Inch Cape Offshore Wind Farm: OSP Underwater Noise Assessment

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01 October 2024

**Subacoustech Environmental Report No.
P271R1102**

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Document No.	Date	Written	Approved	Distribution
P271R1101	21/08/2024	[Redacted]	[Redacted]	[Redacted]
P271R1102	01/10/2024	[Redacted]	[Redacted]	[Redacted]

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

Executive Summary

Subacoustech Environmental Ltd., on behalf of Inch Cape Offshore Ltd., has undertaken a study in order to assess the potential underwater noise and its effects during the installation of foundations for an offshore platform (OSP) at the proposed Inch Cape Offshore Wind Farm project.

Impact piling modelling for OSP foundations were undertaken at a single, representative location. The modelling results were analysed in terms of relevant noise metrics and criteria to assess the effects of impact piling noise on marine mammals and fish, which have been used to aid biological assessments. For marine mammals, maximum permanent threshold shift (PTS) impact ranges were predicted for animals in the low-frequency (LF) cetacean category, with ranges out to 11 km. For fish, the largest recoverable injury ranges were predicted to be 3.6 km for a stationary receptor, reducing to less than 100 m when considering a fleeing receptor.

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

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

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Terminology

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

Units

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

Acronyms

ADD	Acoustic Deterrent Device
BE	Best Estimate
BGS	British Geological Survey
EIA	Environmental Impact Assessment
EMODnet	European Marine Observation and Data Network
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
NMFS	National Marine Fisheries Service
NPL	National Physical Laboratory
OSP	Offshore Substation Platform
PCW	Phocid Carnivores in Water
PPV	Peak Particle Velocity
PTS	Permanent Threshold Shift
RMS	Root Mean Square
SE	Sound Exposure
SEL	Sound Exposure Level
SNH	Scottish Natural Heritage
SPL	Sound Pressure Level
TTS	Temporary Threshold Shift
VHF	Very High-Frequency Cetaceans
WTG	Wind Turbine Generator

1   Introduction

Inch Cape Offshore Wind Farm (Inch Cape) is a proposed offshore wind farm located off the Angus Coast in the North Sea, Scotland. As part of the Environmental Impact Assessment (EIA) process, Subacoustech Environmental Ltd. has undertaken detailed modelling and analysis in relation to the effect of underwater noise on marine mammals and fish during foundation installation of the Offshore Substation Platform (OSP).

The array area for Inch Cape covers an area of 150 km^2, is situated approximately 15 km from the Scottish coastline. The proposed is expected to have an installed capacity of 1.1 GW utilising up to 72 wind turbine generators (WTGs). The location of the Inch Cape site is shown in Figure 1-1.
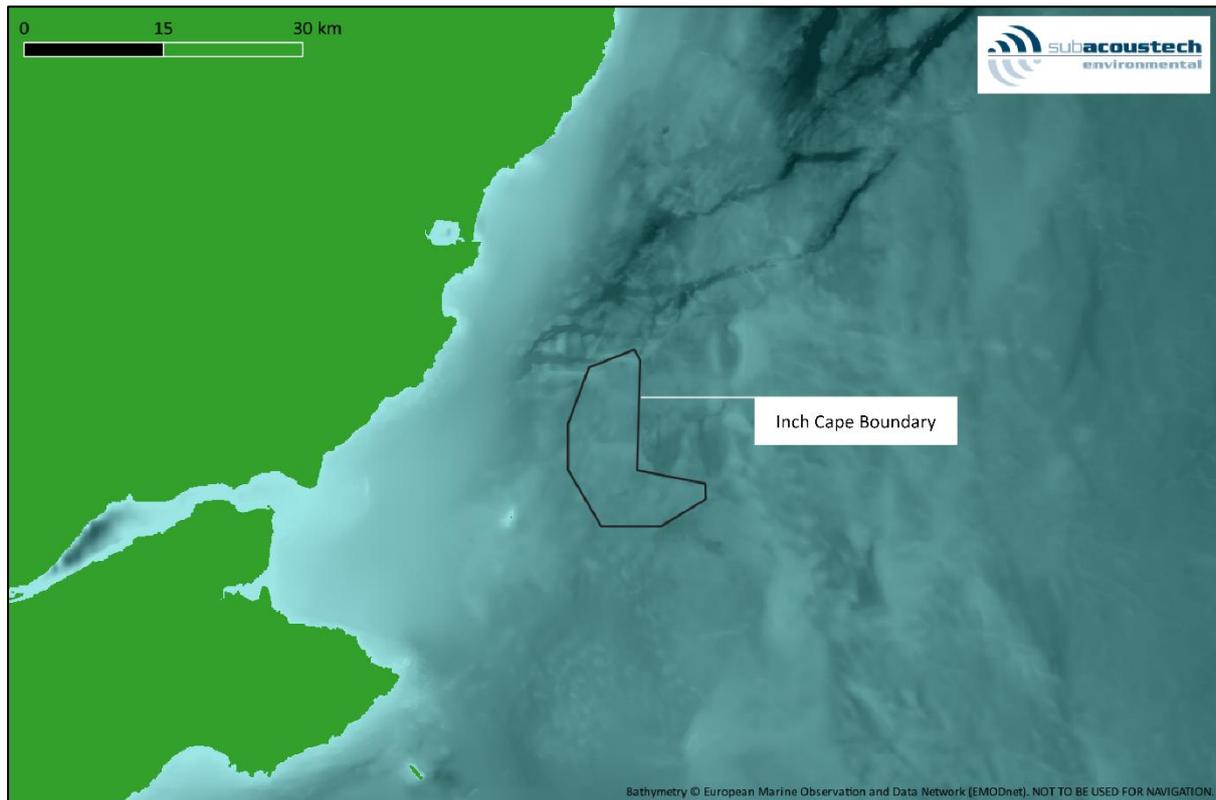
Figure 1-1 Overview map showing the Inch Cape boundary, surrounding bathymetry and coastline.

This report presents a detailed assessment of the potential underwater noise during the installation of OSP foundations at Inch Cape, and includes the following:

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

- Discussion of the approach, input parameters and assumptions for the detailed modelling undertaken (section 3)

- Presentation and interpretation of the detailed subsea noise modelling for impact piling with regards to its effect on marine mammals and fish (section 4), and

- Summary and conclusions (section 5).

Further modelling results are presented in Appendix A.

2   Underwater noise concepts

2.1   Underwater noise

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

2.1.1   Units of measurement

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

The fundamental definition of the dB scale is given by:

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

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

The dB scale represents a ratio. It is therefore used with a reference unit, which expresses the base from which the ratio is expressed. The reference quantity is conventionally smaller than the smallest value to be expressed on the scale so that any level quoted is positive. For example, a reference quantity of 20 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 (Pa) is equal to the pressure exerted by one Newton over one square metre, one micropascal (µPa) equals one millionth of this.

2.1.2   Sound pressure level (L_p or SPL)

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

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

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

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

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

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

2.1.4   Sound exposure level ($L_{E,p,t}$ or SEL)

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

The SEL ($L_{E,p}$) sums the acoustic energy over a measurement period (t), and effectively takes account of both the SPL of the sound and the duration it is present in the acoustic environment. Sound Exposure (SE) is defined by the equation:

$$SE = \int_0^T p^2(t)dt$$

where p is the acoustic pressure in Pa, T is the total duration of sound in seconds, and t is time in seconds. The SE is a measurement of acoustic energy and has units of Pascal squared seconds (Pa²s).

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

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

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

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

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

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

Where a single impulse noise such as the soundwave from a pile strike is considered in isolation, this can be represented by a "single strike" $L_{E,p}$ or SEL_{ss}. A cumulative $L_{E,p,t}$, or SEL_{cum}, accounts for the exposure from multiple

impulses or pile strikes over time, where the number of impulses replaces the T in the equation above, leading to:

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

where $L_{E,p,t}$ is the sound exposure level of one impulse and X is the total number of impulses or strikes. Unless otherwise defined, all $L_{E,p,t}$ noise levels in this report are references to 1 µPa²s.

2.2 Properties of sound

2.2.1 *Impulsive and non-impulsive noise*

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

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

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

Active research is currently underway to define impulsive and non-impulsive noise (see Martin *et al.* (2020)). Although the situation is complex, Hastie *et al.* (2019) concluded that an impulsive sound can be considered effectively non-impulsive 3.5 km from the source. Using these findings, Southall (2021) suggests that noise should be considered non-impulsive when there is no longer energy content above 10 kHz. However, research remains in progress with work ongoing in an attempt to determine numerical values of other pulse characteristics, such as for kurtosis, that can aid categorisation of a pulse as either impulsive or non-impulsive.

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

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

- Non-impulsive noises: cumulative SEL ($L_{E,p,t}$)

2.2.2 *Particle motion*

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

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

a lack of supporting data (Popper and Hawkins, 2018). There continue to be calls for additional research on the levels of and effects with respect to particle motion.

2.3 Analysis of environmental effects: Assessment criteria

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

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

- Physical traumatic injury and fatality,

- Auditory injury (either permanent or temporary), or

- Disturbance and behavioural responses.

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

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

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

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

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

2.3.1 Marine mammals

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

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

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

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

Hearing group	Generalised hearing range	Example species
Low-frequency cetaceans (LF)	7 Hz to 35 kHz	Baleen whales
High-frequency cetaceans (HF)	150 Hz to 160 kHz	Dolphins, toothed whales, beaked whales, bottlenose whales (including bottlenose dolphin)
Very high-frequency cetaceans (VHF)	275 Hz to 160 kHz	True porpoises (including harbour porpoise)
Phocid carnivores in water (PCW)	50 Hz to 86 kHz	True seals (including harbour seals)
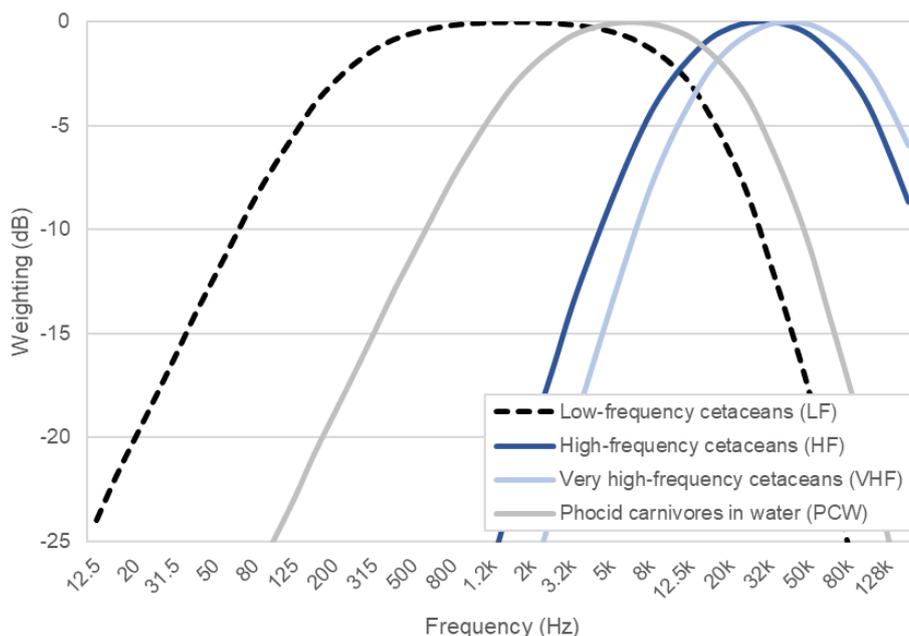
Figure 2-1 Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al., 2019).

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

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

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, several sets of flee speeds have been used for marine mammals, the first cover the standard flee speeds typically used for assessments in Scotland:

- 2.1 m/s for low-frequency cetaceans (LF) (Scottish Natural Heritage; SNH, 2016)

- 1.52 m/s for high-frequency cetaceans (HF) (Bailey and Thompson, 2006)

- 1.4 m/s for very high-frequency cetaceans (VHF) (SNH, 2016), and

- 1.8 m/s for phocid carnivores in water (PCW) (SNH, 2016).

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

In addition, faster flee speeds for LF cetaceans and VHF cetaceans have been modelled for Inch Cape to minimise the compounding of worst-case parameters in the modelling:

- 3.25 m/s for LF cetaceans (Blix and Folkow, 1995), and 1.5 m/s for VHF cetaceans (Otani *et al*. 2000); these are the flee speeds typically used in English and Welsh waters, and

- 4.19 m/s for LF cetaceans (McGarry *et al.*, 2017) and 1.97 m/s for VHF cetaceans (Kastelein *et al.*, 2018); a more realistic flee speed based on measured data.

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

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

- Permanent Threshold Shift (PTS) – unrecoverable (but incremental) hearing damage, and

- Temporary Threshold Shift (TTS) – a temporary reduction in hearing sensitivity.

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

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

- The marine mammal receptors within the area

- The nature of the sound (and subsequently, the appropriate metrics), and

- The type of auditory injury.

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

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

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

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

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

2.3.2   *Fish*

The Popper *et al*. (2014) guidelines are recognised as a suitable reference for underwater noise impacts on marine fauna (aside from marine mammals) in UK waters. While previous studies have applied broad criteria based on limited studies of fish that are not present in UK waters (McCauley *et al*. 2000), or measurement data not intended to be used as criteria (Hawkins *et al.,* 2014), Popper *et al.* (2014) provides a summary of the latest research and guidelines for fish (and other marine fauna) exposure to sound and uses categories for fish that are representative of the species present around the Inch Cape site.

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 have been used.

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

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

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

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

Most species described by Popper *et al.* (2014) are likely to move away from a sound that is loud enough to cause harm (Dahl *et al*., 2015; Popper *et al*., 2014). For those species that flee, a speed of 1.5 m/s (based on Hirata, 1999) is considered a conservative speed at which to base a fleeing animal model. However, considering the diversity of species described by Popper *et al*. (2014), whether an animal flees or remains stationary in response to a loud noise will differ between species. It is recognised that there is limited evidence for fish fleeing

from high level noise sources in the wild. Those species that are likely to remain stationary are thought more likely to be benthic species or species without a swim bladder, due to their reduced hearing capabilities making these species the least sensitive to noise (e.g., Goertner *et al.*, 1994; Goertner *et al.*, 1978; Stephenson *et al.*, 2010; Halvorsen *et al.*, 2012). Despite this, including only a stationary animal model as a worst-case scenario is likely to greatly overestimate the potential risk to fish species. A combined approach is recommended, which considers impact ranges from both fleeing and stationary receptors. Impact ranges from both stationary and fleeing receptors are therefore included in this report.

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

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

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

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. However, it cannot be ignored that convincing evidence of noise impacts to marine invertebrates does exist. 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.

3 Modelling methodology

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

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

The model provides estimates of unweighted $L_{p,pk}$, $L_{E,p,ss}$ and $L_{E,p,t}$ noise levels, as well as other weighted noise metrics. Calculations are made along 180 equally spaced radial transects (one every two degrees). For each modelling run a criterion level can be specified allowing a contour to be drawn, within which a given effect may occur. These results can then be plotted over digital bathymetry data so that impact ranges can be clearly visualised as necessary. INSPIRE also produces these contours as GIS shapefiles.

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

- Piling hammer blow energies

- Soft start, hammer energy ramp up, and strike rate

- Total duration of piling, and

- Receptor swim speeds.

3.1 Modelling confidence

INSPIRE is semi-empirical and as such a validation process is inherently built into the development process. Whenever a new set of good, reliable, impact piling measurement data is gathered through offshore surveys, either by Subacoustech or a third party, it is compared against the outputted levels from INSPIRE and, if necessary, the model can be adjusted. Currently over 80 separate impact piling noise datasets primarily from the Irish and North Sea have been used as part of the development for the latest version of INSPIRE, and in each case, an average fit is used.

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

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

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

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

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

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

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[1] Top Left: 6.0 m pile, 1,010 kJ max hammer energy, off the Suffolk coast, North Sea, 2009; Top Right: 1.8 m pile, 260 kJ max hammer energy, West of Barrow-in-Furness, Irish Sea, 2010; Bottom Left: 5.3 m pile, 1,560 kJ max hammer energy, off the North Welsh coast, 2012; Bottom Right: 9.5 m pile, 1,600 kJ max hammer energy, North Sea, 2020.
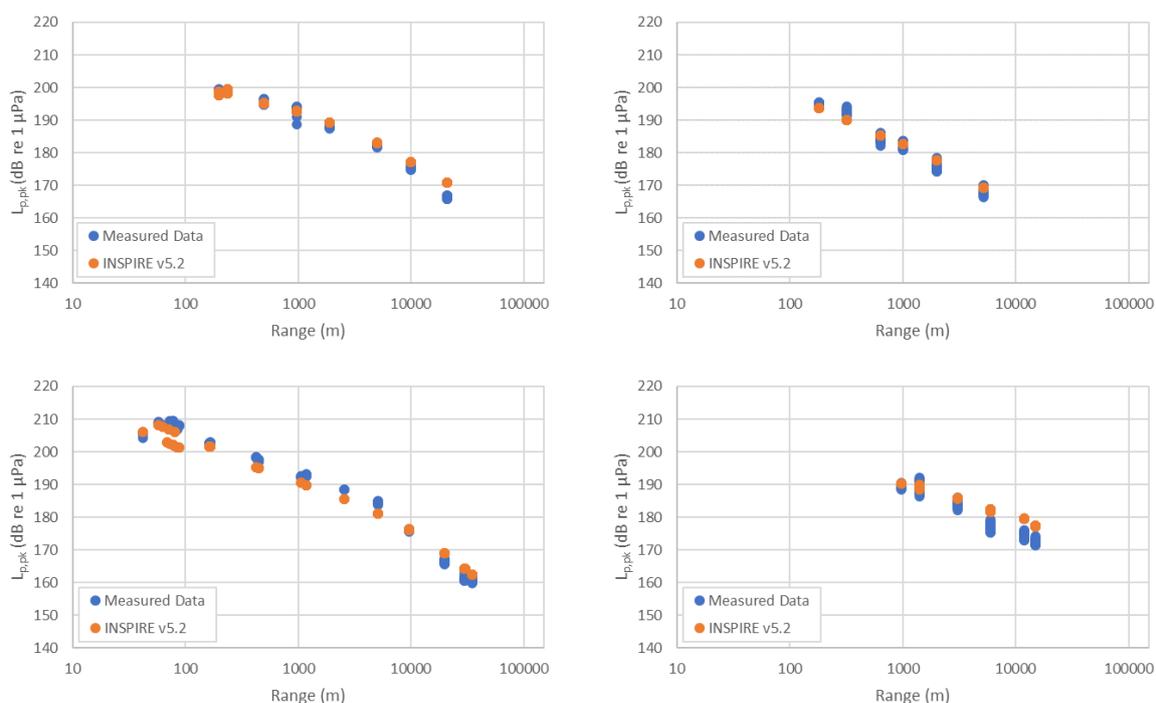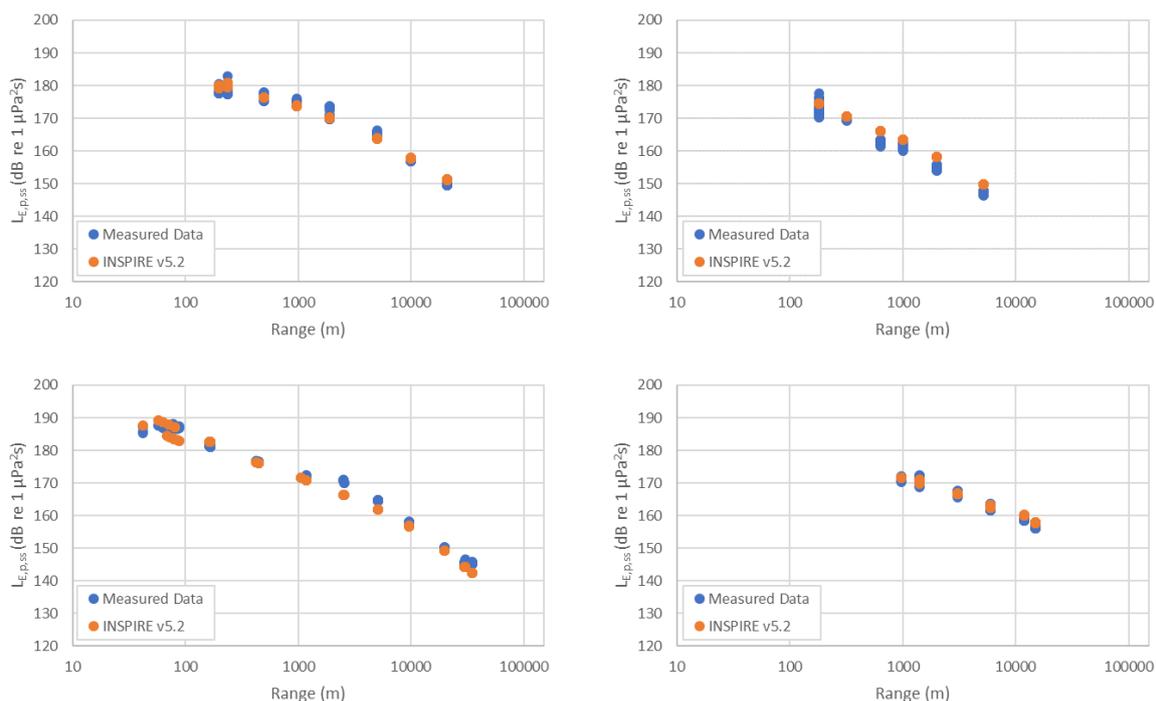
Figure 3-2 Comparison between example measured $L_{E,p,ss}$ impact piling data (blue points) and modelled data using INSPIRE version 5.2 (orange points)[2].

3.2 Modelling parameters

3.2.1 *Modelling locations*

Modelling for OSP foundation impact piling, has been undertaken at a single representative location, this is summarised in Table 3-1 and illustrated in Figure 3-3.

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

Modelling location	Latitude	Longitude	Water depth
OSP	56.47758° N	002.24231° W	45.33 m

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[2] Top Left: 6.0 m pile, 1,010 kJ max hammer energy, off the Suffolk coast, North Sea, 2009; Top Right: 1.8 m pile, 260 kJ max hammer energy, West of Barrow-in-Furness, Irish Sea, 2010; Bottom Left: 5.3 m pile, 1,560 kJ max hammer energy, off the North Welsh coast, 2012; Bottom Right: 9.5 m pile, 1,600 kJ max hammer energy, North Sea, 2020.
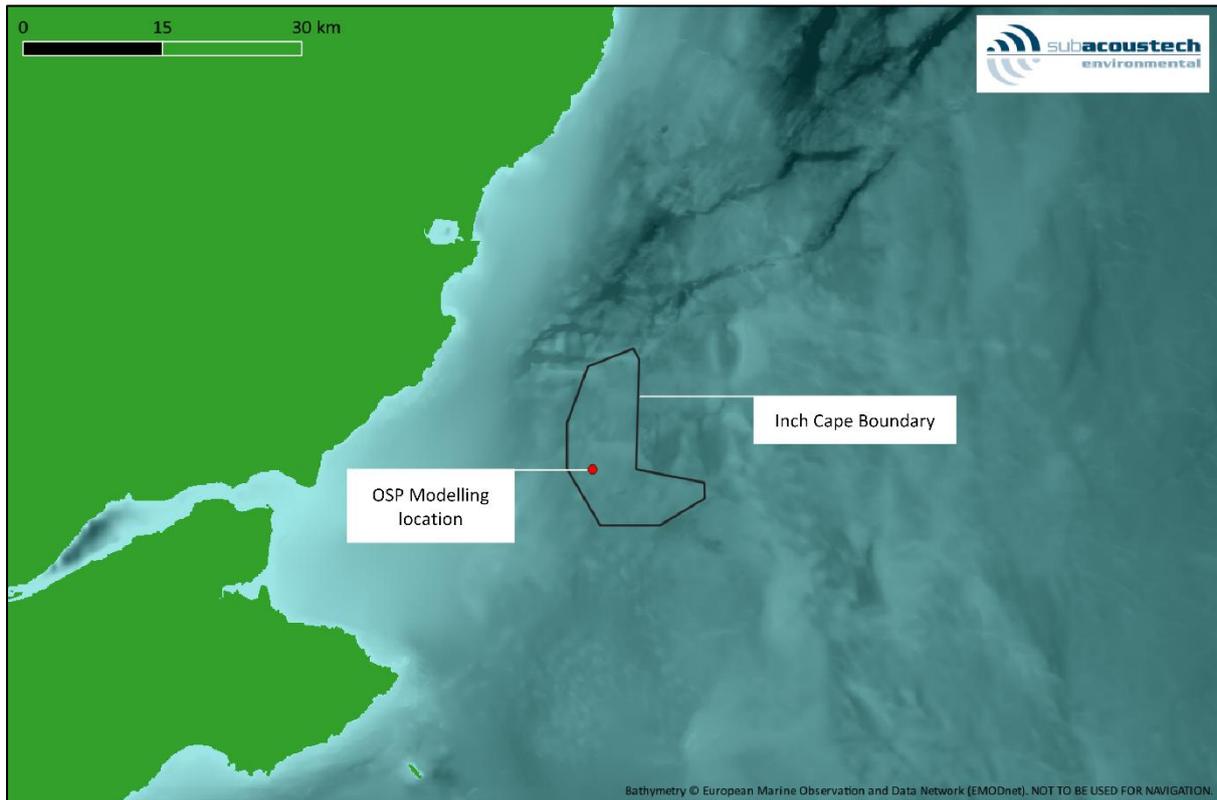
Figure 3-3 Approximate position of the OSP modelling location used for modelling at Inch Cape.

3.2.2 Impact piling parameters

Three multi-leg foundation scenarios have been considered for this study based on different ground conditions, all considering 2.591 m diameter piles and piling hammers with a maximum blow energy of 3500 kJ:

- Best Estimate (BE) ground conditions, where 70% of the maximum hammer energy is used (2450 kJ),

- BE +5 ground conditions, where 100% of the maximum hammer energy is used (3500kJ), and

- BE -5 ground conditions, where 60% of the maximum hammer energy is used.

For $L_{E,p,t}$ criteria, the soft start and ramp up of blow energies along with the total duration of piling and strike rate must also be considered. These are summarised for the three foundation scenarios in Table 3-2 to Table 3-4.

In a 24-hour period, it is expected that 4 foundations can be installed from the same piling vessel, which has been taken into consideration for the modelling. For the OSP foundation piles, a portion of the piling will take place subsea, with the piling hammer submerged. It has been assumed that each pile measures 38.235 m in length, and once fully installed, 14.235 m of the pile will protrude from the seabed. This has been included in the modelling, as the radiating area for noise reduces as the pile is installed.

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

BE	10% 350 kJ	20% 700 kJ	30% 1050 kJ	40% 1400 kJ	50% 1750 kJ	60% 2100 kJ	70% 2450 kJ
No of strikes	6	110	175	150	170	110	490
Duration (mins)	30	3	6	5	7	4	20
Strike rate (bl/min)	0.2	~36.7	~29.2	30.0	~24.3	27.5	24.5
1,211 strikes over 1 hour, 15 minutes per pile **4,844 strikes over 5 hours for four piles**							

Table 3-3 Summary of the soft start and ramp up scenario used for the BE +5 scenario modelling.

BE	10% 350 kJ	20% 700 kJ	30% 1050 kJ	40% 1400 kJ	50% 1750 kJ	60% 2100 kJ	70% 2450 kJ	80% 2800 kJ	90% 3150 kJ	100% 3500 kJ
No of strikes	6	110	175	150	170	135	155	130	135	45
Duration (mins)	30	3	6	5	7	5	6	5	5	2
Strike rate (bl/min)	0.2	~36.7	~29.2	30.0	~24.3	27.0	~25.8	26	27	22.5
1,211 strikes over 1 hour, 14 minutes per pile **4,844 strikes over 4 hours, 56 minutes for four piles**										

Table 3-4 Summary of the soft start and ramp up scenario used for the BE -5 scenario modelling.

BE -5	10% 350 kJ	20% 700 kJ	30% 1050 kJ	40% 1400 kJ	50% 1750 kJ	60% 2100 kJ
No of strikes	6	90	175	470	450	45
Duration (mins)	30	3	6	16	18	2
Strike rate (bl/min)	0.2	30.0	~29.2	~29.4	25.0	22.5
1,236 strikes over 1 hour, 15 minutes per pile **4,944 strikes over 5 hours for four piles**						

3.2.3   *Apparent source levels*

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

The INSPIRE model requires an apparent source level, which is estimated based on the pile diameter and the blow energy imparted on the pile by the hammer. This is adjusted depending on the water depth at the modelling location to allow for the length of the pile (and effective surface area) in contact with the water, which can affect the amount of noise that is transmitted from the pile into its surroundings. The unweighted, single

strike $L_{p,pk}$ and $L_{E,p,ss}$ apparent source levels estimated for this study are provided in Table 3-5. 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 3-5 Summary of the unweighted $L_{p,pk}$ and $L_{E,p,ss}$ (single strike) source levels used for modelling.

Apparent source levels	$L_{p,pk}$ @ 1 m	$L_{E,p,ss}$ @ 1 m
BE Scenario (2.591m diameter pile / 2450 kJ maximum hammer energy)	240.7 dB re 1 μPa @ 1m	221.0 dB re 1 μPa²s @ 1m
BE +5 Scenario (2.591m diameter pile / 3500 kJ maximum hammer energy)	241.2 dB re 1 μPa @ 1m	221.3 dB re 1 μPa²s @ 1m
BE -5 Scenario (2.591m diameter pile / 2100 kJ maximum hammer energy)	240.0 dB re 1 μPa @ 1m	220.0 dB re 1 μPa²s @ 1m

As the piles' apparent source levels as the length of the pile in the water reduces during driving, maximum levels for each scenario are presented in the table above. This is why the presented $L_{E,p,ss}$ source level is marginally lower for the BE +5 scenario compared to the BE scenario, even when higher blow energies are used overall.

3.2.4   *Predicted noise levels at 750 m from the noise source*

In addition to the apparent source levels given in the previous section, it is useful to look at the potential noise levels at a range of 750 m from the noise source, which is a common feature of underwater noise studies for where the primary consideration is impact piling. This has the added advantage of being comparable with other modelling or measurements, where the source level (or apparent source level) may not. A summary of the modelled unweighted levels at a range of 750 m, are given in Table 3-6 considering the transect with the greatest noise transmission at each location while piling at the maximum hammer blow energy.

Table 3-6 Summary of the maximum predicted unweighted $L_{p,pk}$ 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.

Predicted levels at 750 m	$L_{p,pk}$ @ 750 m	$L_{E,p,ss}$ @ 750m
BE Scenario (2.591m diameter pile / 2450 kJ maximum hammer energy)	200.2 dB re 1 μPa	180.5 dB re 1 μPa²s
BE +5 Scenario (2.591m diameter pile / 3500 kJ maximum hammer energy)	200.7 dB re 1 μPa	180.8 dB re 1 μPa²s
BE -5 Scenario (2.591m diameter pile / 2100 kJ maximum hammer energy)	199.5 dB re 1 μPa	179.5 dB re 1 μPa²s

3.2.5   *Environmental conditions*

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

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

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

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

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

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

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

As an example, the graphs Figure 3-4 and Figure 3-5 show the difference in the received $L_{E,p,t}$ from a stationary receptor and a fleeing receptor travelling at a constant speed of 1.5 m/s, using the BE scenario for a single pile installation. This also illustrates the reduction in noise level due to subsea piling and the reducing area of radiation of the pile.

The received single strike $L_{E,p,ss}$ from the stationary receptor, as illustrated in Figure 3-4, shows the noise level gradually increasing as the blow energy increases throughout the piling operation. These step changes are also visible for the fleeing receptor, but as the receptor is further from the noise source by the time the levels increase, the total received exposure reduces, resulting in progressively lower received noise levels. As an example, for the first 30 minutes of piling, where the blow energy is 350 kJ (10% of maximum energy), fleeing at a rate of 1.5 m/s, a receptor has the potential to move 2.7 km from the noise source. After the full installation of 75 minutes, the receptor has the potential to be over 6.7 km from the noise source; for the faster flee speeds considered for this modelling these distances increase further.

Figure 3-5 shows the effect these different received levels have when calculating the $L_{E,p,t}$, clearly showing the difference in the cumulative levels between a receptor remaining still, as opposed to fleeing. To use an extreme example, starting at a range of 1 m, the first strike results in a received level of 212.6 dB re 1 μPa^{2}s. If the receptor were to remain stationary throughout the piling operation, it would receive a cumulative level of 250.4 dB re 1 μPa^{2}s, whereas when fleeing at 1.5 m/s over the same scenario, a cumulative received level of just 212.7 dB re 1 μPa^{2}s is achieved. Figure 3-5 also clearly shows the impact strike rate has on the cumulative level where the initial 30-minute soft start ends and the ~36.7 bl/min strike rate starts.
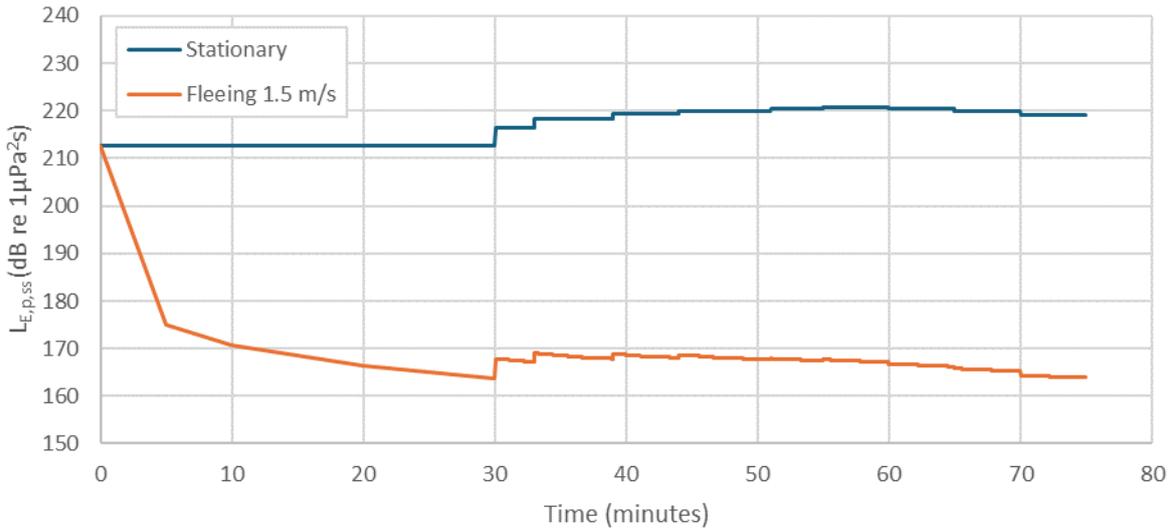
Figure 3-4 Received single strike noise levels (L$_{E,p,ss}$) for receptors during the monopile foundation installation at modelling location 1, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source.
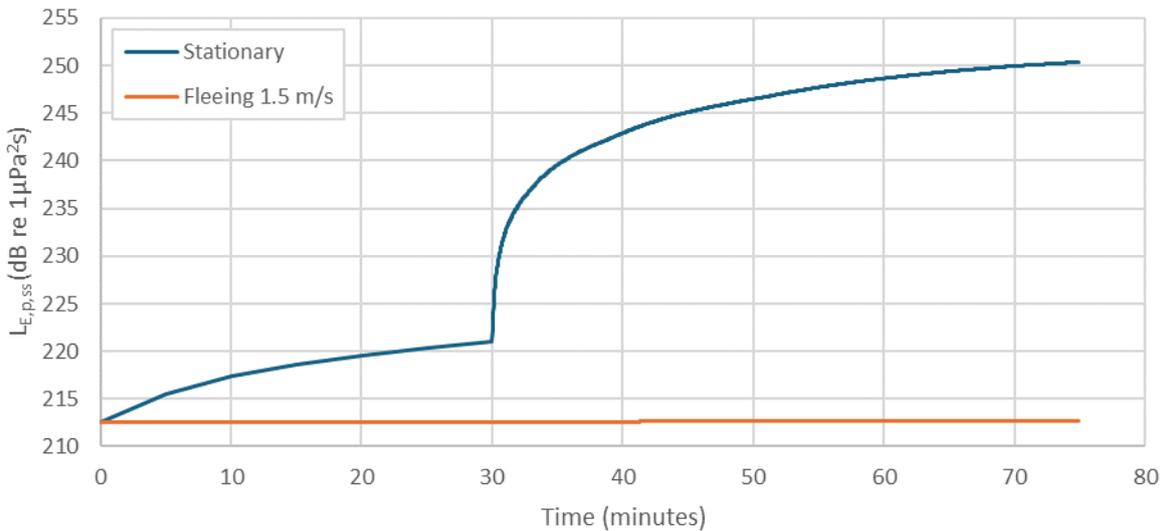
Figure 3-5 Cumulative received noise level (L$_{E,p,t}$) for receptors during monopile foundation installation at modelling location 1, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source.

To summarise, if the receptor were to start fleeing in a straight line from the noise source starting at a range closer than the modelled value, it would receive a noise exposure in excess of the criterion, and if the receptor were to start fleeing from a range further than the modelled value, it would receive a noise exposure below the criterion. This is illustrated in Figure 3-6.
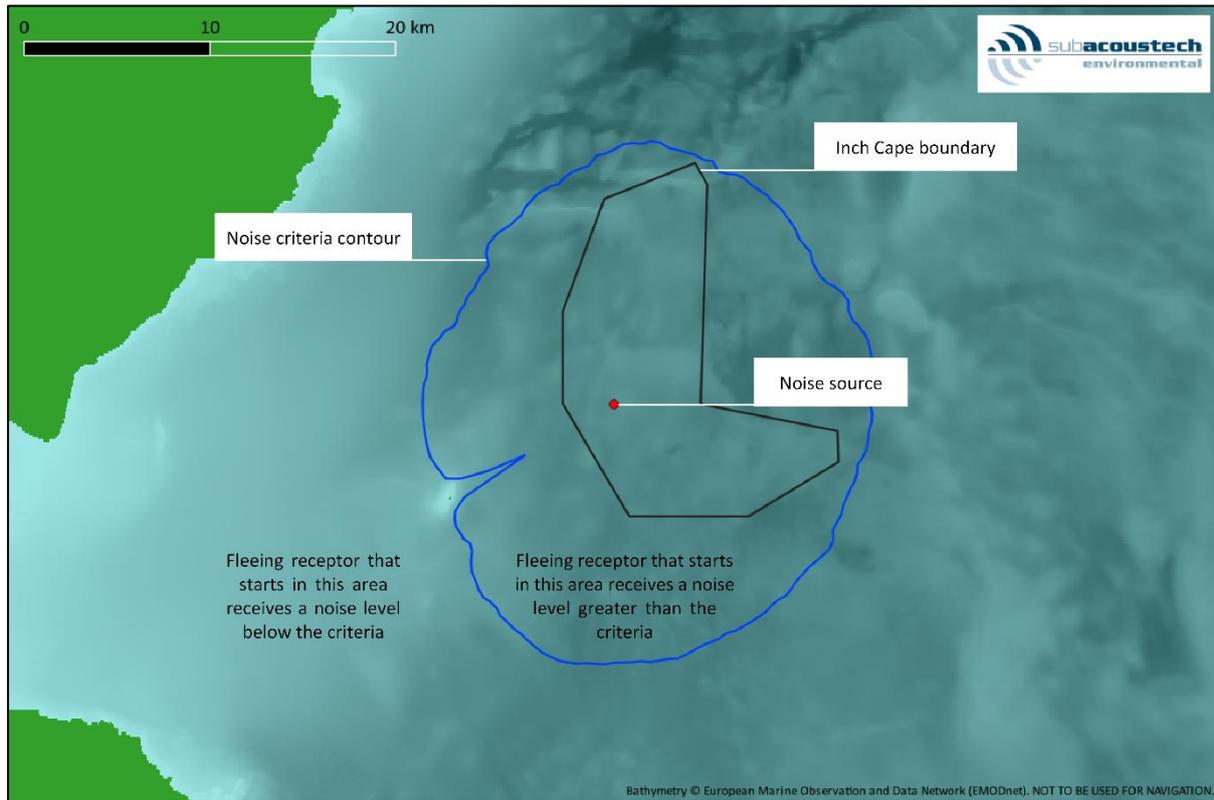
Figure 3-6 Example plot showing a fleeing animal $L_{E,p,t}$ criteria contour and the areas where the cumulative noise exposure will exceed an impact criteria.

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

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

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

Parameters like hammer blow energy can have a clear effect on the impact ranges, with higher energies resulting in high apparent source noise levels and therefore larger impact ranges. When considering cumulative noise levels, these higher levels are compounded, sometimes thousands of times, due to the number of pile strikes. With this in mind, the ramp up from lower to higher blow energies requires careful consideration for fleeing receptors, as levels while the receptor is closer to the noise source will have a greater effect on the overall cumulative exposure level. Figure 3-7 summarises the hammer blow energy ramp up for the three modelled scenarios, showing the same parameters over the first 44 minutes before diverging.
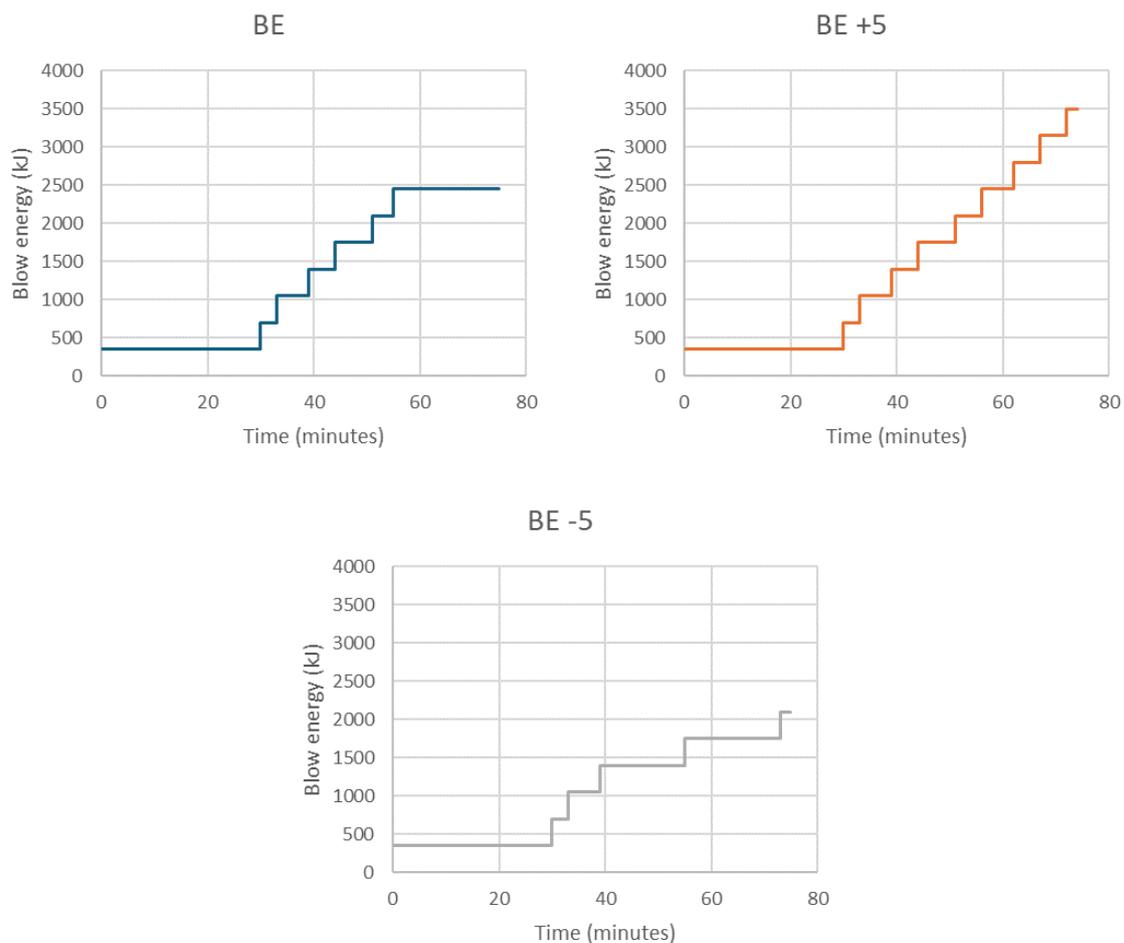
Figure 3-7 Graphical representations of the blow energy for the three OSP ramp up scenarios.

Linked to the effect of the ramp up is the strike rate, as the more pile strikes that occur while the receptor is close to the noise source, the greater the exposure and the greater effect it will have to the $L_{E,p,t}$. The faster the strike rate, the shorter the distance the receptor can flee between each pile strike, which leads to a greater exposure overall. Figure 3-8 shows the strike rate against time for the modelled scenarios, with identical 30-minute soft and slow start periods before sharply rising to maximum strike rates then gradually decreasing as the blow energy increases. The fastest strike rate is expected for the BE and BE +5 scenarios with a period of ~36.7 blows per minute after the initial 30 minutes. The total duration of piling is less important when considering a fleeing animal, as the additional pile strikes at the end of piling occur when the receptor has travelled to a greater distance, where noise levels will have reduced. This can be seen in Figure 3-5 in the previous section.
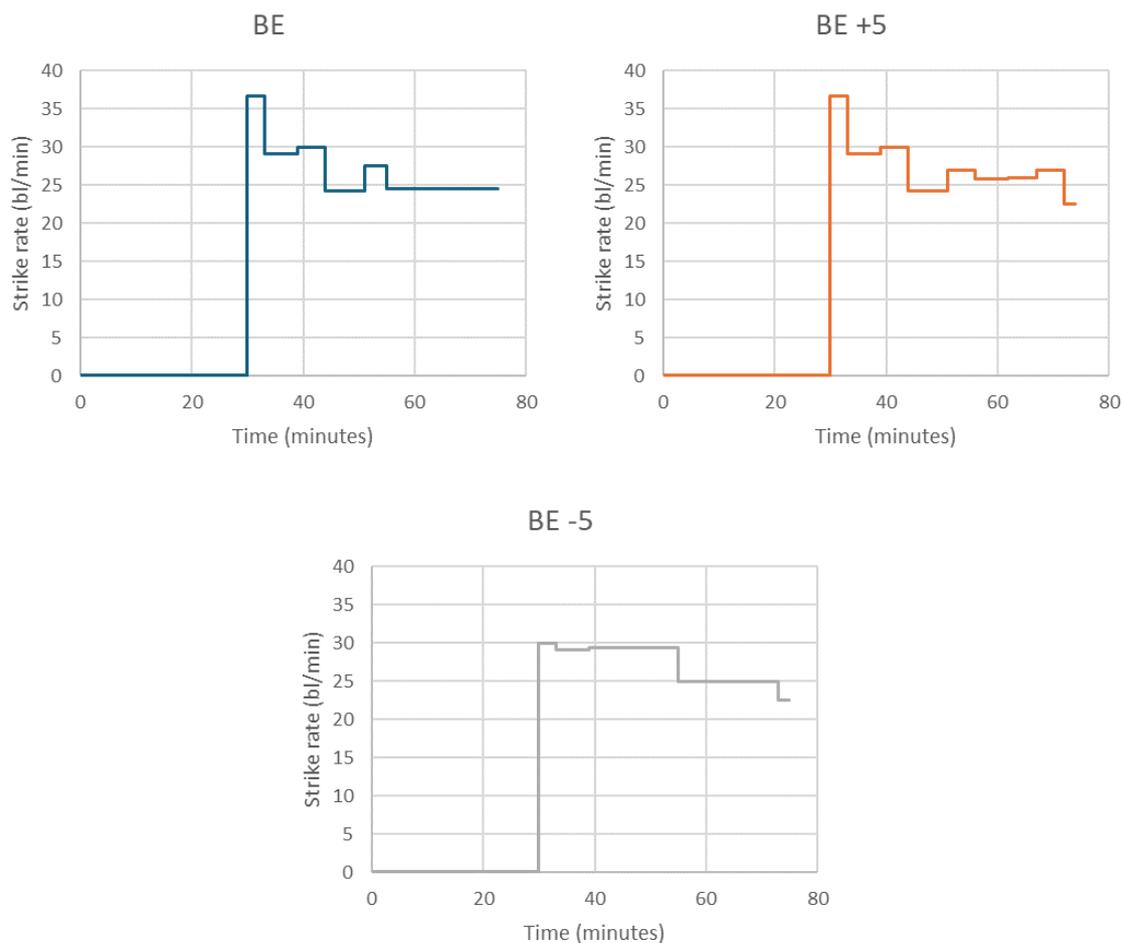
Figure 3-8 Graphical representations of the strike rate for the three OSP ramp up scenarios.

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

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

3.4   Precaution in underwater noise modelling

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

3.4.1   Source

The modelling locations were chosen to provide the greatest extents of the site, in the locations likely to lead to maximum underwater noise transmission. The maximum blow energies were used for a duration unlikely to

occur in practice. A fast strike rate has been included for much of the ramp-up. The total piling duration is not expected to be exceeded on site.

3.4.2   Transmission

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

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. The same goes for the flee speeds considered for modelling.

Frequency specific hearing thresholds are not used for fish as they are with marine mammals, effectively assuming that fish are sensitive to sound at all frequencies, which is not the case. The thresholds calculated for PTS and TTS are the 'onset' to these effects, which means that this is the threshold at which the effect starts to be detected in test species, rather than where this effect is widespread.

4 Modelling results

This section presents the modelled impact ranges for impact piling noise following the parameters detailed in section 3.2, covering the Southall *et al*. (2019) marine mammal criteria (section 2.3.1), and the Popper *et al*. (2014) fish criteria (section 2.3.2).

Throughout this report, any predicted ranges smaller than 50 m and areas less than 0.01 km² for single strike criteria and ranges smaller than 100 m and areas less than 0.1 km² for cumulative criteria have not been presented in detail. At ranges this close to the noise source, the modelling processes are unable to model to a sufficient level of accuracy due to complex acoustic effects present near the source. These ranges are given as "less than" this limit (e.g., < 100 m).

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

4.1 OSP foundation modelling

Table 4-1 to Table 4-12 present the modelling results for the three OSP foundation location scenarios. For these scenarios, the largest marine mammal impact ranges are predicted for the BE +5 scenario, due to the higher blow energies used for this scenario. Maximum PTS ranges are predicted for LF cetaceans out to 9.9 km, when considering the slowest flee speed (2.1 m/s) reducing to 1.8 km when considering a flee speed of 4.19 m/s. For fish, the largest recoverable injury ranges (203 dB $L_{E,p,24h}$) are predicted out to 3.4 km when considering a stationary receptor, reducing to less than 100 m when a fleeing animal is assumed.

4.1.1 BE scenario

Table 4-1 Summary of the $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the OSP foundation modelling for the BE scenario.

Southall *et al*. (2019) $L_{p,pk}$		BE scenario			
		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)	0.95 km²	560 m	550 m	550 m
	PCW (218 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.03 km²	90 m	90 m	90 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	6.4 km²	1.4 km	1.4 km	1.4 km
	PCW (212 dB)	0.04 km²	110 m	110 m	110 m

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Table 4-2 Summary of the $L_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the OSP foundation modelling for the BE scenario assuming a fleeing animal.

Southall *et al.* (2019) $L_{E,p,24h,wtd}$			BE scenario			
			Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	2.1 m/s	240 km²	10 km	3.5 km	8.6 km
	LF (183 dB)	3.25 m/s	56 km²	5.1 km	400 m	4.2 km
	LF (183 dB)	4.19 m/s	5.2 km²	1.8 km	200 m	1.1 km
	HF (185 dB)	1.52 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	1.4 m/s	48 km²	4.2 km	2.6 km	3.9 km
	VHF (155 dB)	1.5 m/s	38 km²	3.8 km	2.3 km	3.5 km
	VHF (155 dB)	1.97 m/s	9.2 km²	2.0 km	1.0 km	1.7 km
	PCW (185 dB)	1.8 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (183 dB)	2.1 m/s	5700 km²	64 km	6.2 km	40 km
	LF (183 dB)	3.25 m/s	4300 km²	56 km	4.1 km	35 km
	LF (183 dB)	4.19 m/s	3500 km²	51 km	2.3 km	31 km
	HF (185 dB)	1.52 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	1.4 m/s	2700 km²	38 km	7.3 km	29 km
	VHF (155 dB)	1.5 m/s	2600 km²	37 km	7.1 km	28 km
	VHF (155 dB)	1.97 m/s	2200 km²	34 km	6.1 km	26 km
	PCW (185 dB)	1.8 m/s	680 km²	18 km	5.3 km	15 km

Table 4-3 Summary of the $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the OSP foundation modelling for the BE scenario.

Popper *et al.* (2014) $L_{p,pk}$		BE scenario			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.03 km²	90 m	90 m	90 m
	207 dB	0.19 km²	250 m	250 m	250 m

Table 4-4 Summary of the $L_{E,p,24h}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the OSP foundation modelling for the BE scenario assuming both a fleeing and stationary animal.

Popper *et al.* (2014) $L_{E,p,24h}$		BE scenario			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	550 km²	15 km	5.5 km	13 km
Stationary (0 m/s)	219 dB	0.26 km²	300 m	280 m	290 m
	216 dB	0.67 km²	480 m	450 m	460 m
	210 dB	4.9 km²	1.3 km	1.2 km	1.3 km
	207 dB	12 km²	2.0 km	1.9 km	2.0 km
	203 dB	37 km²	3.5 km	3.5 km	3.4 km
	186 dB	1900 km²	27 km	10 km	25 km

4.1.2 BE +5 scenario

Table 4-5 Summary of the $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the OSP foundation modelling for the BE +5 scenario.

Southall *et al.* (2019) $L_{p,pk}$		BE +5 scenario			
		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)	1.1 km²	600 m	600 m	600 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)	7.6 km²	1.6 km	1.6 km	1.6 km
	PCW (212 dB)	0.04 km²	120 m	120 m	120 m

Table 4-6 Summary of the $L_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the OSP foundation modelling for the BE +5 scenario assuming a fleeing animal.

Southall *et al.* (2019) $L_{E,p,24h,wtd}$			BE +5 scenario			
			Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	2.1 m/s	260 km²	11 km	3.5 km	9.0 km
	LF (183 dB)	3.25 m/s	65 km²	5.4 km	400 m	4.5 km
	LF (183 dB)	4.19 m/s	7.3 km²	2.1 km	200 m	1.4 km
	HF (185 dB)	1.52 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	1.4 m/s	55 km²	4.5 km	2.8 km	4.2 km
	VHF (155 dB)	1.5 m/s	44 km²	4.1 km	2.5 km	3.8 km
	VHF (155 dB)	1.97 m/s	12 km²	2.2 km	1.1 km	1.9 km
	PCW (185 dB)	1.8 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (183 dB)	2.1 m/s	5900 km²	65 km	6.2 km	40 km
	LF (183 dB)	3.25 m/s	4500 km²	57 km	4.1 km	35 km
	LF (183 dB)	4.19 m/s	3600 km²	52 km	2.3 km	21 km
	HF (185 dB)	1.52 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	1.4 m/s	2900 km²	39 km	7.3 km	29 km
	VHF (155 dB)	1.5 m/s	2700 km²	38 km	7.1 km	29 km
	VHF (155 dB)	1.97 m/s	2300 km²	35 km	6.1 km	26 km
	PCW (185 dB)	1.8 m/s	710 km²	18 km	5.3 km	15 km

Table 4-7 Summary of the $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the OSP foundation modelling for the BE +5 scenario.

Popper *et al.* (2014) $L_{p,pk}$		BE +5 scenario			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.03 km²	100 m	100 m	100 m
	207 dB	0.23 km²	270 m	270 m	270 m

Table 4-8 Summary of the $L_{E,p,24h}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the OSP foundation modelling for the BE +5 scenario assuming both a fleeing and stationary animal.

Popper *et al.* (2014) $L_{E,p,24h}$		BE +5 scenario			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	590 km²	16 km	5.5 km	14 km
Stationary (0 m/s)	219 dB	0.31 km²	330 m	300 m	310 m
	216 dB	0.74 km²	500 m	480 m	490 m
	210 dB	4.9 km²	1.3 km	1.2 km	1.3 km
	207 dB	12 km²	2.0 km	1.9 km	2.0 km
	203 dB	39 km²	3.6 km	3.5 km	3.6 km
	186 dB	2000 km²	28 km	10 km	25 km

4.1.3   BE -5 scenario

Table 4-9 Summary of the $L_{p,pk}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the OSP foundation modelling for the BE -5 scenario.

Southall *et al.* (2019) $L_{p,pk}$		BE -5 scenario			
		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)	0.78 km²	500 m	500 m	500 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km²	90 m	80 m	90 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	5.3 km²	1.3 km	1.3 km	1.3 km
	PCW (212 dB)	0.03 km²	100 m	100 m	100 m

Table 4-10 Summary of the $L_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the OSP foundation modelling for the BE -5 scenario assuming a fleeing animal.

Southall *et al.* (2019) $L_{E,p,24h,wtd}$			BE -5 scenario			
			Area	Maximum range	Minimum range	Mean range
PTS (Impulsive)	LF (183 dB)	2.1 m/s	210 km²	9.2 km	3.5 km	8.0 km
	LF (183 dB)	3.25 m/s	43 km²	4.4 km	300 m	3.6 km
	LF (183 dB)	4.19 m/s	2.1 km²	1.2 km	100 m	700 m
	HF (185 dB)	1.52 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	1.4 m/s	39 km²	3.8 km	2.3 km	3.5 km
	VHF (155 dB)	1.5 m/s	30 km²	3.4 km	2.0 km	3.1 km
	VHF (155 dB)	1.97 m/s	5.8 km²	1.6 km	700 m	1.4 km
	PCW (185 dB)	1.8 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (183 dB)	2.1 m/s	5400 km²	62 km	6.2 km	39 km
	LF (183 dB)	3.25 m/s	4100 km²	54 km	4.0 km	34 km
	LF (183 dB)	4.19 m/s	3300 km²	49 km	2.2 km	30 km
	HF (185 dB)	1.52 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	1.4 m/s	2600 km²	36 km	7.2 km	28 km
	VHF (155 dB)	1.5 m/s	2500 km²	36 km	7.0 km	27 km
	VHF (155 dB)	1.97 m/s	2000 km²	32 km	6.0 km	25 km
	PCW (185 dB)	1.8 m/s	660 km²	17 km	5.2 km	14 km

Table 4-11 Summary of the $L_{p,pk}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the OSP foundation modelling for the BE -5 scenario.

Popper *et al.* (2014) $L_{p,pk}$		BE -5 scenario			
		Area	Maximum range	Minimum range	Mean range
Pile driving	213 dB	0.02 km²	90 m	80 m	90 m
	207 dB	0.15 km²	220 m	220 m	220 m

Table 4-12 Summary of the $L_{E,p,24h}$ impact ranges for fish using the Popper et al. (2014) pile driving criteria for the OSP foundation modelling for the BE -5 scenario assuming both a fleeing and stationary animal.

Popper *et al.* (2014) $L_{E,p,24h}$		BE -5 scenario			
		Area	Maximum range	Minimum range	Mean range
Fleeing (1.5 m/s)	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	490 km²	14 km	5.5 km	12 km
Stationary (0 m/s)	219 dB	0.22 km²	300 m	250 m	270 m
	216 dB	0.6 km²	450 m	430 m	440 m
	210 dB	4.1 km²	1.2 km	1.1 km	1.2 km
	207 dB	9.9 km²	1.9 km	1.7 km	1.8 km
	203 dB	33 km²	3.3 km	3.1 km	3.2 km
	186 dB	1800 km²	26 km	10 km	24 km

5   Summary and conclusions

Subacoustech Environmental has undertaken a study on behalf of Inch Cape Wind to assess the potential underwater noise and its effects during the installation of OSP foundations at the proposed Inch Cape Offshore Wind Farm site, off the Angus Coast, Scotland.

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

A single representative modelling location was chosen along with three piling scenarios considering various ground types.

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

For marine mammals, maximum PTS ranges were predicted for LF cetaceans, with ranges of up to 11 km based on the multi-leg foundation scenario and the slowest considered flee speed (2.1 m/s). For fish, the largest recoverable injury ranges (203 dB $L_{E,p,24h}$) were predicted to be 3.6 km for a stationary receptor, reducing to less than 100 m when considering a fleeing receptor.

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

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Appendix A   Additional modelling results

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

A.1   Single location modelling

Table A 1 Summary of the L$_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the OSP foundation modelling for the BE scenario assuming a fleeing animal.

Southall *et al.* (2019) L$_{E,p,24h,wtd}$			BE scenario			
			Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199 dB)	2.1 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	LF (199 dB)	3.25 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	LF (199 dB)	4.19 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	1.52 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	1.4 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	1.5 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	1.97 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	1.8 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	2.1 m/s	840 km²	20 km	4.9 km	16 km
	LF (179 dB)	3.25 m/s	400 km²	14 km	2.2 km	11 km
	LF (179 dB)	4.19 m/s	200 km²	10 km	200 m	7.8 km
	HF (178 dB)	1.52 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	1.4 m/s	120 km²	6.7 km	4.1 km	6.2 km
	VHF (153 dB)	1.5 m/s	100 km²	6.2 km	3.7 km	5.8 km
	VHF (153 dB)	1.97 m/s	45 km²	4.2 km	2.2 km	3.8 km
	PCW (181 dB)	1.8 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m

Table A 2 Summary of the L$_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the OSP foundation modelling for the BE +5 scenario assuming a fleeing animal.

Southall *et al.* (2019) L$_{E,p,24h,wtd}$			BE +5 scenario			
			Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199 dB)	2.1 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	LF (199 dB)	3.25 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	LF (199 dB)	4.19 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	1.52 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	1.4 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	1.5 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	1.97 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	1.8 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	2.1 m/s	890 km²	21 km	4.9 km	17 km
	LF (179 dB)	3.25 m/s	440 km²	15 km	2.2 km	12 km
	LF (179 dB)	4.19 m/s	220 km²	11 km	200 m	8.1 km
	HF (178 dB)	1.52 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	1.4 m/s	140 km²	7.1 km	4.2 km	6.6 km
	VHF (153 dB)	1.5 m/s	120 km²	6.6 km	3.9 km	6.1 km
	VHF (153 dB)	1.97 m/s	52 km²	4.5 km	2.3 km	4.1 km
	PCW (181 dB)	1.8 m/s	< 0.1 km²	< 100 m	< 100 m	< 100 m

Table A 3 Summary of the L$_{E,p,24h,wtd}$ impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the OSP foundation modelling for the BE -5 scenario assuming a fleeing animal.

Southall *et al.* (2019) L$_{E,p,24h,wtd}$			BE -5 scenario			
			Area	Maximum range	Minimum range	Mean range
PTS (Non-impulsive)	LF (199 dB)	2.1 m/s	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	LF (199 dB)	3.25 m/s	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	LF (199 dB)	4.19 m/s	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	1.52 m/s	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	1.4 m/s	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	1.5 m/s	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	1.97 m/s	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	1.8 m/s	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	2.1 m/s	760 km^2	19 km	4.8 km	15 km
	LF (179 dB)	3.25 m/s	360 km^2	13 km	2.1 km	10 km
	LF (179 dB)	4.19 m/s	170 km^2	9.1 km	200 m	7.1 km
	HF (178 dB)	1.52 m/s	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	1.4 m/s	100 km^2	6.2 km	3.9 km	5.7 km
	VHF (153 dB)	1.5 m/s	87 km^2	5.7 km	3.6 km	5.3 km
	VHF (153 dB)	1.97 m/s	35 km^2	3.7 km	2.0 km	3.3 km
	PCW (181 dB)	1.8 m/s	< 0.1 km^2	< 100 m	< 100 m	< 100 m

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Document No.	Draft	Date	Details of change
P271R1100	02	14/08/2024	Initial writing and internal review
P271R1101	02	21/08/2024	Modelling update following adjustments to input parameters
P271R1102	-	01/10/2024	Issue to client

Originator's current report number	P271R1102
Originator's name and location	[Redacted]; Subacoustech Environmental Ltd.
Contract number and period covered	P271; March 2024 – September 2024
Sponsor's name and location	[Redacted]; Inch Cape Wind
Report classification and caveats in use	RESTRICTED – Distribution to named persons only.
Date written	August – September 2024
Pagination	Cover + vi + 40
References	47
Report title	Inch Cape Offshore Wind Farm: OSP Underwater Noise Assessment
Translation/Conference details (if translation, give foreign title/if part of a conference, give conference particulars)	
Title classification	Unclassified
Author(s)	[Redacted]
Descriptors/keywords	
Abstract	
Abstract classification	Unclassified; Unlimited distribution