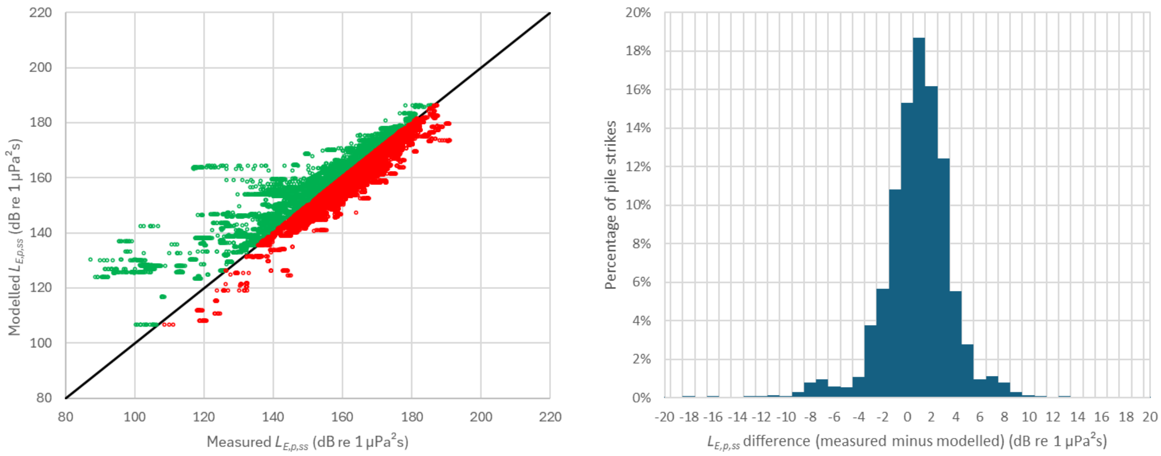


Figure 3.4: Distribution of measured impact piling data against modelled levels using INSPIRE v6.0 for unweighted $L_{E,p,ss}$ (R^2 = 0.89)

[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.

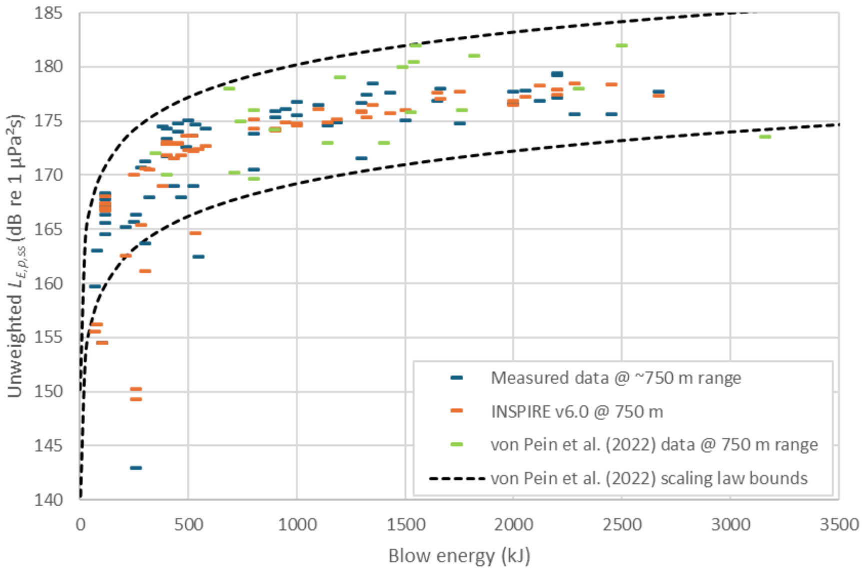


Figure 3.5: Data relating blow energy to noise level ($L_{E,p,ss}$) adapted from von Pein et al. (2022) (green) overlaid with Subacoustech measured data (blue) and INSPIRE v6.0 predictions (orange). Upper and lower scaling law bounds from von Pein (2022).

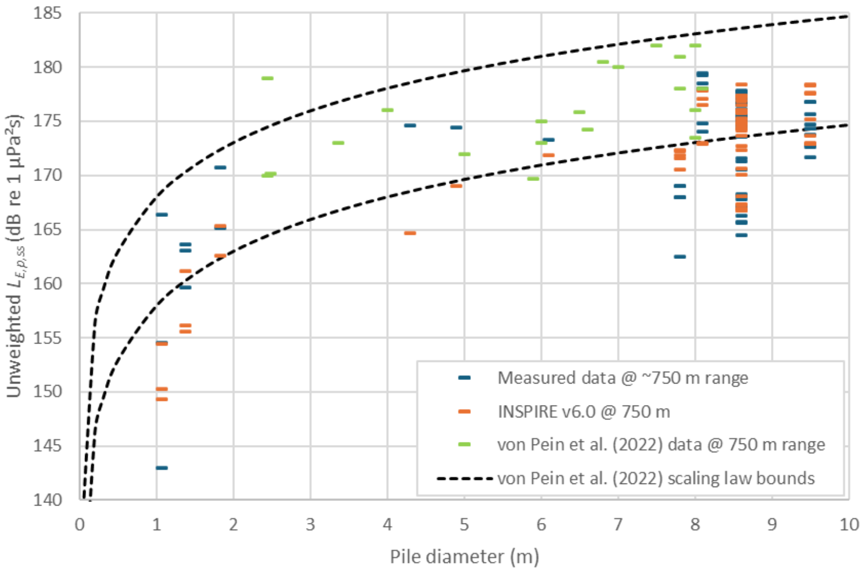


Figure 3.6: Data relating pile diameter to noise level ($L_{E,p,ss}$) adapted from von Pein (2022) (green) overlaid with Subacoustech measured data (blue) and INSPIRE v6.0 predictions (orange). Upper and lower scaling law bounds from von Pein (2022).

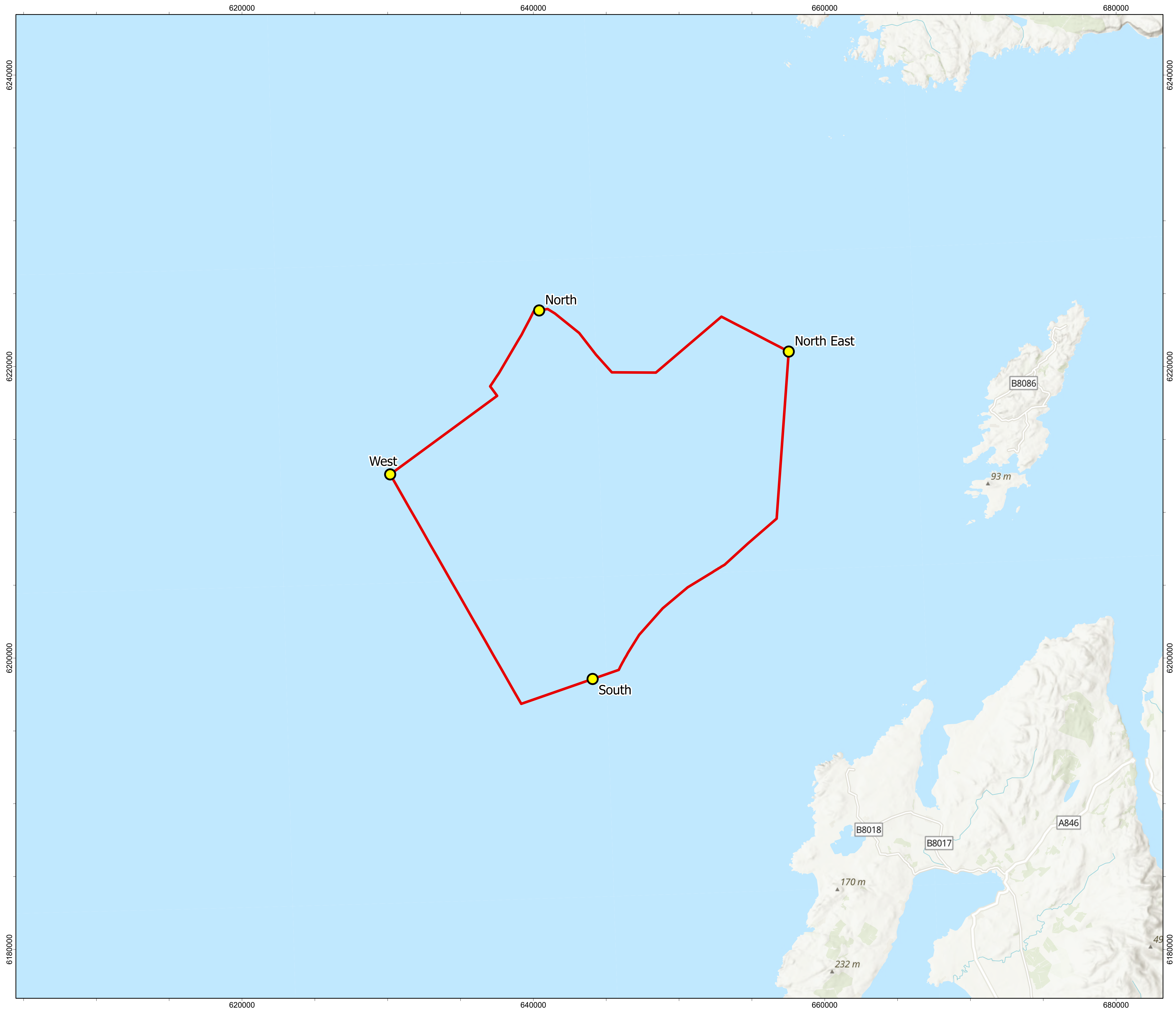
3.2 Input parameters

3.2.1 Modelling locations

Modelling for impact piling noise to install foundations for WTGs and OSPs has been undertaken at four representative locations covering the extents of MachairWind, giving a spread of water depths, distances to shore and bathymetry stretching into deeper water around the site. Both monopile and jacket pin piles are proposed as foundation options. These locations are summarised in Table 3.1 and illustrated in Figure 3.7.

Table 3.1: Summary of the underwater noise modelling locations used for this study.

Modelling locations	Latitude	Longitude	Water depth
North	56.13901°N	006.74055°W	60.0 m
West	56.04091°N	006.91049°W	61.4 m
Northeast	56.10833°N	006.46675°W	42.1 m
South	55.91091°N	006.69509°W	61.0 m



Windfarm Development Area

Modelling locations

N

0 5 10 Kilometres

REV	REV DATE	GIS CREATOR	GIS REVIEWER	TECHNICAL CHECKER	TECHNICAL APPROVER
2	13/11/2025	AB	GC	SB	PM

DRAWING NUMBER	MCW-DWF-ENV-MAP-RHS-000028		
DATUM	ETRS89	PROJECTION	UTM Zone 29N
SCALE	1:250,000	PAGE SIZE	A3
PROJECT TITLE	MachairWind		

Figure 3.7: Approximate positions of the modelling locations used at MachairWind

NOT TO BE USED FOR NAVIGATION

Haskoning
Enhancing Society Together

ScottishPower
Renewables

Project: C:\Users\304634\OneDrive - Royal HaskoningDHV\WIP\03 GIS\A02_Figures\03_EIA\01_WDA\Chap_10_MarineMammals\Appx_10-1_UWN\MCW_EIA_WDA_UWNModelling.aprx
Name: MCW-DWF-ENV-MAP-RHS-000028_ModellingLocations

3.2.2 Environmental conditions

With the inclusion of measured noise propagation data for similar offshore piling operations in UK waters, the INSPIRE model intrinsically accounts for various environmental conditions. This includes the differences that can occur with the temperature and salinity of the water 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 MachairWind is generally made up of sand and gravel over a bedrock of 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

Worst-case scenarios have been considered for monopile and jacket pin piles in this study:

- 15 m diameter monopiles for WTG foundations installed with a maximum blow energy of 6,600 kJ.
- 4.5 m diameter jacket pin piles for WTG and OSP foundations installed with a maximum blow energy of 4,400 kJ.

For $L_{E,p,t}$ criteria, the soft start and blow energies, along with the total duration of piling and strike rate, must be considered; this is summarised for the monopile scenario in Table 3.2 and the jacket pin pile scenario in Table 3.3.

In a 24-hour period it is expected that up to six anchor piles can be sequentially installed from the same piling vessel; this has been taken into consideration for the modelling. Where multiple sequential piles are modelled, no break has been assumed between each one as a worst-case.

Table 3.2: Summary of the soft start and ramp-up used for the monopile modelling scenario.

Monopiles	550 kJ		1,500 kJ	3,000 kJ	4,500 kJ	6,600 kJ
No. of strikes	5	100	800	800	600	5,000
Duration (mins)	5	10	20	20	20	250
Strike rate (bl/min)	1	10	40	40	30	20
7,305 strikes over 5 hours 25 minutes per pile						

Table 3.3: Summary of the soft start and ramp-up used for the jacket pin pile modelling scenario.

Jacket pin pile	450 kJ		750 kJ	1,500 kJ	2,250 kJ	4,400 kJ
No. of strikes	5	100	800	800	800	2,400
Duration (mins)	5	10	20	20	20	120
Strike rate (bl/min)	1	10	40	40	40	20
4,905 strikes over 3 hours 15 minutes per pile 29,430 strikes over 19 hours 30 minutes for six sequentially installed piles						

3.2.4 Mitigation

The effect of using noise abatement systems (NAS) as mitigation for impact piling noise has also been investigated. A generic broadband dB reduction in source level has been applied to the noise modelling to give an idea of the benefits of various NAS without committing to a specific methodology or piece of equipment.

For this study a 10 dB reduction has been assumed, and this level gives an achievable estimate based on data presented in Verfuss *et al*. (2019). In this paper, data for a big bubble curtain (BBC), a commonly deployed method, show that it provides a minimum of 10 dB attenuation in the frequency bands where marine mammals are most sensitive (i.e., 250 Hz and above). It is noted that use of a BBC is dependent on water depth and tidal speed, however, other methodologies such as piling sleeves, hydro sound dampers or hammer attachments could be used to achieve this 10 dB reduction at MachairWind.

Impact ranges with this mitigation included have been included for the North and West modelling locations.

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 3.4 and Table 3.5 for the maximum hammer energy and first pile strike hammer energy respectively. Due to the deep water at MachairWind, the majority of the apparent source levels are the same when rounded to one decimal place.

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.

Table 3.4: 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
Monopile (15 m diameter pile / 6,600 kJ maximum energy)	North	247.5 dB re 1 µPa	220.9 dB re 1 µPa²s
	West	247.5 dB re 1 µPa	220.9 dB re 1 µPa²s
	Northeast	247.5 dB re 1 µPa	220.9 dB re 1 µPa²s
	South	247.5 dB re 1 µPa	220.9 dB re 1 µPa²s
Jacket pin pile (4.5 m diameter pile / 4,400 kJ maximum energy)	North	246.0 dB re 1 µPa	218.1 dB re 1 µPa²s
	West	246.0 dB re 1 µPa	218.2 dB re 1 µPa²s
	Northeast	245.8 dB re 1 µPa	217.9 dB re 1 µPa²s
	South	246.0 dB re 1 µPa	218.2 dB re 1 µPa²s

Table 3.5: Summary of the unweighted and unmitigated apparent source levels used for modelling at the first pile strike.

Apparent source levels	Modelling location	$L_{p,pk}$ @ 1 m	$L_{E,p,ss}$ @ 1 m
Monopile (15 m diameter pile / 550 kJ energy)	North	243.0 dB re 1 µPa	213.8 dB re 1 µPa²s
	West	243.0 dB re 1 µPa	213.8 dB re 1 µPa²s
	Northeast	243.0 dB re 1 µPa	213.8 dB re 1 µPa²s
	South	243.0 dB re 1 µPa	213.8 dB re 1 µPa²s
Jacket pin pile (4.5 m diameter pile / 450 kJ energy)	North	240.9 dB re 1 µPa	211.3 dB re 1 µPa²s
	West	240.9 dB re 1 µPa	211.3 dB re 1 µPa²s
	Northeast	240.7 dB re 1 µPa	211.0 dB re 1 µPa²s
	South	240.9 dB re 1 µPa	211.3 dB re 1 µPa²s

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 3.6 and Table 3.7, 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. Due to the similar water depths at and surrounding each location, the differences in levels at the North, West, and South locations are minimal when rounded to one decimal place.

Table 3.6: Summary of the maximum predicted $L_{p,pk}$ and $L_{E,p,ss}$ (single strike) noise levels at a range of 750 m from the noise source when considering the maximum hammer blow energy.

Predicted levels	Modelling location	$L_{p,pk}$ @ 750 m	$L_{E,p,ss}$ @ 750 m
Monopile (15 m diameter pile / 6,600 kJ maximum energy)	North	203.8 dB re 1 µPa	181.9 dB re 1 µPa²s
	West	203.8 dB re 1 µPa	181.9 dB re 1 µPa²s
	Northeast	202.9 dB re 1 µPa	181.6 dB re 1 µPa²s
	South	203.9 dB re 1 µPa	181.9 dB re 1 µPa²s
Jacket pin pile (4.5 m diameter pile / 4,400 kJ maximum energy)	North	202.3 dB re 1 µPa	179.1 dB re 1 µPa²s
	West	202.3 dB re 1 µPa	179.2 dB re 1 µPa²s
	Northeast	201.2 dB re 1 µPa	178.6 dB re 1 µPa²s
	South	202.3 dB re 1 µPa	179.2 dB re 1 µPa²s

Table 3.7: Summary of the maximum predicted $L_{p,pk}$ and $L_{E,p,ss}$ (single strike) noise levels at a range of 750 m from the noise source when considering the hammer blow energy at the first pile strike.

Predicted levels	Modelling location	$L_{p,pk}$ @ 750 m	$L_{E,p,ss}$ @ 750 m
Monopile (15 m diameter pile / 550 kJ energy)	North	199.3 dB re 1 µPa	174.8 dB re 1 µPa²s
	West	199.3 dB re 1 µPa	174.8 dB re 1 µPa²s
	Northeast	198.4 dB re 1 µPa	174.5 dB re 1 µPa²s
	South	199.4 dB re 1 µPa	174.8 dB re 1 µPa²s
Jacket pin pile (4.5 m diameter pile / 450 kJ energy)	North	197.2 dB re 1 µPa	172.3 dB re 1 µPa²s
	West	197.2 dB re 1 µPa	172.3 dB re 1 µPa²s
	Northeast	196.1 dB re 1 µPa	171.8 dB re 1 µPa²s
	South	197.3 dB re 1 µPa	172.3 dB re 1 µPa²s

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 (302°; WNW) from the West modelling location during installation of a monopile using the maximum hammer energy (6,600 kJ). It should not be assumed necessarily comparable to any other transect or blow energy, although it is expected to present a worst-case scenario.

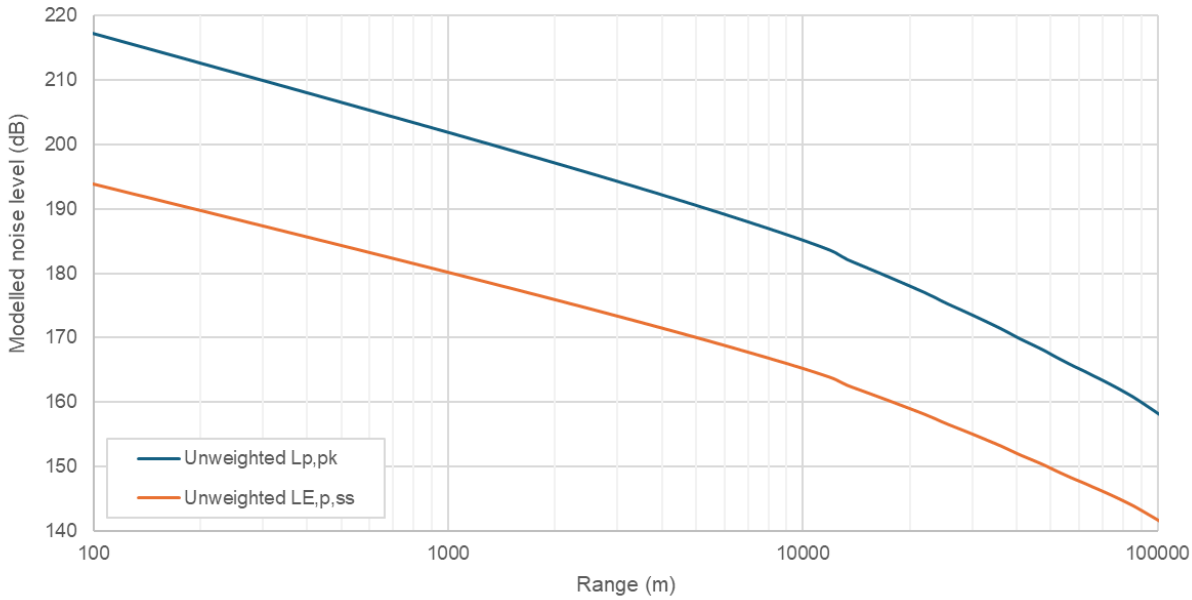


Figure 3.8: Modelled unweighted $L_{p,pk}$ and $L_{E,p,ss}$ noise levels with range for the monopile scenario assuming maximum blow energy along a WNW transect (302°) from the West modelling location.

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.

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 also 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 m/s, 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 m/s using the transect with the largest transmission (302°) for the monopile installation at the West 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 550 kJ, a receptor fleeing at a rate of 1.5 m/s has the potential to move 1.8 km away from the noise source. After the full installation of 5 hours and 25 minutes, a receptor has the potential to be almost 30 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 213.8 dB re 1 µPa²s. If the receptor were to remain stationary for the entire piling operation it would receive a cumulative noise exposure of 258.9 dB re 1 µPa²s, whereas when a receptor flees at a constant speed of 1.5 m/s over the same scenario, the cumulative received exposure is calculated to be just 214.4 dB re 1 µPa²s, only 0.6 dB higher than the first pile strike.

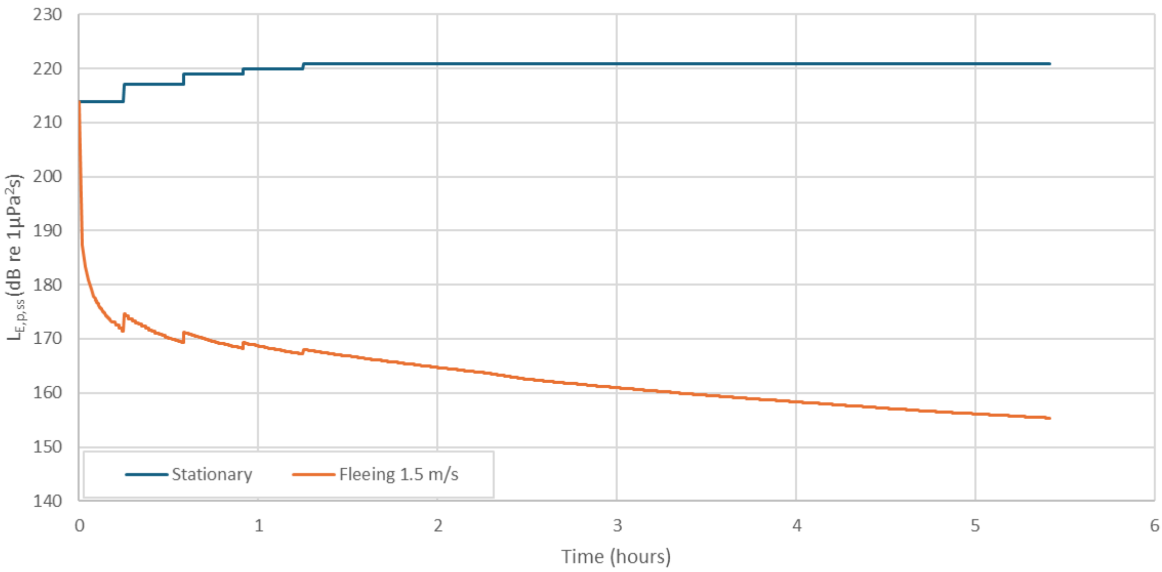


Figure 3.9: Received single strike noise levels ($L_{E,p,ss}$) for receptors during monopile installation at the West modelling location, assuming both stationary and fleeing receptors starting at a location 1 m from the noise source.

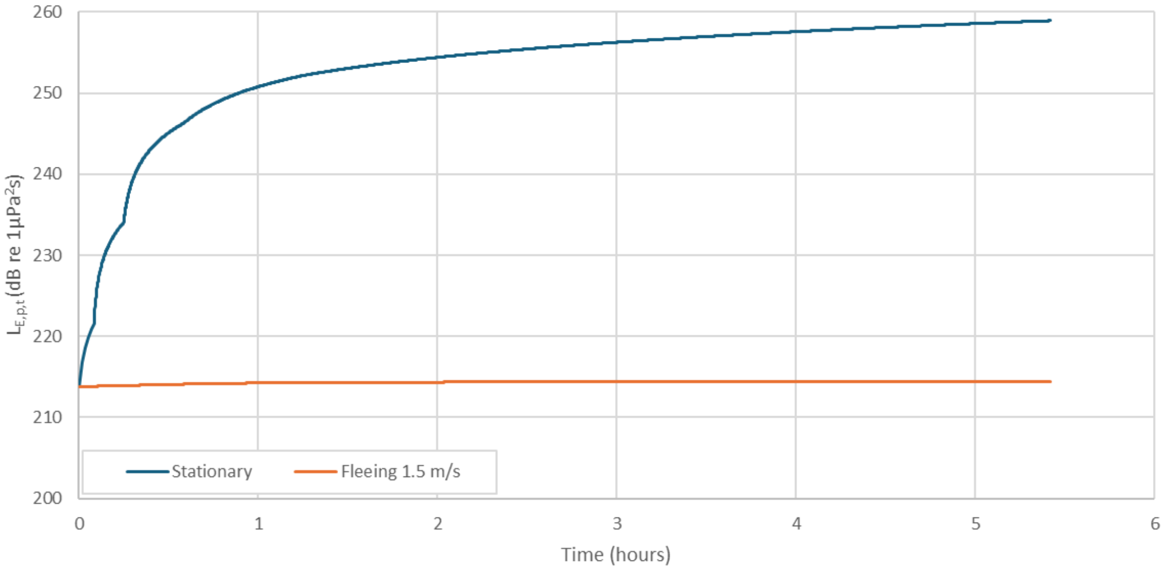
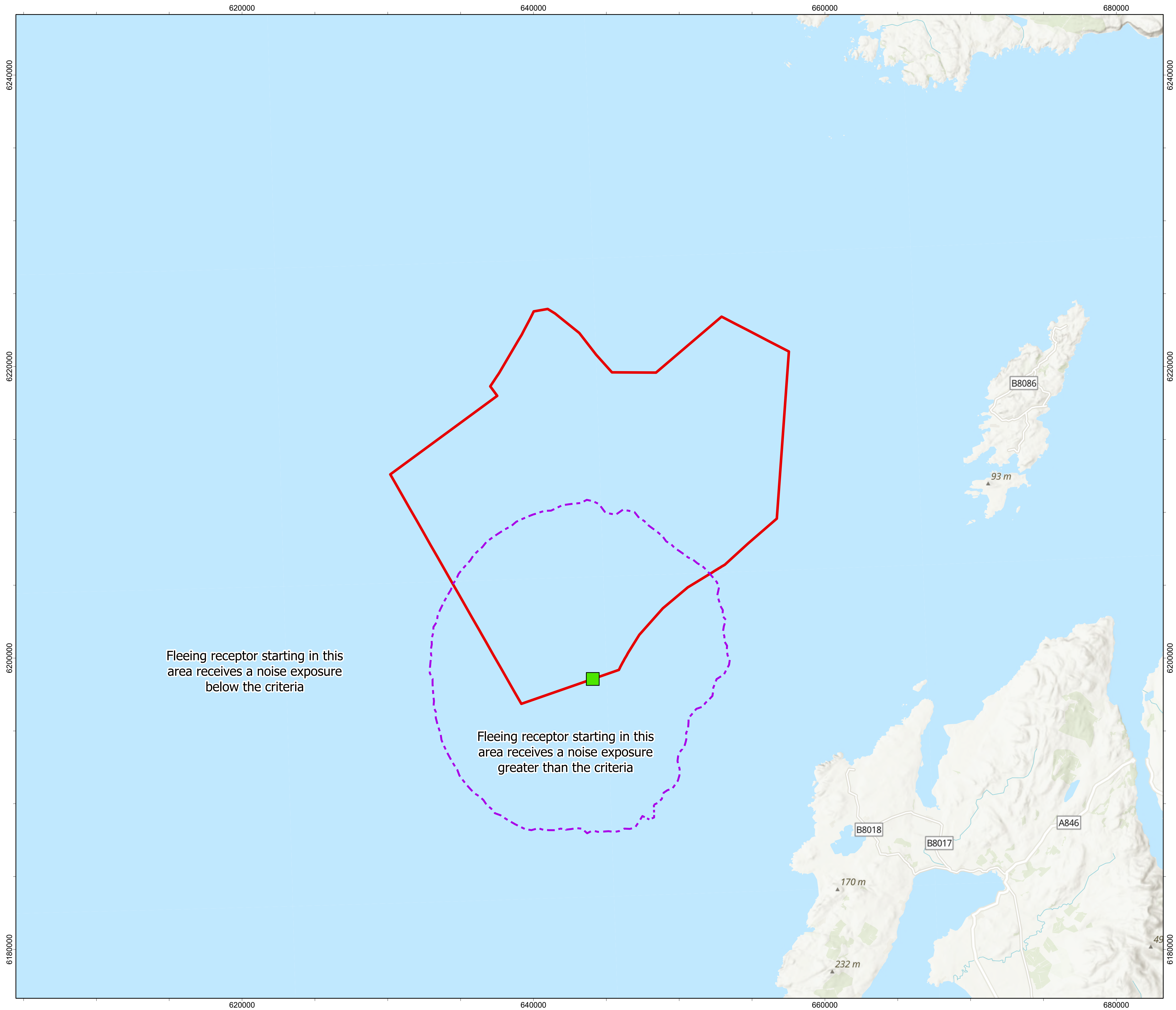


Figure 3.10: Cumulative received noise level ($L_{E,p,t}$) for receptors during monopile installation at the West modelling location, assuming both stationary and fleeing receptors starting at a location 1 m from the noise source.

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. The approach taken in this study does not include this, however the efficacy of using an ADD can still be inferred from the results. For example, if a receptor were to flee for 20 minutes from an ADD at a rate of 1.5 m/s, it would travel 1.8 km before piling begins. If a calculated cumulative $L_{E,p,t}$ impact range was below 1.8 km, it can be assumed that the ADD will be effective in eliminating the risk of exceedance of the threshold. The noise from an ADD is of a much lower level than impact piling, and as such its overall effect on the total $L_{E,p,t}$ exposure would be minimal.



Windfarm Development Area
Modelling location
Noise Contour

N

0 5 10 Kilometres

2	13/11/2025	AB	GC	SB	PM
REV	REV DATE	GIS CREATOR	GIS REVIEWER	TECHNICAL CHECKER	TECHNICAL APPROVER

DRAWING NUMBER	MCW-DWF-ENV-MAP-RHS-000029

DATUM	ETRS89	PROJECTION	UTM Zone 29N
SCALE	1:250,000	PAGE SIZE	A3

PROJECT TITLE	MachairWind

Figure 3.11: Example plot showing a fleeing animal LE,p,t criteria contour and the areas where the cumulative noise exposure will exceed a given impact

NOT TO BE USED FOR NAVIGATION

Haskoning Enhancing Society Together
ScottishPower Renewables

Project: C:\Users\304634\OneDrive - Royal HaskoningDHV\WIP\03 GIS\A02_Figures\03_EIA\01_WDA\Chap_10_MarineMammals\Appx_10-1_UWN\MCW_EIA_WDA_UWNModelling.aprx
Name: MCW-DWF-ENV-MAP-RHS-000029_CulumativeNoiseExposure

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

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. The possibility that the worst-case conservative parameters could all occur together is highly unlikely, but necessary for the purposes of the assessment.

3.4.1 Source

The modelling locations were chosen to provide the greatest extents of the site, and specifically the locations likely to lead to maximum underwater noise transmission. The largest diameter for all types of pile has been used for the worst case. The maximum blow energies were used for a duration unlikely to occur in practice. A fast strike rate (40 bl/min) has been included for much of the ramp-up. The total piling duration is at the top of expectations and not expected to be exceeded on site.

3.4.2 Transmission

Sound attenuates over distance from the source. The model considers fundamental noise spreading predictions adjusted to empirical data, accounting for frequency content, water depth, and other environmental factors, but fits to this data can still overestimate levels (see section 0).

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.

Flee speeds specified by NatureScot have been used in the modelling, although studies have shown that these are typical swimming speeds (Williams, 2009) and 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. While the faster flee speeds may or may not apply over extended timescales, the swim speeds requested by NatureScot are the lowest available and highly precautionary.

The risk of PTS will not remain constant throughout a modelled PTS range 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 onset.

As 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 PTS onset thresholds beyond 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 and jacket pin pile foundations at MachairWind 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 the Popper *et al*. (2014) fish criteria (section 2.3.2). To aid navigation, Table 4.1 gives a list of the results tables presented in this section. The largest modelled ranges from impact piling at MachairWind are predicted at the West modelling location due to the deep water to the north and west of that location.

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.

The modelling results for the first pile strike and the Southall *et al*. (2019) non-impulsive criteria are presented in Annex A.

Table 4.1: List of the impact piling modelling results tables presented in this section.

Table (page)	Scenario	Location	Criteria		
Table 4.2 (p31)	Monopile, unmitigated (4.1)	North (4.1.1)	Southall *et al*. (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4.3 (p32)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)	Single pile
Table 4.4 (p32)			Popper *et al*. (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4.5 (p32)				Unweighted $L_{E,p,24h}$ (Pile driving)	Single pile
Table 4.6 (p33)		West (4.1.2)	Southall *et al*. (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4.7 (p33)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)	Single pile
Table 4.8 (p34)			Popper *et al*. (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4.9 (p33)				Unweighted $L_{E,p,24h}$ (Pile driving)	Single pile
Table 4.10 (p34)		Northeast (4.1.3)	Southall *et al*. (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4.11 (p35)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)	Single pile
Table 4.12 (p35)			Popper *et al*. (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4.13 (p34)				Unweighted $L_{E,p,24h}$ (Pile driving)	Single pile
Table 4.14 (p36)		South (4.1.4)	Southall *et al*. (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4.15 (p36)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)	Single pile
Table 4.16 (p36)			Popper *et al*. (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4.17 (p37)				Unweighted $L_{E,p,24h}$ (Pile driving)	Single pile
Table 4.18 (p37)	Jacket pin pile, unmitigated (4.2)	North (4.2.1)	Southall *et al*. (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4.19 (p37)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)	Single pile
Table 4.20 (p38)					Six piles
Table 4.21 (p38)			Popper *et al*. (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4.22 (p38)				Unweighted $L_{E,p,24h}$ (Pile driving)	Single pile
Table 4.23 (p38)					Six piles
Table 4.24 (p39)		West (4.2.2)	Southall *et al*. (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4.25 (p39)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)	Single pile
Table 4.26 (p39)					Six piles
Table 4.27 (p40)			Popper *et al*. (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4.28 (p40)				Unweighted $L_{E,p,24h}$ (Pile driving)	Single pile
Table 4.29 (p40)					Six piles
Table 4.30 (p41)		Northeast (0)	Southall *et al*. (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4.31 (p41)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)	Single pile
Table 4.32 (p42)					Six piles
Table 4.33 (p42)			Popper *et al*. (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4.34 (p42)				Unweighted $L_{E,p,24h}$ (Pile driving)	Single pile

Table (page)	Scenario	Location	Criteria		
Table 4.35 (p43)					Six piles
Table 4.36 (p43)	Jacket pin pile, unmitigated (4.2)	South (4.2.4)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4.37 (p43)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)	Single pile
Table 4.38 (p44)					Six piles
Table 4.39 (p44)			Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4.40 (p44)				Unweighted $L_{E,p,24h}$ (Pile driving)	Single pile
Table 4.41 (p45)					Six piles
Table 4.42 (p45)	Monopile, mitigated (4.3.1)	North (4.3.1.1)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4.43 (p45)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)	Single pile
Table 4.44 (p46)			Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4.45 (p46)				Unweighted $L_{E,p,24h}$ (Pile driving)	Single pile
Table 4.46 (p46)		West (4.3.1.2)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4.47 (p47)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)	Single pile
Table 4.48 (p45)			Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4.49 (p47)				Unweighted $L_{E,p,24h}$ (Pile driving)	Single pile
Table 4.50 (p48)	Jacket pin pile, mitigated (4.3.2)	North (4.3.2.1)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4.51 (p48)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)	Single pile
Table 4.52 (p48)					Six piles
Table 4.53 (p48)			Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4.54 (p49)				Unweighted $L_{E,p,24h}$ (Pile driving)	Single pile
Table 4.55 (p49)					Six piles
Table 4.56 (p49)		West (4.3.2.2)	Southall *et al.* (2019)	Unweighted $L_{p,pk}$ (Impulsive)	
Table 4.57 (p50)				Weighted $L_{E,p,24h,wtd}$ (Impulsive)	Single pile
Table 4.58 (p50)					Six piles
Table 4.59 (p50)			Popper *et al.* (2014)	Unweighted $L_{p,pk}$ (Pile driving)	
Table 4-60 (p50)				Unweighted $L_{E,p,24h}$ (Pile driving)	Single pile
Table 4.61 (p51)					Six piles

Table 4.2 to Table 4.61 present the impact piling modelling results for MachairWind, covering monopile and jacket pin pile foundation installation for both unmitigated and mitigated scenarios. For these scenarios, the largest marine mammal impact ranges are predicted at the West modelling location during monopile installation, with maximum unmitigated PTS onset ranges for LF cetaceans out to 27 km; when mitigation is considered, these reduce to 2.1 km. For fish, the largest recoverable injury ranges (203 dB $L_{E,p,24h}$) are predicted out to 15 km when considering a stationary receptor during unmitigated sequential installation of six jacket pin piles at the West modelling location, reducing to 3.5 km when mitigation is considered. Maximum recoverable injury ranges assuming a fleeing fish are predicted for the monopile installation at the West modelling location, with ranges of up to 1.6 km, reducing to less than 50 m when noise reductions due to mitigation are included.

It is worth noting the large differences between the maximum and minimum ranges for some of the $L_{E,p,t}$ criteria at the North, West and Northeast modelling locations. This is due to the presence of small skerries close to the north of the MachairWind boundary, specifically those surrounding the Dubh Artach Lighthouse. The modelling processes used do not consider noise transmission outside of the calculated straight-line transect (i.e., it only considers line-of-sight). It is acknowledged that there will be some noise present behind these skerries, however this is difficult to quantify. The calculated maximum impact ranges still represent an uninterrupted sound transmission path and the methods used for this study are considered current best practice.

Mitigation modelling was only undertaken in the North and West locations.

4.1 Monopile foundations, unmitigated

4.1.1 North

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 monopile installation scenario at the North modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Monopile foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	0.02 km²	80 m	80 m	80 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	3.0 km²	980 m	980 m	980 m
	PCW (218 dB)	0.03 km²	90 m	90 m	90 m
TTS (Impulsive)	LF (213 dB)	0.11 km²	190 m	190 m	190 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	17 km²	2.3 km	2.3 km	2.3 km
	PCW (212 dB)	0.15 km²	220 m	220 m	220 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 monopile installation (single pile) scenario at the North modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Monopile foundation (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	960 km²	24 km	3.0 km	17 km
	HF (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	110 km²	6.9 km	1.6 km	5.9 km
	PCW (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	12,000 km²	110 km	5.0 km	56 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	4,500 km²	61 km	4.5 km	36 km
	PCW (170 dB)	1,200 km²	27 km	3.3 km	19 km

Table 4.4: 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 monopile installation scenario at the North modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Monopile foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.11 km²	190 m	190 m	190 m
	207 dB	0.69 km²	470 m	470 m	470 m

Table 4.5: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile installation (single pile) scenario at the North modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Monopile foundation (single pile)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	4.9 km²	1.4 km	230 m	1.2 km
	186 dB	3,300 km²	49 km	4.2 km	31 km
Stationary (0 m/s)	219 dB	2.4 km²	870 m	870 m	870 m
	216 dB	6.4 km²	1.4 km	1.4 km	1.4 km
	210 dB	42 km²	3.7 km	3.6 km	3.7 km
	207 dB	100 km²	5.8 km	5.5 km	5.7 km
	203 dB	290 km²	10 km	8.4 km	9.8 km
	186 dB	6,100 km²	63 km	30 m	46 km

4.1.2 West

Table 4.6: 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 monopile installation scenario at the West modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Monopile foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	0.02 km²	80 m	80 m	80 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	3.0 km²	980 m	970 m	980 m
	PCW (218 dB)	0.03 km²	90 m	90 m	90 m
TTS (Impulsive)	LF (213 dB)	0.11 km²	190 m	190 m	190 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	17 km²	2.4 km	2.3 km	2.3 km
	PCW (212 dB)	0.15 km²	220 m	220 m	220 m

Table 4.7: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile installation (single pile) scenario at the West modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Monopile foundation (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	1,100 km²	27 km	11 km	18 km
	HF (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	120 km²	8.0 km	4.7 km	6.2 km
	PCW (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	15,000 km²	120 km	17 km	63 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	5,500 km²	71 km	16 km	40 km
	PCW (170 dB)	1,300 km²	31 km	12 km	20 km

Table 4.8: 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 monopile installation scenario at the West modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Monopile foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.11 km²	190 m	190 m	190 m
	207 dB	0.68 km²	470 m	470 m	470 m

Table 4.9: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the monopile installation (single pile) scenario at the West modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Monopile foundation (single pile)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	5.4 km²	1.6 km	960 m	1.3 km
	186 dB	4,000 km²	57 km	15 km	35 km
Stationary (0 m/s)	219 dB	2.4 km²	880 m	880m	880 m
	216 dB	7.1 km²	1.5 km	1.5 km	1.5 km
	210 dB	44 km²	3.8 km	3.7 km	3.7 km
	207 dB	100 km²	5.9 km	5.6 km	5.8 km
	203 dB	310 km²	11 km	9.3 km	9.9 km
	186 dB	7,200 km²	71 km	19 km	47 km

4.1.3 Northeast

Table 4.10: 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 monopile installation scenario at the Northeast modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Monopile foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	0.02 km²	70 m	70 m	70 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	2.3 km²	850 m	850 m	850 m
	PCW (218 dB)	0.02 km²	80 m	80 m	80 m
TTS (Impulsive)	LF (213 dB)	0.09 km²	170 m	170 m	170 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	12 km²	2.0 km	2.0 km	2.0 km
	PCW (212 dB)	0.12 km²	200 m	200 m	200 m

Table 4.11: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the monopile installation (single pile) scenario at the Northeast modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Monopile foundation (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	630 km²	21 km	6.0 km	14 km
	HF (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	76 km²	6.3 km	3.0 km	4.9 km
	PCW (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	6,800 km²	94 km	9.1 km	41 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	2,800 km²	46 km	8.8 km	28 km
	PCW (170 dB)	750 km²	23 km	6.5 km	15 km

Table 4.12: 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 monopile installation scenario at the Northeast modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Monopile foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.09 km²	170 m	170 m	170 m
	207 dB	0.53 km²	410 m	410 m	410 m

Table 4.13: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the monopile installation (single pile) scenario at the Northeast modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Monopile foundation (single pile)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	1.8 km²	960 m	440 m	750 m
	186 dB	2,100 km²	39 km	8.4 km	24 km
Stationary (0 m/s)	219 dB	2.2 km²	840 m	830 m	830 m
	216 dB	6.2 km²	1.4 km	1.4 km	1.4 km
	210 dB	37 km²	3.5 km	3.4 km	3.4 km
	207 dB	87 km²	5.4 km	5.2 km	5.3 km
	203 dB	250 km²	9.5 km	8.7 km	8.9 km
	186 dB	4,100 km²	54 km	14 km	41 km

4.1.4 South

Table 4.14: 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 monopile installation scenario at the South modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Monopile foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	0.02 km²	80 m	80 m	80 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	3.0 km²	990 m	980 m	980 m
	PCW (218 dB)	0.02 km²	90 m	90 m	90 m
TTS (Impulsive)	LF (213 dB)	0.11 km²	190 m	190 m	190 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	17 km²	2.4 km	2.3 km	2.3 km
	PCW (212 dB)	0.15 km²	220 m	220 m	220 m

Table 4.15: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the monopile installation (single pile) scenario at the South modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Monopile foundation (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	770 km²	19 km	9.1 km	15 km
	HF (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	91 km²	6.2 km	4.2 km	5.4 km
	PCW (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	10,000 km²	98 km	14 km	52 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	3,700 km²	50 km	13 km	33 km
	PCW (170 dB)	880 km²	21 km	9.7 km	16 km

Table 4.16: 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 monopile installation scenario at the South modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Monopile foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.11 km²	190 m	190 m	190 m
	207 dB	0.69 km²	470 m	470m	470 m

Table 4.17: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the monopile installation (single pile) scenario at the South modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Monopile foundation (single pile)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	4.1 km²	1.3 km	870 m	1.1 km
	186 dB	2,800 km²	41 km	13 km	29 km
Stationary (0 m/s)	219 dB	2.4 km²	880 m	880 m	880 m
	216 dB	7.1 km²	1.5 km	1.5 km	1.5 km
	210 dB	43 km²	3.8 km	3.7 km	3.7 km
	207 dB	100 km²	5.8 km	5.6 km	5.7 km
	203 dB	290 km²	10 km	9.3 km	9.6 km
	186 dB	5,300 km²	54 km	22 km	44 km

4.2 Jacket pin pile foundations, unmitigated

4.2.1 North

Table 4.18: 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 jacket pin pile installation scenario at the North modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Jacket pin pile foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	0.01 km²	60 m	60 m	60 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.9 km²	780 m	780 m	780 m
	PCW (218 dB)	0.02 km²	70 m	70 m	70 m
TTS (Impulsive)	LF (213 dB)	0.07 km²	150 m	150 m	150 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	11 km²	1.9 km	1.9 km	1.9 km
	PCW (212 dB)	0.1 km²	170 m	170 m	170 m

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 jacket pin pile installation (single pile) scenario at the North modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	450 km²	14 km	2.4 km	12 km
	HF (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	28 km²	3.3 km	690 m	2.9 km
	PCW (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	7,900 km²	85 km	4.8 km	47 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	2,900 km²	44 km	4.3 km	30 km
	PCW (170 dB)	670 km²	18 km	2.8 km	14 km

Table 4.20: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the jacket pin pile installation (six sequential piles) scenario at the North modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (six sequential piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	530 km²	18 km	2.4 km	13 km
	HF (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	41 km²	4.5 km	690 m	3.5 km
	PCW (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	10,000 km²	110 km	4.8 km	52 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	3,900 km²	59 km	4.3 km	33 km
	PCW (170 dB)	800 km²	23 km	2.8 km	16 km

Table 4.21: 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 jacket pin pile installation scenario at the North modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Jacket pin pile foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.07 km²	150 m	150 m	150 m
	207 dB	0.43 km²	370 m	370 m	370 m

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 jacket pin pile installation (single pile) scenario at the North modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Jacket pin pile foundation (single pile)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	1,700 km²	30 km	3.9 km	23 km
Stationary (0 m/s)	219 dB	0.43 km²	370 m	370 m	370 m
	216 dB	1.2 km²	610 m	610 m	610 m
	210 dB	9.1 km²	1.7 km	1.7 km	1.7 km
	207 dB	23 km²	2.7 km	2.7 km	2.7 km
	203 dB	73 km²	4.9 km	4.8 km	4.8 km
	186 dB	3,200 km²	39 km	25 km	32 km

Table 4.23: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the jacket pin pile installation (six sequential piles) scenario at the North modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Jacket pin pile foundation (six sequential piles)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	2,200 km²	42 km	3.9 km	26 km
Stationary (0 m/s)	219 dB	6.2 km²	1.4 km	1.4 km	1.4 km
	216 dB	15 km²	2.2 km	2.2 km	2.2 km
	210 dB	91 km²	5.5 km	5.2 km	5.4 km

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Jacket pin pile foundation (six sequential piles)			
		Area	Maximum range	Minimum range	Mean range
	207 dB	200 km²	8.3 km	7.0 km	8.1 km
	203 dB	550 km²	14 km	12 km	13 km
	186 dB	8,100 km²	78 km	30 km	54 km

4.2.2 West

Table 4.24: 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 jacket pin pile installation scenario at the West modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Jacket pin pile foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	0.01 km²	60 m	60 m	60 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.9 km²	780 m	780 m	780 m
	PCW (218 dB)	0.02 km²	70 m	70 m	70 m
TTS (Impulsive)	LF (213 dB)	0.07 km²	150 m	150 m	150 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	11 km²	1.9 km	1.8 km	1.9 km
	PCW (212 dB)	0.1 km²	170 m	170 m	170 m

Table 4.25: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the jacket pin pile installation (single pile) scenario at the West modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	490 km²	16 km	8.4 km	12 km
	HF (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	30 km²	3.7 km	2.6 km	3.1 km
	PCW (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	9,800 km²	95 km	17 km	53 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	3,500 km²	50 km	15 km	33 km
	PCW (170 dB)	740 km²	21 km	9.9 km	15 km

Table 4.26: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the jacket pin pile installation (six sequential piles) scenario at the West modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (six sequential piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	610 km²	21 km	8.4 km	14 km
	HF (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	47 km²	5.4 km	2.8 km	3.8 km
	PCW (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	13,000 km²	120 km	17 km	59 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	4,800 km²	71 km	15 km	37 km
	PCW (170 dB)	940 km²	28 km	9.9 km	17 km

Table 4.27: 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 jacket pin pile installation scenario at the West modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Jacket pin pile foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.07 km²	150 m	150 m	150 m
	207 dB	0.43 km²	370 m	370 m	370 m

Table 4.28: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the jacket pin pile installation (single pile) scenario at the West modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Jacket pin pile foundation (single pile)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	1,900 km²	34 km	14 km	25 km
Stationary (0 m/s)	219 dB	0.43 km²	370 m	370 m	370 m
	216 dB	1.2 km²	610 m	610 m	610 m
	210 dB	9.1 km²	1.7 km	1.7 km	1.7 km
	207 dB	22 km²	2.7 km	2.6 km	2.7 km
	203 dB	74 km²	5.0 km	4.7 km	4.9 km
	186 dB	3,500 km²	43 km	19 km	33 km

Table 4.29: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the jacket pin pile installation (six sequential piles) scenario at the West modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Jacket pin pile foundation (six sequential piles)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	2,700 km²	50 km	14 km	28 km
Stationary (0 m/s)	219 dB	6.2 km²	1.4 km	1.4 km	1.4 km
	216 dB	15 km²	2.2 km	2.2 km	2.2 km
	210 dB	92 km²	5.6 km	5.3 km	5.4 km
	207 dB	210 km²	8.6 km	7.8 km	8.2 km
	203 dB	570 km²	15 km	13 km	14 km
	186 dB	9,800 km²	88 km	36 km	57 km

4.2.3 Northeast

Table 4.30: 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 jacket pin pile installation scenario at the Northeast modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Jacket pin pile 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)	1.4 km²	660 m	660 m	660 m
	PCW (218 dB)	0.01 km²	60 m	60 m	60 m
TTS (Impulsive)	LF (213 dB)	0.05 km²	130 m	130 m	130 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	7.6 km²	1.6 km	1.5 km	1.6 km
	PCW (212 dB)	0.07 km²	150 m	150 m	150 m

Table 4.31: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the jacket pin pile installation (single pile) scenario at the Northeast modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	280 km²	13 km	4.6 km	9.3 km
	HF (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	19 km²	2.9 km	1.7 km	2.5 km
	PCW (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	4,500 km²	67 km	8.7 km	34 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	2,000 km²	38 km	8.3 km	24 km
	PCW (170 dB)	440 km²	16 km	5.5 km	12 km

Table 4.32: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the jacket pin pile installation (six sequential piles) scenario at the Northeast modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (six sequential piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	320 km²	14 km	4.6 km	9.8 km
	HF (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	25 km²	3.8 km	1.7 km	2.8 km
	PCW (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	5,600 km²	87 km	8.7 km	37 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	2,300 km²	44 km	8.3 km	25 km
	PCW (170 dB)	500 km²	18 km	5.5 km	12 km

Table 4.33: 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 jacket pin pile installation scenario at the Northeast modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Jacket pin pile foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.05 km²	130 m	130 m	130 m
	207 dB	0.32 km²	320 m	320 m	320 m

Table 4.34: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the jacket pin pile installation (single pile) scenario at the Northeast modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Jacket pin pile foundation (single pile)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	1,000 km²	26 km	7.3 km	18 km
Stationary (0 m/s)	219 dB	0.36 km²	340 m	340 m	340 m
	216 dB	1.0 km²	560 m	560 m	560 m
	210 dB	7.1 km²	1.5 km	1.5 km	1.5 km
	207 dB	18 km²	2.4 km	2.4 km	2.4 km
	203 dB	58 km²	4.4 km	4.2 km	4.3 km
	186 dB	2,100 km²	34 km	13 km	27 km

Table 4.35: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the jacket pin pile installation (six sequential piles) scenario at the Northeast modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Jacket pin pile foundation (six sequential piles)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	1,200 km²	29 km	7.3 km	19 km
Stationary (0 m/s)	219 dB	5.3 km²	1.3 km	1.3 km	1.3 km
	216 dB	13 km²	2.0 km	2.0 km	2.0 km
	210 dB	72 km²	4.9 km	4.7 km	4.8 km
	207 dB	160 km²	7.5 km	7.0 km	7.2 km
	203 dB	440 km²	13 km	11 km	12 km
	186 dB	5,000 km²	62 km	14 km	47 km

4.2.4 South

Table 4.36: 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 jacket pin pile installation scenario at the South modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Jacket pin pile foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (219 dB)	0.01 km²	60 m	60 m	60 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.9 km²	780 m	780 m	780 m
	PCW (218 dB)	0.02 km²	70 m	70 m	70 m
TTS (Impulsive)	LF (213 dB)	0.07 km²	150 m	150 m	150 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	11 km²	1.9 km	1.9 km	1.9 km
	PCW (212 dB)	0.1 km²	170 m	170 m	170 m

Table 4.37: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the jacket pin pile installation (single pile) scenario at the South modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (single pile)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	350 km²	12 km	7.1 km	11 km
	HF (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	25 km²	3.1 km	2.5 km	2.8 km
	PCW (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	7,000 km²	73 km	14 km	44 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	2,300 km²	36 km	13 km	27 km
	PCW (170 dB)	510 km²	15 km	8.3 km	13 km

Table 4.38: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the jacket pin pile installation (six sequential piles) scenario at the South modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (six sequential piles)			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	410 km²	14 km	7.1 km	11 km
	HF (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (155 dB)	33 km²	3.8 km	2.5 km	3.2 km
	PCW (185 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (168 dB)	8,700 km²	93 km	14 km	48 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	<50 m
	VHF (140 dB)	3,100 km²	48 km	13 km	30 km
	PCW (170 dB)	600 km²	17 km	8.3 km	14 km

Table 4.39: 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 jacket pin pile installation scenario at the South modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Jacket pin pile foundation (maximum energy)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.07 km²	150 m	150 m	150 m
	207 dB	0.43 km²	370 m	370 m	370 m

Table 4.40: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the jacket pin pile installation (single pile) scenario at the South modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Jacket pin pile foundation (single pile)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	1,300 km²	25 km	11 km	20 km
Stationary (0 m/s)	219 dB	0.43 km²	370 m	370 m	370 m
	216 dB	1.2 km²	610 m	610 m	610 m
	210 dB	9.1 km²	1.7 km	1.7 km	1.7 km
	207 dB	22 km²	2.7 km	2.6 km	2.7 km
	203 dB	73 km²	4.9 km	4.7 km	4.8 km
	186 dB	2,600 km²	34 km	17 km	29 km

Table 4.41: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the jacket pin pile installation (six sequential piles) scenario at the South modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Jacket pin pile foundation (six sequential piles)			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	1,700 km²	33 km	11 km	23 km
Stationary (0 m/s)	219 dB	6.2 km²	1.4 km	1.4 km	1.4 km
	216 dB	15 km²	2.2 km	2.2 km	2.2 km
	210 dB	90 km²	5.5 km	5.3 km	5.4 km
	207 dB	200 km²	8.3 km	7.8 km	8.1 km
	203 dB	520 km²	14 km	12 km	13 km
	186 dB	7,200 km²	68 km	28 km	53 km

4.3 Mitigation

4.3.1 Monopile foundations

4.3.1.1 North

Table 4.42: 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 monopile installation scenario including mitigation at the North modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Monopile foundation (maximum energy), 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)	0.2 km²	220 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)	0.92 km²	540 m	540 m	540 m
	PCW (212 dB)	< 0.01 km²	50 m	50 m	50 m

Table 4.43: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the monopile installation (single pile) scenario including mitigation at the North modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Monopile foundation (single pile), mitigated			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	7.1 km²	1.8 km	130 m	1.5 km
	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)	2,800 km²	45 km	3.7 km	29 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	670 km²	18 km	3.0 km	14 km
	PCW (170 dB)	20 km²	2.9 km	360 m	2.5 km

Table 4.44: 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 monopile installation scenario including mitigation at the North modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Monopile foundation (maximum energy), mitigated			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	< 0.01 km²	40 m	40 m	40 m
	207 dB	0.03 km²	100 m	100 m	100 m

Table 4.45: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the monopile installation (single pile) scenario including mitigation at the North modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Monopile foundation (single pile), mitigated			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	320 km²	12 km	2.5 km	10 km
Stationary (0 m/s)	219 dB	0.09 km²	170 m	170 m	170 m
	216 dB	0.25 km²	280 m	280 m	280 m
	210 dB	1.7 km²	750 m	740 m	740 m
	207 dB	5.3 km²	1.3 km	1.3 km	1.3 km
	203 dB	18 km²	2.4 km	2.4 km	2.4 km
	186 dB	1,400 km²	23 km	16 km	21 km

4.3.1.2 West

Table 4.46: 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 monopile installation scenario including mitigation at the West modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Monopile foundation (maximum energy), 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)	0.2 km²	220 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)	0.92 km²	540 m	540 m	540 m
	PCW (212 dB)	< 0.01 km²	50 m	50 m	50 m

Table 4.47: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the monopile installation (single pile) scenario including mitigation at the West modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Monopile foundation (single pile), mitigated			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	8.2 km²	2.1 km	1.1 km	1.6 km
	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)	3,400 km²	52 km	14 km	32 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	750 km²	21 km	9.9 km	15 km
	PCW (170 dB)	22 km²	3.5 km	1.9 km	2.6 km

Table 4.48: 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 monopile installation scenario including mitigation at the West modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Monopile foundation (maximum energy), 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 4.49: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the monopile installation (single pile) scenario including mitigation at the West modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Monopile foundation (single pile), mitigated			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	360 km²	14 km	7.5 km	11 km
Stationary (0 m/s)	219 dB	0.09 km²	170 m	170 m	170 m
	216 dB	0.25 km²	280 m	280 m	280 m
	210 dB	1.7 km²	750 m	740 m	740 m
	207 dB	5.3 km²	1.3 km	1.3 km	1.3 km
	203 dB	17 km²	2.4 km	2.3 km	2.4 km
	186 dB	1,500 km²	26 km	19 km	22 km

4.3.2 Jacket pin pile foundations

4.3.2.1 North

Table 4.50: 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 jacket pin pile installation scenario including mitigation at the North modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		**Jacket pin pile foundation (maximum energy), 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)	0.1 km²	170 m	170 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)	0.58 km²	430 m	430 m	430 m
	PCW (212 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m

Table 4.51: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the jacket pin pile installation (single pile) scenario including mitigation at the North modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**Jacket pin pile foundation (single pile), mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	0.02 km²	90 m	< 50 m	70 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)	1,600 km²	30 km	3.5 km	22 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	310 km²	11 km	2.3 km	9.8 km
	PCW (170 dB)	1.4 km²	790 m	< 50 m	640 m

Table 4.52: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the jacket pin pile installation (six sequential piles) scenario including mitigation at the North modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		**Jacket pin pile foundation (six sequential piles), mitigated**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	0.03 km²	140 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)	1,900 km²	38 km	3.5 km	24 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	410 km²	15 km	2.3 km	11 km
	PCW (170 dB)	2.2 km²	1.2 km	< 50 m	800 m

Table 4.53: 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 jacket pin pile installation scenario including mitigation at the North modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		**Jacket pin pile foundation (maximum energy), mitigated**			
		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	80 m	80 m	80 m

Table 4.54: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the jacket pin pile installation (single pile) scenario including mitigation at the North modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Jacket pin pile foundation (single pile), mitigated			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	67 km²	5.1 km	1.4 km	4.6 km
Stationary (0 m/s)	219 dB	0.02 km²	70 m	70 m	70 m
	216 dB	0.1 km²	120 m	120 m	120 m
	210 dB	0.3 km²	310 m	310 m	310 m
	207 dB	0.85 km²	520 m	520 m	520 m
	203 dB	3.1 km²	1.0 km	1.0 km	1.0 km
	186 dB	450 km²	13 km	9.0 km	12 km

Table 4.55: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the jacket pin pile installation (six sequential piles) scenario including mitigation at the North modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Jacket pin pile foundation (six sequential piles), mitigated			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	93 km²	6.8 km	1.4 km	5.4 km
Stationary (0 m/s)	219 dB	0.21 km²	260 m	260 m	260 m
	216 dB	0.55 km²	420 m	420 m	420 m
	210 dB	4.5 km²	1.2 km	1.2 km	1.2 km
	207 dB	11 km²	1.9 km	1.9 km	1.9 km
	203 dB	38 km²	3.5 km	3.5 km	3.5 km
	186 dB	2,300 km²	31 km	21 km	27 km

4.3.2.2 West

Table 4.56: 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 jacket pin pile installation scenario including mitigation at the West modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Jacket pin pile foundation (maximum energy), 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)	0.1 km²	170 m	170 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)	0.58 km²	430 m	430 m	430m
	PCW (212 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m

Table 4.57: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) impulsive criteria for the jacket pin pile installation (single pile) scenario including mitigation at the West modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (single pile), mitigated			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	0.02 km²	110 m	60 m	80 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)	1,900 km²	34 km	13 km	24 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	330 km²	13 km	7.8 km	10 km
	PCW (170 dB)	1.6 km²	960 m	490 m	690 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 jacket pin pile installation (six sequential piles) scenario including mitigation at the West modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (six sequential piles), mitigated			
		Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	0.04 km²	220 m	60 m	110 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)	2,400 km²	46 km	13 km	27 km
	HF (170 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (140 dB)	470 km²	19 km	7.8 km	12 km
	PCW (170 dB)	2.8 km²	1.5 km	490 m	900 m

Table 4.59: 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 jacket pin pile installation scenario including mitigation at the West modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Jacket pin pile foundation (maximum energy), mitigated			
		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	80 m	80 m	80 m

Table 4-60: Unweighted $L_{E,p,24h}$ impact areas and ranges for fish using the Popper et al (2014) pile driving criteria for the jacket pin pile installation (single pile) scenario including mitigation at the West modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Jacket pin pile foundation (single pile), mitigated			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	73 km²	5.6 km	4.1 km	4.8 km
Stationary (0 m/s)	219 dB	0.02 km²	70 m	70 m	70 m
	216 dB	0.1 km²	120 m	120 m	120 m
	210 dB	0.3 km²	310 m	310 m	310 m
	207 dB	0.85 km²	520 m	520 m	520 m
	203 dB	3.1 km²	1.0 km	1.0 km	1.0 km
	186 dB	480 km²	13 km	12 km	12 km

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 jacket pin pile installation (six sequential piles) scenario including mitigation at the West modelling location assuming both fleeing and stationary receptors.

Popper *et al.* (2014) Unweighted $L_{E,p,24h}$		Jacket pin pile foundation (six sequential piles), mitigated			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	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	110 km²	8.1 km	4.1 km	5.8 km
Stationary (0 m/s)	219 dB	0.21 km²	260 m	260 m	260 m
	216 dB	0.55 km²	420 m	420 m	420 m
	210 dB	4.5 km²	1.2 km	1.2 km	1.2 km
	207 dB	11 km²	1.9 km	1.9 km	1.9 km
	203 dB	38 km²	3.5 km	3.4 km	3.5 km
	186 dB	2,400 km²	34 km	19 km	28 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 will be present and need to be considered. These noise sources have been presented alongside relevant biological criteria (see section 2.3) in this section.

Table 5.1 provides a list of the various noise producing sources, aside from impact piling, that are expected to be present during the construction and operation of MachairWind.

Table 5.1: Summary of the possible noise-making activities, other than impact piling, present during the construction and operation of MachairWind.

Activity	Description
Cable laying	Noise from the cable laying vessel and other associated sounds produced during the offshore cable installation.
Dredging	Dredging may be required for seabed preparation work for certain foundation types as well as export cable, inter-array cable and offshore substation platform link cable installation. Both backhoe and suction dredging have been considered for this study.
Drilling	There is the potential for WTG foundations to be installed or partially installed using drilling depending on seabed type or if a pile refuses during impact piling operations.
Rock placement	Rock placement may be required on site for installation of offshore cables (cable crossings and cable protection), and scour protection around foundation structures.
Trenching	Trenching will be utilised during the installation of offshore cables. The trenching method will be defined following detailed design.
Vessel noise	Jack-up barges and dynamic positioning vessels are expected to be used for piling substructure and foundation installation. Other large and medium sized vessels will be required to carry out other construction tasks such as anchor handling and survey work. Small vessels will be required for crew transport and maintenance on site.
Operation WTGs	Noise transmitted through the water from operational WTGs. Currently, MachairWind is considering fixed-bottom turbines with power outputs of between 15 and 24 MW.
UXO clearance	There is a possibility that UXO may exist within the MachairWind array and cable corridor boundaries. This would need to be cleared before construction can begin, likely using a low-order clearance technique.

The majority of these activities are covered in section 0 with operational WTG noise and UXO clearance assessed in sections 5.2 and 5.3 respectively.

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

5.1 Noise making activities (construction)

For the purposes of identifying the greatest effects from noise, approximate underwater noise levels have been predicted using a simple modelling approach. This is based on measurement data from Subacoustech Environmental's underwater noise measurement database scaled to relevant parameters for MachairWind, and to the specific noise sources to be used. The calculation of underwater noise transmission loss for these non-impulsive sources is based on empirical analysis of the noise measurements taken along transects around these sources by Subacoustech Environmental. The predictions use the following principle fitted to the measured data, where R is the range from the source, N is the transmission loss coefficient, and α is the absorption loss coefficient:

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

Predicted source levels and propagation calculations for the construction activities are presented in Table 5.2 along with a summary of the number of datasets used in each case. Impact ranges have been calculated using the Southall *et al*. (2019) non-impulsive criteria for marine mammals (Table 2.3) and the Popper *et al*. (2014) shipping and continuous noise criteria for fish (Table 2.6). As before, 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, MachairWind.

Table 5.2: Summary of the estimated unweighted source levels and transmission losses for the considered construction activities

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 worst-case 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	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 containerships 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 MachairWind are deep relative to the locations where the original data here was derived, although the levels relative to the thresholds under consideration will mean that the 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 worst-case 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 flee 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 5.2. Details of the reductions in source level for each of the Southall *et al*. (2019) marine mammal weightings are given in Table 5.3.

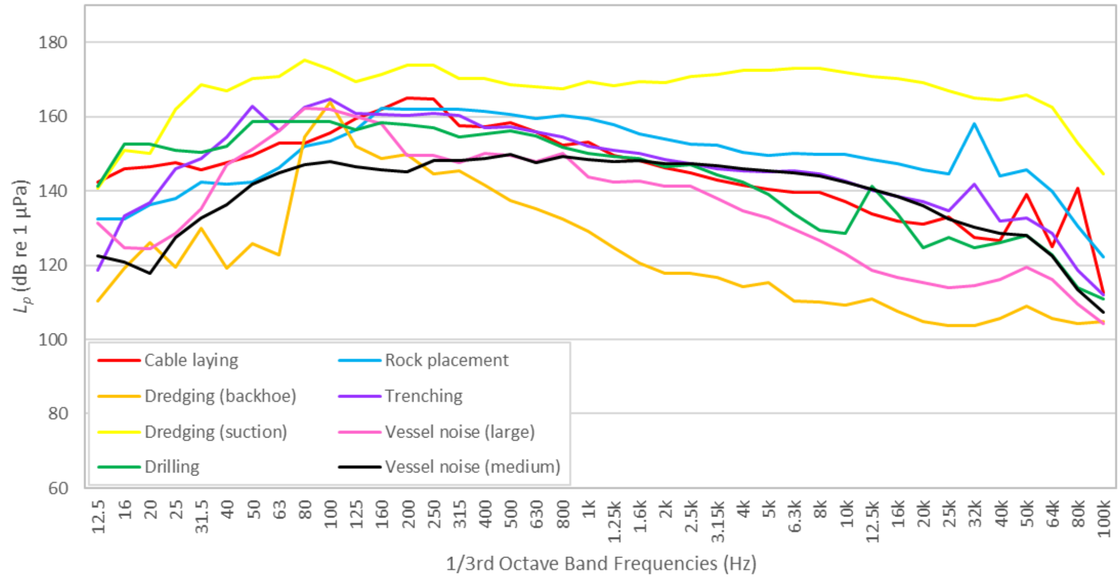


Figure 5.1: Summary of the 1/3rd octave frequency bands to which the weightings from Southall et al (2019) have been applied.

Table 5.3: 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

The modelled impact ranges for these sources are presented in Table 5.4 to Table 5.6.

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 5.4: 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 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 5.5: 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 5.6: 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 windfarms, 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 empirical data from the 17 datasets.

Indicative power outputs have been used to calculate the impacts for this study. For MachairWind, WTGs with power outputs from 15 to 24 MW have been used.

The WTG sizes under consideration at MachairWind 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*. (2023) 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 MachairWind using the Tougaard *et al*. (2020) equation, assuming an average wind speed of 10 m/s.

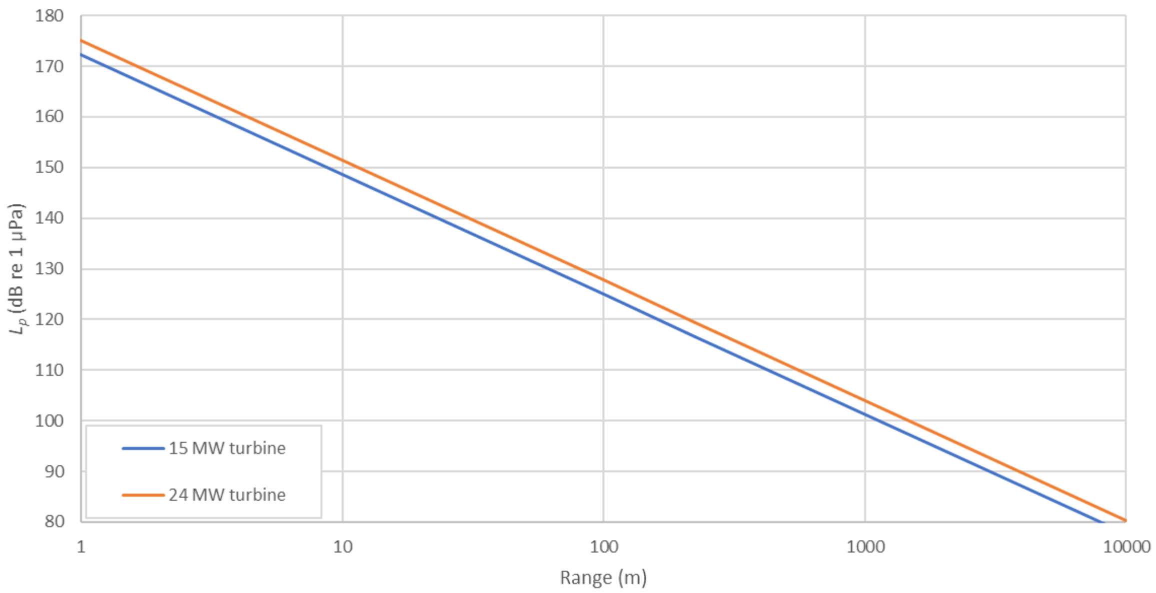


Figure 5.2: Predicted unweighted L_p from operational WTGs using the calculation from Tougaard et al. (2020).

Using this data, a summary of the predicted impact ranges for operational WTG noise has been produced, presented in Table 5.7 and Table 5.8. The operational WTG source is considered non-impulsive or continuous. For $L_{E,p,t}$ calculations, a worst-case stationary animal has been used, and it is assumed that the operational WTG noise is present 24 hours a day.

Table 5.7: 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)	PTS (Non-impulsive)				TTS (Non-impulsive)			
$L_{E,p,24h,wtd}$ (Stationary)	LF (199 dB)	HF (198 dB)	VHF (173 dB)	PCW (201 dB)	LF (179 dB)	HF (178 dB)	VHF (153 dB)	PCW (181 dB)
15 MW turbine	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
24 MW turbine	< 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 5.8: 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)
15 MW turbine	< 50 m	< 50 m
24 MW turbine	< 50 m	< 50 m

Using the Popper *et al*. (2014) criteria for continuous noise, any individual would have to be closer than 50 m to the operational WTG for 12 hours to achieve the for TTS onset criteria.

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 MachairWind, and using that threshold, it is estimated that larger WTG may only reach the Level B behavioural threshold at ranges of 230 m using the Tougaard *et al*. (2020) equation (Figure 5.2). As the distance between turbines at MachairWind is expected to be greater than this, any array effect from the turbines is not expected. Bellman *et al*. (2023) takes this further and shows that the predictions of underwater noise during the operational phase in Stöber and Thomsen (2021) represent significant over-estimations of the actual levels seen on site.

5.3 UXO clearance

It is possible that UXO devices, with a range of charge weights (or quantity of contained explosive), are present within and around the MachairWind 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. 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

5.3.1.1 Low-order clearance

Techniques other than high-order clearance will be the first choice for any UXO clearance at MachairWind, 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.

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 0.25 kg, to breach the casing and ignite the internal high explosive 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 high explosive 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. A prediction of this impact is based on a charge weight of 0.25 kg. The worst-case scenario would, of course, be a high-order detonation with maximum pressures from complete detonation of the UXO. This has been calculated separately, as part of the high-order clearance assessment, for comparison.

5.3.1.2 High-order clearance

The noise produced by the detonation of explosives is affected by 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 worst-case 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.

It should be noted that a high-order clearance technique would be a last resort, after the use of a less intrusive and quieter technique, such as low-order clearance remains unsuccessful following three consecutive attempts (section 5.3.1.11).

The maximum equivalent charge weight for the potential UXO devices that could be present at MachairWind has been estimated as 750 kg. This has been modelled alongside a range of smaller devices, at charge weights of 25, 55, 120, 240, 525, and 698 kg, which have been chosen to give a spread of potential devices that have been identified at other sites around the UK. In each case, an additional donor charge weighing 0.5 kg has been included to initiate detonation.

Estimation of the source noise level for each charge weight has been carried out in accordance with the methodology from Soloway and Dahl (2014), which follows Arons (1954) and the Marine Technical Directorate (MTD) (1996). This is covered in more detail in section 5.3.2.

5.3.2 Estimation of underwater noise propagation

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

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

and for $L_{E,p}$:

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

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

These equations give a relatively simple calculation which can be used to give an indication of the range of effect. The equation does not consider variable bathymetry or seabed type, and thus 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 measurements of high intensity noise propagation taken in the North Sea and Irish Sea. This uses standard frequency-based absorption coefficients for the seawater conditions expected in the region.

Despite this attenuation correction, the resulting noise levels still need to be considered carefully, for example, $L_{p,pk}$ noise levels over larger distances are difficult to predict accurately (von Benda-Beckmann *et al.*, 2015). Soloway and Dahl (2014) only verify results from the equation above for small charges at ranges of less than 1 km, although the results are similar to the measurements presented by von Benda-Beckamann (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. This consideration may begin at ranges of 3.5 km (Hastie *et al*., 2019) to 5 km (Matei *et al*., 2023), 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 5.9.

Table 5.9: 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 (0.25 kg)	269.8 dB re 1 µPa	215.2 dB re 1 µPa²s
25 kg (+ donor)	284.9 dB re 1 µPa	228.0 dB re 1 µPa²s
55 kg (+ donor)	287.5 dB re 1 µPa	230.1 dB re 1 µPa²s
120 kg (+ donor)	290.0 dB re 1 µPa	232.3 dB re 1 µPa²s
240 kg (+ donor)	292.3 dB re 1 µPa	234.2 dB re 1 µPa²s
525 kg (+ donor)	294.8 dB re 1 µPa	236.4 dB re 1 µPa²s
698 kg (+ donor)	295.7 dB re 1 µPa	237.1 dB re 1 µPa²s
750 kg (+ donor)	296.0 dB re 1 µPa	237.3 dB re 1 µPa²s

5.3.3 Impact ranges

Table 5.10 to Table 5.13 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 5.10 to Table 5.13 are large, the duration the noise is present must also be considered. For the detonation of a UXO, each explosion is a single noise event, compared to the multiple pulse nature and longer durations of impact piling.

Table 5.10: 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 (0.25 kg)	170 m	60 m	990 m	190 m	320 m	100 m	1.8 km	360 m
25 kg (+ donor)	820 m	260 m	4.6 km	910 m	1.5 km	490 m	8.5 km	1.6 km
55 kg (+ donor)	1.0 km	340 m	6.0 km	1.1 km	1.9 km	640 m	11 km	2.1 km
120 kg (+ donor)	1.3 km	450 m	7.8 km	1.5 km	2.5 km	830 m	14 km	2.8 km
240 kg (+ donor)	1.7 km	560 m	9.8 km	1.9 km	3.2 km	1.0 km	18 km	3.5 km
525 kg (+ donor)	2.2 km	730 m	12 km	2.5 km	4.1 km	1.3 km	23 km	4.6 km
698 kg (+ donor)	2.4 km	810 m	13 km	2.7 km	4.5 km	1.4 km	25 km	5.0 km
750 kg (+ donor)	2.5 km	830 m	14 km	2.8 km	4.6 km	1.5 km	26 km	5.1 km

Table 5.11: 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 (0.25 kg)	230 m	< 50 m	80 m	< 50 m	3.2 km	< 50 m	750 m	570 m
25 kg (+ donor)	2.2 km	< 50 m	570 m	390 m	29 km	150 m	2.4 km	5.2 km
55 kg (+ donor)	3.2 km	< 50 m	740 m	570 m	41 km	210 m	2.8 km	7.5 km
120 kg (+ donor)	4.7 km	< 50 m	950 m	830 m	57 km	300 m	3.2 km	10 km
240 kg (+ donor)	6.5 km	< 50 m	1.1 km	1.1 km	76 km	390 m	3.5 km	14 km
525 kg (+ donor)	9.5 km	50 m	1.4 km	1.6 km	100 km	530 m	4.0 km	19 km
698 kg (+ donor)	10 km	60 m	1.5 km	1.9 km	110 km	590 m	4.1 km	22 km
750 kg (+ donor)	11 km	60 m	1.5 km	2.0 km	110 km	600 m	4.2 km	22 km

Table 5.12: 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) $L_{E,p,wtd}$ (Single pulse)	PTS (Non-impulsive)				TTS (Non-impulsive)			
	LF (199 dB)	HF (198 dB)	VHF (173 dB)	PCW (201 dB)	LF (179 dB)	HF (178 dB)	VHF (153 dB)	PCW (181 dB)
Low order (0.25 kg)	< 50 m	< 50 m	< 50 m	< 50 m	460 m	< 50 m	110 m	80 m
25 kg (+ donor)	130 m	< 50 m	< 50 m	< 50 m	4.4 km	< 50 m	730 m	790 m
55 kg (+ donor)	190 m	< 50 m	< 50 m	< 50 m	6.4 km	60 m	940 m	1.1 km
120 kg (+ donor)	280 m	< 50 m	70 m	< 50 m	9.4 km	80 m	1.1 km	1.6 km
240 kg (+ donor)	390 m	< 50 m	100 m	70 m	13 km	110 m	1.4 km	2.3 km
525 kg (+ donor)	570 m	< 50 m	130 m	100 m	18 km	160 m	1.7 km	3.3 km
698 kg (+ donor)	660 m	< 50 m	150 m	110 m	21 km	180 m	1.8 km	3.8 km
750 kg (+ donor)	680 m	< 50 m	160 m	120 m	22 km	190 m	1.8 km	4.0 km

Table 5.13: Unweighted $L_{p,pl}$ impact ranges for fish using the Popper et al. (2014) explosions criteria for UXO clearance noise.

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

5.3.4 Summary

The maximum PTS 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 680 m), it is likely that the long-range smoothing of the pulse peak would reduce its potential harm, making the impulsive range precautionary.

A low-order clearance would produce a maximum PTS onset impact range of 990 m 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 UXO clearance at MachairWind, with high-order being a last resort.

6 Summary and conclusions

Subacoustech Environmental has undertaken a study on behalf of Haskoning to assess the potential underwater noise and its effects on marine fauna during the construction and operation of MachairWind, located Northwest of Islay and West of Colonsay off the west coast of Scotland.

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

Four modelling locations were chosen to give spatial variation across MachairWind as well as accounting for changes in water depth. The monopile scenario considered 15 m diameter piles installed with a maximum hammer blow energy of 6,600 kJ. The jacket pin pile scenario considered 4.5 m diameter piles installed with a maximum hammer blow energy of 4,400 kJ and up to six piles installed sequentially in a 24-hour period.

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

For marine mammals, maximum PTS onset ranges from impact piling were predicted for LF cetaceans, with ranges of up to 27 km. When mitigation is considered, the maximum range to the same criterion is reduced to 2.1 km. For fish, the largest recoverable injury ranges (203 dB $L_{E,p,24h}$) were predicted out to 15 km when considering a stationary receptor during sequential installation of six jacket pin piles at the West modelling location, this reduced to 3.5 km when mitigation is considered. It should be noted that the greatest impact ranges predicted here for impulsive noise are well beyond the estimated fully-impulsive range of 3.5 km (Matei *et al.* 2024). The equivalent impact ranges calculated using the non-impulsive thresholds are substantially lower. The real risk of PTS assuming fully impulsive thresholds at distances such as 27 km is expected to be overstated.

Noise sources other than impact piling have been considered using several high-level modelling approaches, these 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 MachairWind site. There is a risk of PTS onset up to 990 m 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 (750 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 worst-case criterion and calculation methodology that does not account for any smoothing of the pulse over long ranges, which would reduce the pulse peak and other characteristics of the sound that cause injury.

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 impacts of underwater noise on marine mammals and fish at MachairWind in their respective assessments.

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Annex A Additional modelling results

A.1 First strike results

Table A.1 to Table A.24 present the single strike ($L_{p,pk}$) impact ranges for impact piling when considering the first pile strike of the monopile and jacket pin pile scenarios.

A.1.1 Monopile foundations, unmitigated

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 monopile installation scenario at the North modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Monopile 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)	0.8 km²	500 m	500 m	500 m
	PCW (218 dB)	< 0.01 km²	50 m	50 m	50 m
TTS (Impulsive)	LF (213 dB)	0.03 km²	100 m	100 m	100 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	4.7 km²	1.2 km	1.2 km	1.2 km
	PCW (212 dB)	0.04 km²	110 m	110 m	110 m

Table A.2: 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 monopile installation scenario at the North modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Monopile foundation (first strike)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.03 km²	100 m	100 m	100 m
	207 dB	0.18 km²	240 m	240 m	240 m

Table A.3: 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 monopile installation scenario at the West modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Monopile 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)	0.79 km²	500 m	500 m	500 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.03 km²	100 m	100 m	100 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	4.7 km²	1.2 km	1.2 km	1.2 km
	PCW (212 dB)	0.04 km²	110 m	110 m	110 m

Table A.4: 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 monopile installation scenario at the West modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Monopile foundation (first strike)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.03 km²	100 m	100 m	100 m
	207 dB	0.18 km²	240 m	240 m	240 m

Table A.5: 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 monopile installation scenario at the Northeast modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Monopile 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)	0.62 km²	440 m	440 m	440 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km²	90 m	90 m	90 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	3.5 km²	1.1 km	1.0 km	1.1 km
	PCW (212 dB)	0.03 km²	100 m	100 m	100 m

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 monopile installation scenario at the Northeast modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Monopile foundation (first strike)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.02 km²	90 m	90 m	90 m
	207 dB	0.14 km²	210 m	210 m	210 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 monopile installation scenario at the South modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Monopile 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)	0.8 km²	510 m	500 m	500 m
	PCW (218 dB)	< 0.01 km²	50 m	40 m	40 m
TTS (Impulsive)	LF (213 dB)	0.03 km²	100 m	100 m	100 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	4.7 km²	1.2 km	1.2 km	1.2 km
	PCW (212 dB)	0.04 km²	110 m	110 m	110 m

Table A.8: 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 monopile installation scenario at the South modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Monopile foundation (first strike)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.03 km²	100 m	100 m	100 m
	207 dB	0.18 km²	240 m	240 m	240 m

A.1.2 Jacket pin pile foundations, unmitigated

Table A.9: 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 jacket pin pile installation scenario at the North modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Jacket pin pile 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	370 m	370 m	370 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km²	70 m	70 m	70 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	2.5 km²	900 m	890 m	900 m
	PCW (212 dB)	0.02 km²	80 m	80 m	80 m

Table A.10: 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 jacket pin pile installation scenario at the North modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Jacket pin pile foundation (first strike)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.02 km²	70 m	70 m	70 m
	207 dB	0.09 km²	170 m	170 m	170 m

Table A.11: 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 jacket pin pile installation scenario at the West modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Jacket pin pile 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	370 m	370 m	370 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km²	70 m	70 m	70 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	2.5 km²	900 m	890 m	900 m
	PCW (212 dB)	0.02 km²	80 m	80 m	80 m

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 jacket pin pile installation scenario at the West modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Jacket pin pile foundation (first strike)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.02 km²	70 m	70 m	70 m
	207 dB	0.09 km²	170 m	170 m	170 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 jacket pin pile installation scenario at the Northeast modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Jacket pin pile 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)	0.32 km²	320 m	320 m	320 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)	1.8 km²	760 m	760 m	760 m
	PCW (212 dB)	0.02 km²	70 m	70 m	70 m

Table A.14: 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 jacket pin pile installation scenario at the Northeast modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Jacket pin pile 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	0.07 km²	150 m	150 m	150 m

Table A.15: 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 jacket pin pile installation scenario at the South modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Jacket pin pile 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)	0.43 km²	370 m	370 m	370 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km²	70 m	70 m	70 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	2.5 km²	900 m	900 m	900 m
	PCW (212 dB)	0.02 km²	80 m	80 m	80 m

Table A.16: 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 jacket pin pile installation scenario at the South modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Jacket pin pile foundation (first strike)			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.02 km²	70 m	70 m	70 m
	207 dB	0.09 km²	170 m	170 m	170 m

A.1.3 Mitigation

Table A.17: 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 monopile installation scenario including mitigation at the North modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Monopile 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)	0.2 km²	220 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)	0.92 km²	540 m	540 m	540 m
	PCW (212 dB)	< 0.01 km²	50 m	50 m	50 m

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 monopile installation scenario including mitigation at the North modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Monopile 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.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 monopile installation scenario including mitigation at the West modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		Monopile 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)	0.04 km²	110 m	110 m	110 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)	0.24 km²	280 m	280 m	280m
	PCW (212 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m

Table A.20: 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 monopile installation scenario including mitigation at the West modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		Monopile 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	< 0.01 km²	50 m	50 m	50 m

Table A.21: 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 jacket pin pile installation scenario including mitigation at the North modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		**Jacket pin pile 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)	0.02 km²	80 m	80 m	80 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)	0.13 km²	200 m	200 m	200 m
	PCW (212 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m

Table A.22: 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 jacket pin pile installation scenario including mitigation at the North modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		**Jacket pin pile 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	< 0.01 km²	< 50 m	< 50 m	< 50 m

Table A.23: 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 jacket pin pile installation scenario including mitigation at the West modelling location.

Southall *et al.* (2019) Unweighted $L_{p,pk}$		**Jacket pin pile 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)	0.02 km²	80 m	80 m	80 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)	0.13 km²	200 m	200 m	200 m
	PCW (212 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m

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 jacket pin pile installation scenario including mitigation at the West modelling location.

Popper *et al.* (2014) Unweighted $L_{p,pk}$		**Jacket pin pile 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	< 0.01 km²	< 50 m	< 50 m	< 50 m

A.2 Non-impulsive criteria

Following the discissions around impulsive and non-impulsive noise sources in section 2.2.1, Table A.25 to Table A-42 present the modelled impact piling noise in terms of the non-impulsive criteria from Southall *et al*. (2019). The predicted impact ranges here fall well below those presented for the impulsive criteria in section 4.

A.2.1 Monopile foundations, unmitigated

Table A.25: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the monopile installation (single pile) scenario at the North modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Monopile foundation (single pile)			
		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)	2,300 km²	40 km	3.6 km	26 km
	HF (178 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	260 km²	11 km	2.2 km	9.0 km
	PCW (181 dB)	7.6 km²	1.9 km	90 m	1.5 km

Table A.26: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the monopile installation (single pile) scenario at the West modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Monopile foundation (single pile)			
		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)	2,800 km²	46 km	14 km	29 km
	HF (178 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	290 km²	13 km	6.7 km	9.5 km
	PCW (181 dB)	8.8 km²	2.2 km	1.1 km	1.7 km

Table A.27: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the monopile installation (single pile) scenario at the Northeast modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Monopile foundation (single pile)			
		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)	1,500 km²	33 km	7.5 km	21 km
	HF (178 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	180 km²	9.8 km	4.3 km	7.4 km
	PCW (181 dB)	3.8 km²	1.5 km	520 m	1.1 km

Table A.28: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the monopile installation (single pile) scenario at the South modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Monopile foundation (single pile)			
		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)	1,900 km^2	33 km	11 km	24 km
	HF (178 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	200 km^2	9.4 km	6.0 km	8.0 km
	PCW (181 dB)	5.9 km^2	1.7 km	950 m	1.4 km

A.2.2 Jacket pin pile foundations, unmitigated

Table A.29: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the jacket pin pile installation (single pile) scenario at the North modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (single pile)			
		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)	1,300 km^2	27 km	3.3 km	20 km
	HF (178 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	90 km^2	5.9 km	1.4 km	5.3 km
	PCW (181 dB)	0.05 km^2	180 m	< 50 m	120 m

Table A.30: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the jacket pin pile installation (six sequential piles) scenario at the North modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (six sequential piles)			
		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)	1,600 km^2	34 km	3.3 km	22 km
	HF (178 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	120 km^2	8.0 km	1.4 km	6.2 km
	PCW (181 dB)	0.15 km^2	370 m	< 50 m	200 m

Table A.31: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the jacket pin pile installation (single pile) scenario at the West modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (single pile)			
		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)	1,500 km²	30 km	12 km	21 km
	HF (178 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	97 km²	6.7 km	4.7 km	5.5 km
	PCW (181 dB)	0.08 km²	270 m	70 m	140 m

Table A.32: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the jacket pin pile installation (six sequential piles) scenario at the West modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (six sequential piles)			
		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)	1,900 km²	40 km	12 km	24 km
	HF (178 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	140 km²	9.7 km	4.7 km	6.6 km
	PCW (181 dB)	0.25 km²	580 m	70 m	250 m

Table A.33: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the jacket pin pile installation (single pile) scenario at the Northeast modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (single pile)			
		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)	830 km²	23 km	6.4 km	16 km
	HF (178 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	65 km²	5.4 km	2.9 km	4.5 km
	PCW (181 dB)	< 0.01 km²	80 m	< 50 m	< 50 m

Table A.34: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the jacket pin pile installation (six sequential piles) scenario at the Northeast modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (six sequential piles)			
		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)	930 km²	25 km	6.4 km	16 km
	HF (178 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	81 km²	6.8 km	2.9 km	5.0 km
	PCW (181 dB)	0.02 km²	170 m	< 50 m	70 m

Table A.35: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the jacket pin pile installation (single pile) scenario at the South modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (single pile)			
		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)	1,000 km²	22 km	9.8 km	18 km
	HF (178 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	77 km²	5.5 km	4.2 km	4.9 km
	PCW (181 dB)	0.03 km²	150 m	50 m	90 m

Table A.36: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the jacket pin pile installation (six sequential piles) scenario at the South modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (six sequential piles)			
		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)	1,200 km²	27 km	9.8 km	19 km
	HF (178 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (153 dB)	99 km²	6.6 km	4.2 km	5.6 km
	PCW (181 dB)	0.07 km²	240 m	50 m	140 m

A.2.3 Mitigation

Table A.37: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the monopile installation (single pile) scenario including mitigation at the North modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Monopile foundation (single pile), 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)	120 km²	7.3 km	1.3 km	6.1 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.38: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the monopile installation (single pile) scenario including mitigation at the West modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Monopile foundation (single pile), 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)	130 km²	8.4 km	4.6 km	6.5 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.39: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the jacket pin pile installation (single pile) scenario including mitigation at the North modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (single pile), 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)	25 km²	3.2 km	460 m	2.8 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.40: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the jacket pin pile installation (six sequential piles) scenario including mitigation at the North modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (six sequential piles), 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)	31 km²	3.9 km	460 m	3.1 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.41: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the jacket pin pile installation (single pile) scenario including mitigation at the West modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (single pile), 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)	27 km²	3.6 km	2.3 km	2.9 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.42: Weighted $L_{E,p,24h,wtd}$ impact areas and ranges for marine mammals using the Southall et al (2019) non-impulsive criteria for the jacket pin pile installation (six sequential piles) scenario including mitigation at the West modelling location assuming fleeing receptors.

Southall *et al.* (2019) Weighted $L_{E,p,24h,wtd}$		Jacket pin pile foundation (six sequential piles), 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)	35 km²	4.6 km	2.3 km	3.3 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

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