NORTH FALLS

Offshore Wind Farm

ENVIRONMENTAL STATEMENT

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North Falls Offshore Wind Farm: Underwater noise assessment

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Acronyms

Term	Definition
ADD	Acoustic Deterrent Device
EIA	Environmental Impact Assessment
EMODnet	European Marine Observation and Data Network
FPSO	Floating Production Storage and Offloading
GIS	Geographic Information System
HF	High-Frequency Cetaceans (from Southall *et al.*, 2019)
INSPIRE	Impulse Noise Sound Propagation and Range Estimator (Subacoustech Environmental's noise model for estimating impact piling noise)
LF	Low-Frequency Cetaceans (from Southall *et al.*, 2019)
MTD	Marine Technology Directorate
NMFS	National Marine Fisheries Service
NPL	National Physical Laboratory
PCW	Phocid Carnivores in Water (from Southall *et al.*, 2019)
PPV	Peak Particle Velocity
PTS	Permanent Threshold Shift
RMS	Root Mean Square
SE	Sound Exposure
SEL	Sound Exposure Level
SEL_{cum}	Cumulative Sound Exposure Level
SEL_{ss}	Single Strike Sound Exposure Level
SPL	Sound Pressure Level
SPL_{peak}	Peak Sound Pressure Levels
$SPL_{peak\text{-}to\text{-}peak}$	Peak-to-peak Sound Pressure Level
SPL_{RMS}	Root Mean Square Sound Pressure Level
TNT	Trinitrotoluene (explosive)
TTS	Temporary Threshold Shift
UXO	Unexploded Ordnance
VHF	Very High-Frequency Cetaceans (from Southall *et al.*, 2019)
WTG	Wind Turbine Generator

Glossary

Term	Definition
Decibel (dB)	A customary scale commonly used (in various ways) for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be $10 \log_{10}$(actual/reference) where (actual/reference) is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is $20 \log_{10}$(actual pressure/reference pressure). The standard reference for underwater sound is 1 micropascal (μPa). The dB symbol is followed by a second symbol identifying the specific reference value (e.g., re 1 μPa).
Peak pressure	The highest pressure above or below ambient that is associated with a sound wave.
Peak-to-peak pressure	The sum of the highest positive and negative pressures that are associated with a sound wave.
Permanent Threshold Shift (PTS)	A permanent total or partial loss of hearing caused by acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the air, and thus a permanent reduction of hearing acuity.
Root Mean Square (RMS)	The square root of the arithmetic average of a set of squared instantaneous values. Used for presentation of an average sound pressure level.
Sound Exposure Level (SEL)	The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.
Sound Exposure Level, cumulative (SEL_{cum})	Single value for the collected, combined total of sound exposure over a specified time or multiple instances of a noise source.
Sound Exposure Level, single strike (SEL_{ss})	Calculation of the sound exposure level representative of a single noise impulse, typically a pile strike.
Sound Pressure Level (SPL)	The sound pressure level is an expression of sound pressure using the decibel (dB) scale; the standard frequency pressures of which are 1 μPa for water and 20 μPa for air.
Sound Pressure Level Peak (SPL_{peak})	The highest (zero-peak) positive or negative sound pressure, in decibels.
Temporary Threshold Shift (TTS)	Temporary reduction of hearing acuity because of exposure to sound over time. Exposure to high levels of sound over relatively short time periods could cause the same level of TTS as exposure to lower levels of sound over longer time periods. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory cells. The duration of TTS varies depending on the nature of the stimulus.
Unweighted sound level	Sound levels which are "raw" or have not been adjusted in any way, for example to account for the hearing ability of a species.
Weighted sound level	A sound level which has been adjusted with respect to a "weighting envelope" in the frequency domain, typically to make an unweighted level relevant to a particular species. Examples of this are the dB(A), where the overall sound level has been adjusted to account for the hearing ability of humans in air, or the filters used by Southall *et al.* (2019) for marine mammals.

Units

Term	Definition
dB	Decibel (sound pressure)
GW	Gigawatt (power)
Hz	Hertz (frequency)
kg	Kilogram (mass)
kJ	Kilojoule (energy)
kHz	Kilohertz (frequency)
km	Kilometre (distance)
km^2	Square kilometre (area)
m	Metre (distance)
mms^{-1}	Millimetres per second (speed / particle velocity)
ms^{-1}	Metres per second (speed)
MW	Megawatt (power)
Pa	Pascal (pressure)
Pa^2s	Pascal squared seconds (acoustic energy)
μPa	Micropascal (pressure)

1 Introduction

North Falls Offshore Wind Farm (North Falls) is a proposed offshore wind farm in the southern North Sea. As part of the Environmental Impact Assessment (EIA) process, Subacoustech Environmental Ltd. have undertaken detailed underwater noise modelling and analysis in relation to marine mammals and fish at the North Falls site.

The North Falls site covers an area of approximately 100 km^2 and is situated, at its closest point, 42 km from the shore at The Naze, Essex. The site is located adjacent to the south and west edges of the existing Greater Gabbard and Galloper Offshore Wind Farms. The project has a proposed capacity of up to 504 MW, potentially using up to 57 Wind Turbine Generators (WTGs). The location of North Falls is shown in Figure 1-1.

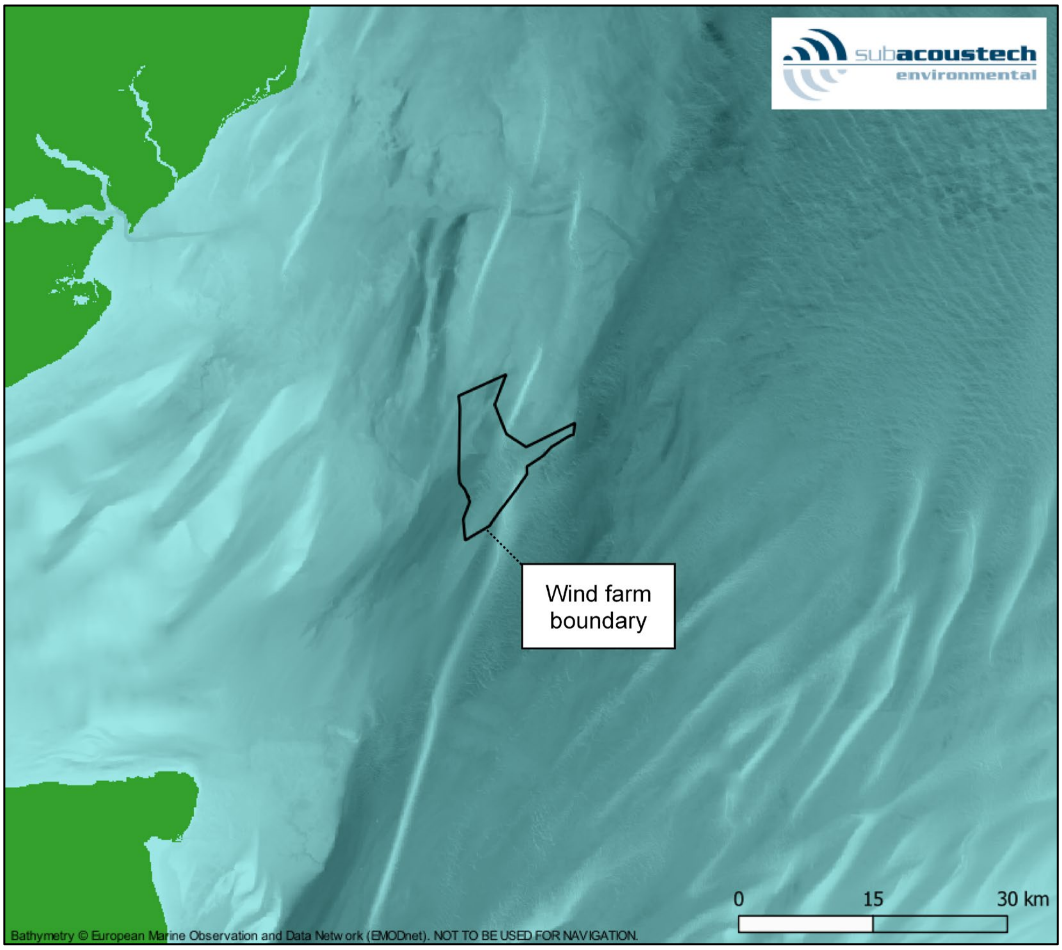


Figure 1-1 Overview map showing the North Falls boundary and the surrounding bathymetry

This report presents a detailed assessment of the potential underwater noise during the construction and operation of North Falls, 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 noise modelling undertaken (Section 3);

- Presentation and interpretation of the detailed subsea noise modelling for impact piling with regards to its effects on marine mammals and fish (Section 4);
- Noise modelling of the other noise sources expected around the construction and operation of North Falls including cable laying, rock placement, dredging, trenching, vessel activity, operational WTG noise, and Unexploded Ordnance (UXO) clearance (Section 5); and
- Summary and conclusions (Section 6).

Further modelling results are presented in Appendix A of this report.

2 Background to underwater noise metrics

2.1 Underwater noise

Sound travels much faster in water (approximately 1,500 ms^{-1}) than in air (340 ms^{-1}). 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 should not be confused with noise levels in air, which use a different scale.

2.1.1 Units of measurement

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

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

The fundamental definition of the dB scale is given by:

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

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

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

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.

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

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

2.1.2 Sound Pressure Level (SPL)

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

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

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

2.1.3 Peak Sound Pressure Level (SPL_{peak})

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

A further variation of this is the peak-to-peak SPL ($SPL_{peak\text{-}to\text{-}peak}$) where the maximum variation of the pressure from positive to negative is considered. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak pressure will be twice the peak level, or 6 dB higher (see section 2.1.1).

2.1.4 Sound Exposure Level (SEL)

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

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

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

where p is the acoustic pressure in Pascals, T is the total duration of the sound in seconds, and t is the 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 level (${p^2}_{ref}$) and a reference time (T_{ref}). The SEL is then defined by:

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

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

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

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

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

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

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

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

2.2 Analysis of environmental effects

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

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

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

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

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

- Southall *et al*. (2019) marine mammal exposure criteria; and
- Popper *et al*. (2014) sound exposure guidelines for fishes and sea turtles.

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

2.2.1 Marine mammals

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

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

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 seal)

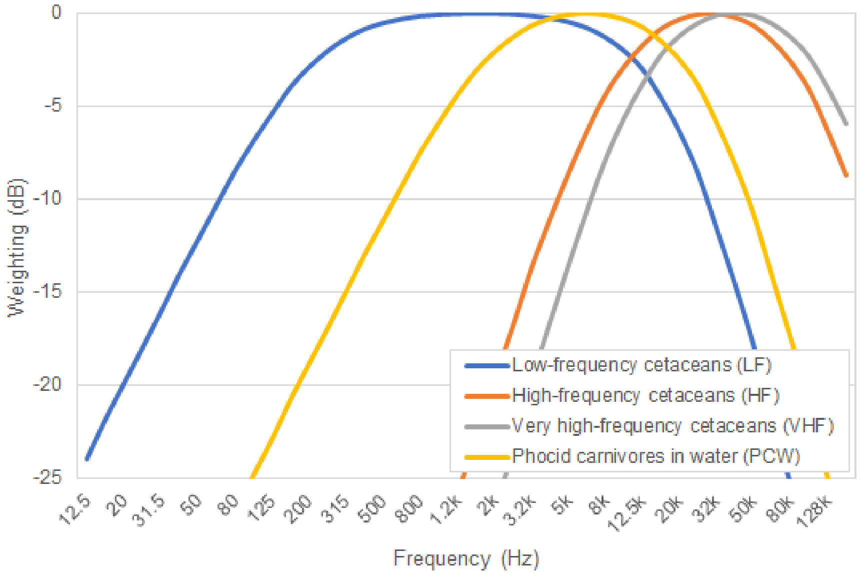


Figure 2-1 Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al., 2019)

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

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

As sound pulses propagate through the environment and dissipate, they also lose their most injurious characteristics (e.g., rapid pulse rise time and high peak sound pressure) and become more like a “non-pulse” at greater distances; Southall *et al*. (2019) briefly discusses this. Active research is currently underway into the identification of the distance at which the pulse can be considered effectively non-impulsive, and Hastie *et al*. (2019) have analysed a series of impulsive data to investigate it. Although the situation is complex, the paper reported that most of the signals crossed their threshold for rapid rise time and high peak sound pressure characteristics associated with impulsive noise at around

3.5 km from the source. Southall *et al.* (2021) discusses this further and suggests that the impulsive characteristics can correspond with significant energy content of the pulse above 10 kHz. This will naturally change depending on the noise source and the environment over which it travels.

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

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

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

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

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

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

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

It is worth noting that, comparing Southall *et al.* (2019) to NMFS (2018), the guidance applies different names to otherwise identical marine mammal groups and weightings, which are otherwise numerically identical. For example, what Southall *et al*. (2019) calls high-frequency cetaceans (HF), NMFS (2018) calls mid-frequency cetaceans (MF), and what Southall *et al*. (2019) calls very high-frequency cetaceans (VHF), NMFS (2018) refers to as high-frequency cetaceans (HF). As such, care should be taken when comparing results using the Southall *et al*. (2019) and NMFS (2018) criteria, especially as the HF groupings and criteria cover different species depending on which study is being used.

2.2.2 Fish

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

The Popper *et al*. (2014) study groups species of fish by whether they possess a swim bladder, and whether it is involved in its hearing; a group for fish eggs and larvae is also included. The guidance also gives specific criteria (as both unweighted SPL_{peak} and unweighted SEL_{cum} values) for a variety of noise sources.

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

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

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

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

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

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

Type of animal	Mortality and potential mortal injury
Fish: no swim bladder	229 – 234 dB peak
Fish: swim bladder is not involved in hearing	229 – 234 dB peak
Fish: swim bladder involved in hearing	229 – 234 dB peak
Sea turtles	229 – 234 dB peak
Eggs and larvae	> 13 mms^{-1} peak velocity

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

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

Type of animal	Impairment			Behaviour
	Recoverable injury	TTS	Masking	
Fish: no swim bladder	See Table 2-4	See Table 2-4	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing	See Table 2-4	See Table 2-4	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder involved in hearing	See Table 2-4	See Table 2-4	(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate
Sea turtles	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) High (I) Moderate (F) Low
Eggs and larvae	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low

Table 2-8 Summary of the qualitative effects on fish from continuous noise from Popper et al. (2014) (N = Near-field; I = Intermediate-field; F = Far-field)

Type of animal	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder involved in hearing	(N) Low (I) Low (F) Low	See Table 2-5	See Table 2-5	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
Sea turtles	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) High (I) Moderate (F) Low
Eggs and larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) Moderate (I) Moderate (F) Low

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

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

Both fleeing animal and stationary animal models have been used to cover the SEL_{cum} criteria for fish. It is recognised that there is limited evidence for fish fleeing from high level noise sources in the wild, and it would reasonably be expected that the reaction would differ between species. Most species are likely to move away from a sound that is loud enough to cause harm (Dahl *et al.*, 2015; Popper *et al.*, 2014), some may seek protection in the sediment and others may dive deeper in the water column. For those species that flee, the speed chosen for this study of 1.5 ms^{-1} is relatively slow in relation to data from Hirata (1999) and thus is considered somewhat conservative.

Although it is feasible that some species will not flee, those that are likely to remain are thought more likely to be benthic species or species without a swim bladder; these are the least sensitive species. For example, from Popper *et al*. (2014): “There is evidence (e.g., Goertner *et al*., 1994; Stephenson *et al*., 2010; Halvorsen *et al*., 2012) that little or no damage occurs to fish without a swim bladder except at very short ranges from an in-water explosive event. Goertner (1978) showed that the range from an explosive event over which damage may occur to a non-swim bladder fish is in the order of 100 times less than that for swim bladder fish.”

Stationary animal modelling has been included in this study, based on research from Hawkins *et al*. (2014) and other modelling for similar EIA projects. However, basing the modelling on a stationary (zero flee speed) receptor is likely to greatly overestimate the potential risk to fish species, assuming that an individual would remain in the high noise level region of the water column, especially when considering the precautionary nature of the parameters already built into the cumulative exposure calculations.

2.2.2.1 Particle Motion

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

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

The primary reason for the continuing use of sound pressure as the criteria, despite particle motion appearing to be the physical measure to which the fish react or sense, is a lack of data (Popper and Hawkins, 2018) both in respect of predictions of the particle motion level as a consequence of a noise source such as piling, and a lack of knowledge of the sensitivity of a fish, or a wider category of fish, to a particle motion value. There continue to be calls for additional research on the levels of and effects with respect to levels of particle motion. Until sufficient data are available to enable revised thresholds based on the particle motion metric, Popper *et al.* (2014) continues to be the best source of criteria in respect to fish impacts (Andersson *et al.,* 2016, Popper and Hawkins*,* 2019).

3 Modelling methodology

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

Of those considered, the noise source most important to consider is impact piling due to the noise level and duration it will be present (Bailey *et al*., 2014). As such, the noise related to impact piling activities is the primary focus of this study.

The modelling of impact piling has been undertaken using the INSPIRE underwater noise model. The INSPIRE model (currently version 5.1) is a semi-empirical underwater noise propagation model based around a combination of numerical modelling, based around a combined geometric and energy flow/hysteresis loss method, and actual measured data. It is designed to calculate the propagation of noise in shallow, mixed water, typical of the conditions around the UK and very well suited to the region around North Falls. 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 SPL_{peak}, SEL_{ss}, and SEL_{cum} noise levels, as well as various other weighted noise metrics. Calculations are made along 180 equally spaced radial transects (one every two degrees). For each modelling run a criterion level can be specified allowing a contour to be drawn, within which a given effect may occur. These results can then be plotted over digital bathymetry data so that impact ranges can be clearly visualised, as necessary. INSPIRE also produces these contours as GIS shapefiles.

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

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

A simple modelling approach has been used for noise sources other than piling that may be present during construction and operation of North Falls, and these are discussed in Section 5.

3.1 Modelling confidence

INSPIRE is semi-empirical and thus a validation process is inherently built into the development process. Whenever a new set of good, reliable, impact piling measurement data is gathered through offshore surveys it is compared against the outputted levels from INSPIRE and, if necessary, the model can be adjusted accordingly. Currently over 80 separate impact piling noise datasets from all around the UK have been used as part of the development for the latest version of INSPIRE, and in each case, an average fit is used.

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

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

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

Figure 3-1 presents a small selection of measured impact piling noise data plotted against outputs from INSPIRE. The plots show data points from measured data (in blue) plotted alongside modelled data (in orange) using INSPIRE version 5.1, matching the pile size, blow energy and range from the measured data. These show the fit to the data, with the INSPIRE model data points sitting, more or less, in the middle of the measured noise levels at each range. When combined with the worst-case assumptions in parameter selection, modelled results will remain precautionary.

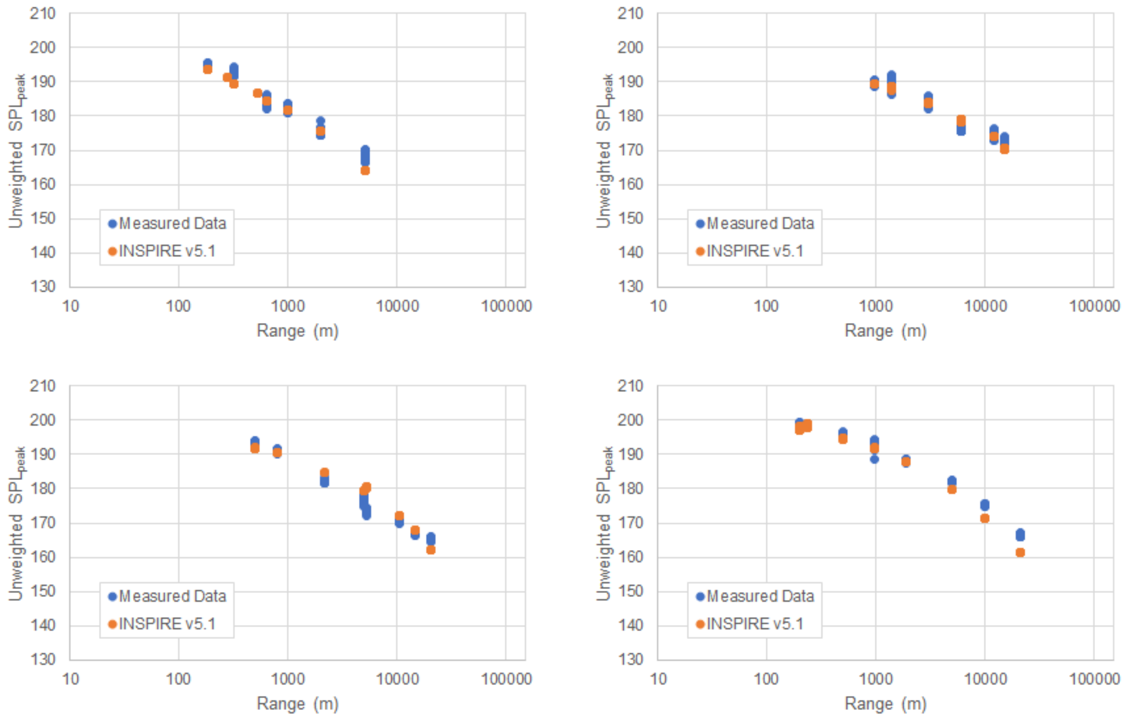


Figure 3-1 Comparison between example measured impact piling data (blue points) and modelled data using INSPIRE version 5.1 (orange points)

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

3.2 Modelling parameters

3.2.1 Modelling locations

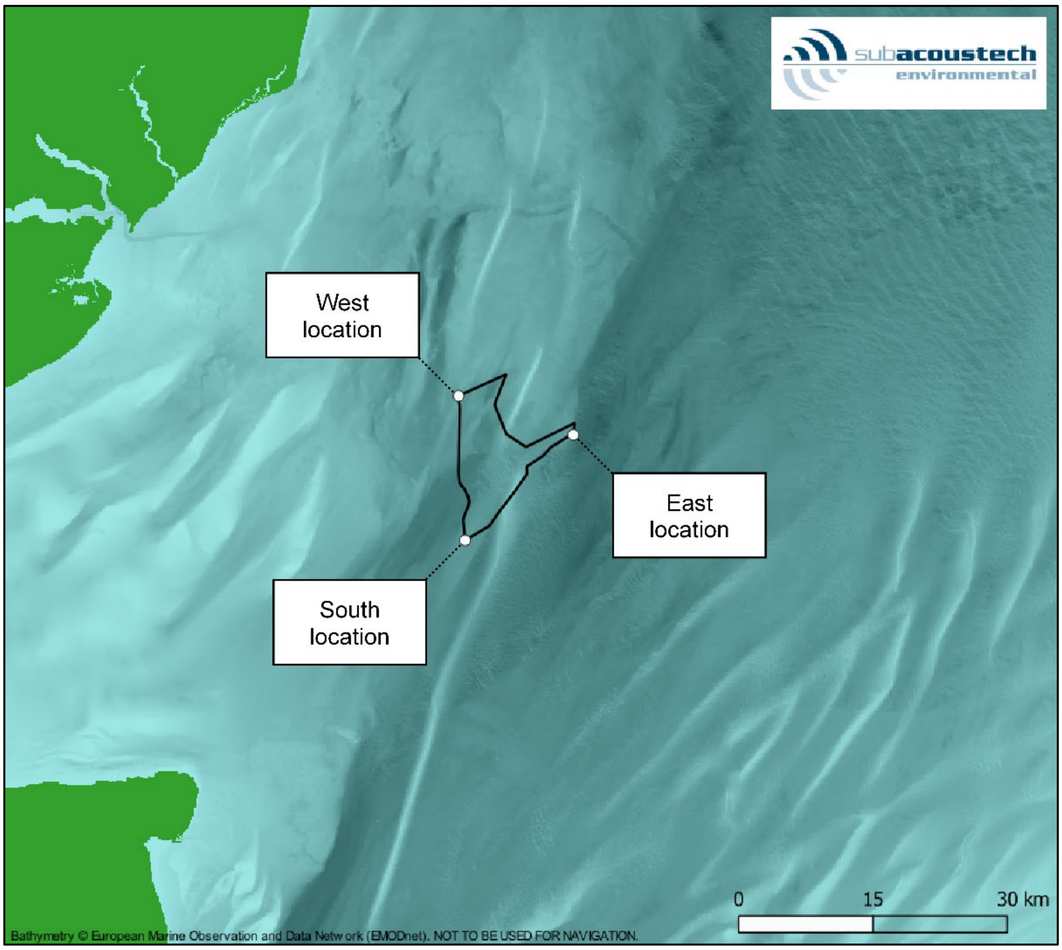
Modelling for WTG foundation impact piling has been undertaken at three representative locations covering the extents and various water depths at the North Falls site.

- East – situated on the eastern edge of North Falls showing noise propagation to the east into the wider North Sea;
- South – situated on the southernmost point of North Falls; and
- West – situated at the northwest corner of North Falls close to the shallower sand banks of the Thames Estuary.

These locations are summarised in Table 3-1 and illustrated in Figure 3-2.

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

Modelling locations	East	South	West
Latitude	51.7368° N	51.6293°N	51.7742°N
Longitude	002.0443° E	001.8721°E	001.8578°E
Water depth	34.7 m	34.0 m	31.2 m



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

Figure 3-2 Approximate positions of the modelling locations at North Falls

3.2.2 *WTG foundation and impact piling parameters*

Two foundation scenarios have been considered for this study; these are:

- A monopile worst case scenario, installing a 17 m diameter pile with a maximum blow energy of 6,000 kJ; and
- A pin pile worst case scenario, installing a 6 m diameter pile with a maximum blow energy of 4,400 kJ.

For SEL_{cum} 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 in Table 3-2 and Table 3-3 for the two piling scenarios.

In a 24-hour period it is expected that up to three monopile foundations or six pin pile foundations can be installed. Scenarios covering a single pile installation, multiple sequential pile installation and simultaneous multiple location installation have been considered for this study.

Table 3-2 Summary of the soft start and ramp-up scenario used for the monopile worst case modelling

Monopile worst case	**900 kJ**	**1,800 kJ**	**2,700 kJ**	**3,700 kJ**	**4,800 kJ**	**6,000 kJ**
Number of Strikes	100	600	600	600	600	10,880
Duration	10 mins	30 mins	30 mins	30 mins	30 mins	320 mins
Strike rate	10 blows/min	20 blows/min				34 blows/min
13,380 strikes, 7.5 hours per pile / 40,140 strikes, 22.5 hours for 3 piles						

Table 3-3 Summary of the soft start and ramp-up scenario used for the pin pile worst case modelling

Pin pile worst case	**660 kJ**	**1,320 kJ**	**1,980 kJ**	**2,640 kJ**	**3,520 kJ**	**4,400 kJ**
Number of Strikes	100	400	400	400	400	6,120
Duration	10 mins	20 mins	20 mins	20 mins	20 mins	180 mins
Strike rate	10 blows/min	20 blows/min				34 blows/min
7,820 strikes, 4.5 hours per pile / 46,920 strikes, 27 hours for 6 piles						

There is also the potential for multiple piling rigs to be operating concurrently. Scenarios have been chosen that lead to the greatest (i.e., worst case) impact ranges, generally where the rigs are operating at the greatest separation between piling locations. This has been done for both the monopile and pin pile foundation types, considering concurrent piling at the East and South modelling locations.

3.2.3 *Apparent source levels*

Noise modelling requires knowledge of the source level, which is the theoretical noise level at one metre from the noise source. The INSPIRE model assumes that the noise source – the hammer striking the pile – acts as an effective single point, as it will appear at distance. 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) and piling situations (Ainslie, 2020). In practice, for underwater noise modelling such as this, it is effectively an ‘apparent source level’ or ‘point source equivalent’ (Wood *et al.*, 2023) value that is used, essentially a value that can be used to produce accurate noise levels at range (for a specific model), as required in impact assessments.

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

The unweighted, single strike SPL_{peak} and SEL_{ss} apparent source levels estimated for this study are provided in Table 3-4. These figures are presented in accordance with typical requires by regulatory authorities, although as indicated above they are not necessarily compatible or comparable with any other model or predicted source level. In each case, the differences in apparent source level for each location within a scenario are minimal.

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

Apparent source levels	**Location**	**Monopile worst case** 17.0 m / 6,000 kJ	**Pin pile worst-case** 6.0 m / 4,400 kJ
Unweighted SPL_{peak}	East	243.0 dB re 1 µPa @ 1 m	242.5 dB re 1 µPa @ 1 m
	South	243.0 dB re 1 µPa @ 1 m	242.5 dB re 1 µPa @ 1 m
	West	243.0 dB re 1 µPa @ 1 m	242.5 dB re 1 µPa @ 1 m
Unweighted SEL_{ss}	East	224.2 dB re 1 µPa^{2}s @ 1 m	223.6 dB re 1 µPa^{2}s @ 1 m
	South	224.2 dB re 1 µPa^{2}s @ 1 m	223.6 dB re 1 µPa^{2}s @ 1 m
	West	224.2 dB re 1 µPa^{2}s @ 1 m	223.6 dB re 1 µPa^{2}s @ 1 m

3.2.4 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 surrounding the site. Data from the British Geological Survey show that the seabed in and around North Falls is generally made up of various combinations of sandy gravel.

Digital bathymetry, from the European Marine Observation and Data Network (EMODnet), has been used for this modelling. A tidal depth of 2 m above LAT, the approximate mean tide at Sunk Head, has been used throughout.

3.3 Cumulative SELs and fleeing receptors

Expanding on the information in Section 2.2 regarding SEL_{cum} and the fleeing animal model used for modelling, it is important to understand the meaning of the results presented in the following sections.

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

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

When considering a stationary receptor (i.e., one that stays at the same position throughout piling), calculating the SEL_{cum} is fairly straightforward: all the noise levels produced and received at a single point along a transect are aggregated to calculate the SEL_{cum}. If this calculated level is greater than the threshold being modelled, the model steps away from the noise source and the noise levels from that new location are aggregated to calculate a new SEL_{cum}. This continues outward until the threshold is met.

For a fleeing animal, the receptor's distance from the noise source while moving away also needs to be considered. To model this, a starting point close to the source is chosen and the received noise level for each noise event (e.g., pile strike) while the receptor is fleeing is noted. For example, if a noise pulse occurs every six seconds and an animal is fleeing at a rate of 1.5 ms^{-1}, it is 9 m further from the source after each noise pulse, resulting in a slightly reduced noise level each time. These values are the aggregated into an SEL$_{cum}$ over the entire operation. The faster an animal is fleeing the greater distance travelled between noise events. The impact range outputted by the model for this situation is the distance the receptor must be at the start of the operation to exactly meet the exposure threshold.

The graphs in Figure 3-3 and Figure 3-4 show the difference in the received SELs by a stationary receptor and a fleeing receptor travelling at a constant speed of 1.5 ms^{-1}, using the monopile worst case scenario at the East location for a single pile installation, as an example.

The received SEL$_{ss}$ from the stationary receptor, as illustrated in Figure 3-3, shows the noise level gradually increasing as the blow energy increases throughout the piling operation. These step changes are also visible for the fleeing receptor, but as the receptor is further from the source by the time the levels increase, the total received exposure reduces, resulting in progressively lower received noise levels. As an example, for the first 10 minutes of the piling scenario where the blow energy is 900 kJ, at a rate of 1.5 ms^{-1} the fleeing will have moved the receptor 900 m away. After the full piling duration of 7.5 hours, the receptor will be over 40 km from the pile.

Figure 3-4 shows the effect these different received levels have when calculating the SEL$_{cum}$. It clearly shows the difference in cumulative effect of the receptor remaining still, as opposed to fleeing. To use an extreme example, starting at a range of 1 m, the first strike results in a received level of 218.7 dB re 1 μPa based on the apparent source level used. If the receptor were to remain stationary throughout the 7.5 hours of piling it would receive a cumulative level of 265.2 dB re 1 μPa, whereas fleeing at 1.5 ms^{-1} over the same piling scenario would result in a cumulative received level of just 219.5 dB re 1 μPa for the receptor.

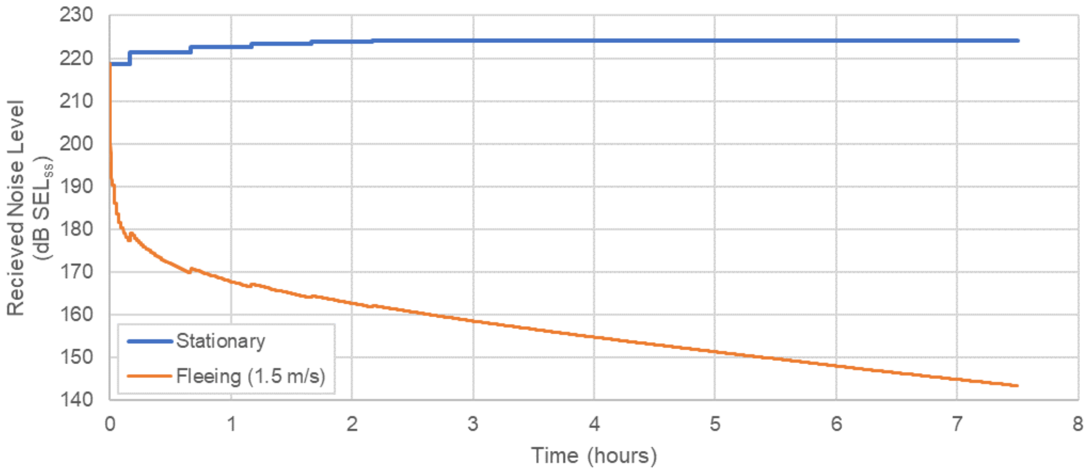


Figure 3-3 Received single-strike noise levels (SEL$_{ss}$) for receptors during the worst case monopile foundation parameters at the East location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source

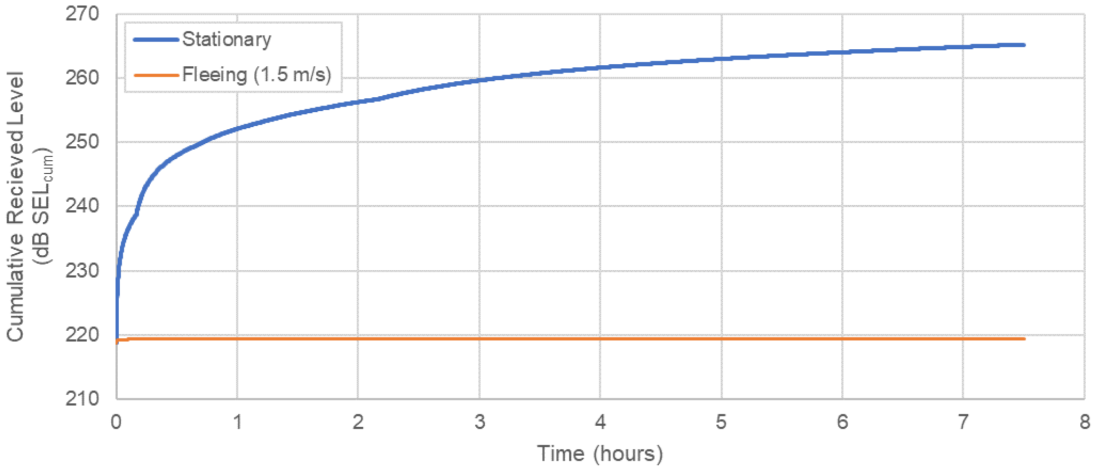


Figure 3-4 Cumulative received noise levels (SEL$_{cum}$) for receptors during worst case monopile foundation parameters at the East location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source

To summarise, if the receptor were to start fleeing in a straight line from the noise source starting at a range closer than the modelled value it would receive a noise exposure in excess of the criteria, and if the receptor were to start fleeing from a range further than the modelled value it would receive a noise exposure below the criteria. This is illustrated in Figure 3-5.

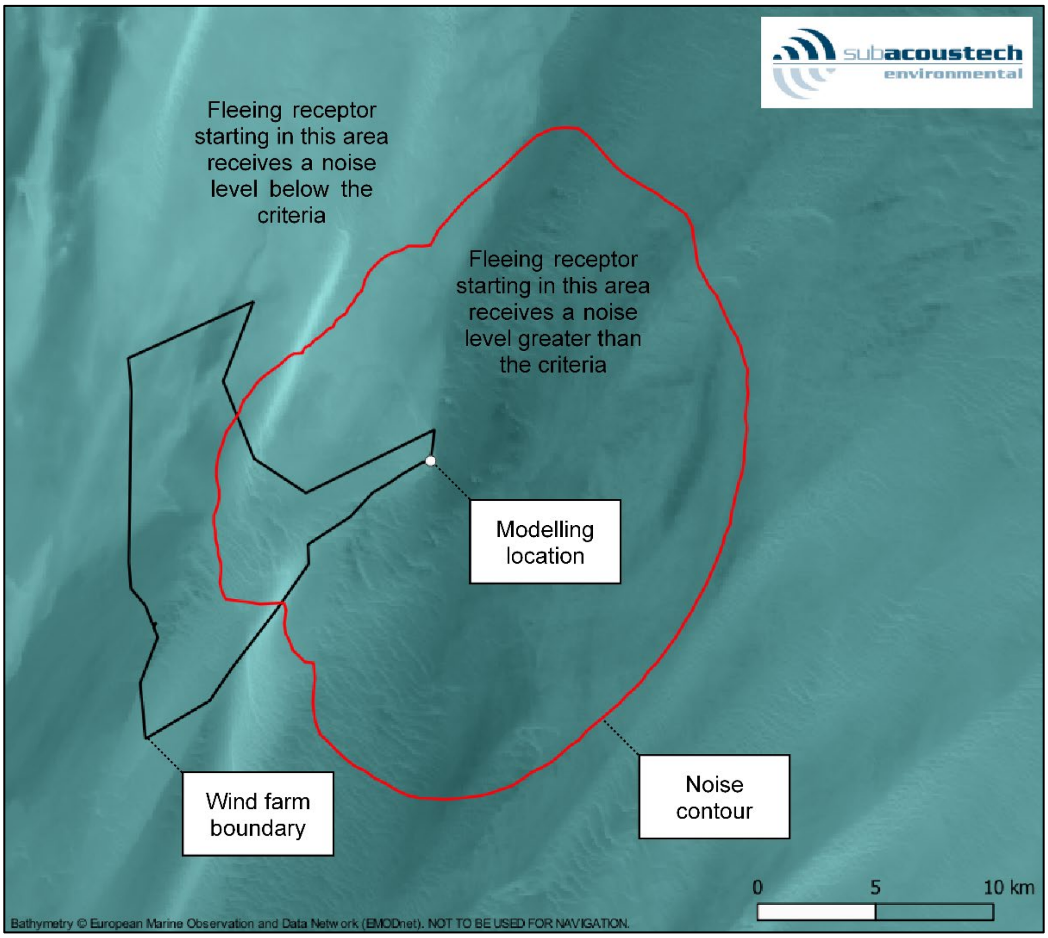


Figure 3-5 Plot showing a fleeing animal SEL$_{cum}$ criteria contour and the areas where the cumulative noise exposure will exceed the impact criteria

Some modelling approaches include the effects of Acoustic Deterrent Devices (ADDs) that cause receptors to flee from the immediate area around the pile before activity commences. Subacoustech Environmental's modelling approach does not include this, as 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 ms^{-1}, it would travel 1.8 km before piling begins. If a cumulative SEL impact range from INSPIRE was calculated to be below 1.8 km, it can safely be assumed that the ADD will be effective in eliminating the risk of injury on the receptor. The noise from an ADD is of a much lower level than impact piling, and as such, the overall effect on the SEL_{cum} exposure on a receptor would be negligible.

3.3.1 The effects of input parameters on cumulative SELs and fleeing receptors

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

Parameters like hammer blow energy can have a clear effect on impact ranges, with higher energies resulting in higher source noise levels and therefore larger impact ranges. When considering cumulative noise levels, these higher levels are compounded sometimes thousands of times due to the number of pile strikes. With this in mind, the ramp up from low blow energies to higher ones requires careful consideration for fleeing animals, as the levels while the receptors are relatively close to the noise source will have a greater effect on the overall cumulative exposure level.

Figure 3-6 summarises the hammer blow energy ramp up for the two modelled scenarios, showing how the pin pile scenario reaches its maximum energy over a shorter period of time and that the monopile scenario reaches higher energies for a longer period. Also shown in the plots are the effect of the multiple consecutive piling operations; for a precautionary modelling prediction, it is assumed that subsequent piles follow on directly from the previous installation with no pause.

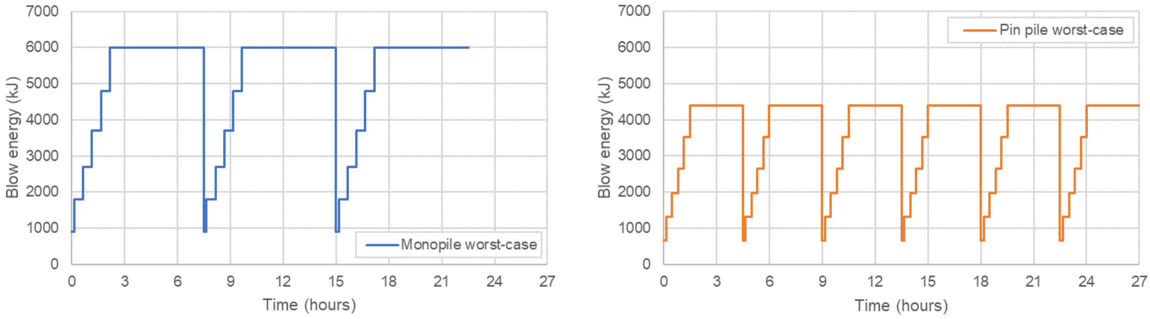


Figure 3-6 Graphical representation of the blow energy for the modelled ramp up scenarios

Linked to the effect of the ramp up is the strike rate, as the more 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 SEL_{cum}. The faster the strike rate, the shorter the distance the receptor can flee between each pile strike, which leads to greater exposure. Figure 3-7 summarises the strike rates for the two modelling scenarios showing how the pin pile scenario reaches a faster strike rate sooner than the monopile scenario.

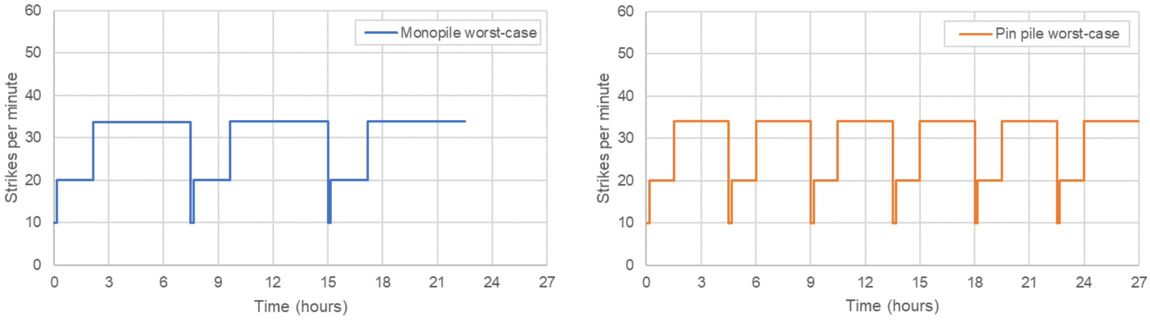


Figure 3-7 Graphical representation of the strike rate for the modelled ramp up scenarios

4 Modelling results

This section presents the modelled impact ranges for impact piling noise following the parameters detailed in Section 3.2, covering the Southall *et al*. (2019) marine mammal criteria (Section 2.2.1) and the Popper *et al*. (2014) fish criteria (Section 2.2.2). To aid navigation, Table 4-1 contains a list of the impact range tables in this section. The concurrent location modelling results are presented in section 4.3.

For the results presented throughout this section any predicted ranges smaller than 50 m and areas less than 0.01 km^2 for single strike criteria and ranges smaller than 100 m and areas less than 0.1 km^2 for cumulative criteria, have not been presented. At ranges this close to the noise source, the modelling processes are unable to model to a sufficient level of accuracy due to complex acoustic effects present near the pile. These ranges are given as “less than” this limit.

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

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

Table (page)	Parameters		Criteria	
Table 4-3 (p22)	East	Monopile worst case	Southall *et al*. (2019) -- Marine mammals	Unweighted SPL$_{\text{peak}}$
Table 4-4 (p23)				Weighted SEL$_{\text{cum}}$ (Impulsive)
Table 4-5 (p23)		Pin pile worst case		Unweighted SPL$_{\text{peak}}$
Table 4-6 (p23)				Weighted SEL$_{\text{cum}}$ (Impulsive)
Table 4-7 (p24)	South	Monopile worst case		Unweighted SPL$_{\text{peak}}$
Table 4-8 (p24)				Weighted SEL$_{\text{cum}}$ (Impulsive)
Table 4-9 (p24)		Pin pile worst case		Unweighted SPL$_{\text{peak}}$
Table 4-10 (p25)				Weighted SEL$_{\text{cum}}$ (Impulsive)
Table 4-11 (p25)	West	Monopile worst case		Unweighted SPL$_{\text{peak}}$
Table 4-12 (p25)				Weighted SEL$_{\text{cum}}$ (Impulsive)
Table 4-13 (p26)		Pin pile worst case		Unweighted SPL$_{\text{peak}}$
Table 4-14 (p26)				Weighted SEL$_{\text{cum}}$ (Impulsive)
Table 4-15 (p27)	East	Monopile worst case	Popper *et al*. (2014) -- Fish	Unweighted SPL$_{\text{peak}}$
Table 4-16 (p27)				Unweighted SEL$_{\text{cum}}$ (Pile driving)
Table 4-17 (p27)		Pin pile worst case		Unweighted SPL$_{\text{peak}}$
Table 4-18 (p28)				Unweighted SEL$_{\text{cum}}$ (Pile driving)
Table 4-19 (p28)	South	Monopile worst case		Unweighted SPL$_{\text{peak}}$
Table 4-20 (p28)				Unweighted SEL$_{\text{cum}}$ (Pile driving)
Table 4-21 (p29)		Pin pile worst case		Unweighted SPL$_{\text{peak}}$
Table 4-22 (p29)				Unweighted SEL$_{\text{cum}}$ (Pile driving)
Table 4-23 (p29)	West	Monopile worst case		Unweighted SPL$_{\text{peak}}$
Table 4-24 (p30)				Unweighted SEL$_{\text{cum}}$ (Pile driving)
Table 4-25 (p30)		Pin pile worst case		Unweighted SPL$_{\text{peak}}$
Table 4-26 (p30)				Unweighted SEL$_{\text{cum}}$ (Pile driving)

4.1 Predicted noise level at 750 m from the noise source

In addition to the apparent source levels given in section 3.2.3, it is useful to look at the potential noise levels at a range of 750 m from the noise source, which is a common consideration for underwater noise studies at offshore wind farms, and has the added advantage of being comparable with other modelling or measurements. A summary of the modelled unweighted levels at a range of 750 m are given in Table 4-2 considering the transect with the greatest noise transmission at each location while piling at the maximum hammer blow energy.

Table 4-2 Summary of the maximum predicted unweighted SPL$_{peak}$ and SEL$_{ss}$ noise levels at a range of 750 m from the noise source when considering the maximum blow energy

Predicted level at 750 m range	**Location**	**Monopile worst case** 17.0 m / 6,000 kJ	**Pin pile worst-case** 6.0 m / 4,400 kJ
Unweighted SPL$_{peak}$	East	202.4 dB re 1 μPa	201.9 dB re 1 μPa
	South	202.1 dB re 1 μPa	201.6 dB re 1 μPa
	West	202.0 dB re 1 μPa	201.5 dB re 1 μPa
Unweighted SEL$_{ss}$	East	184.2 dB re 1 μPa^{2}s	183.6 dB re 1 μPa^{2}s
	South	184.0 dB re 1 μPa^{2}s	183.3 dB re 1 μPa^{2}s
	West	183.8 dB re 1 μPa^{2}s	183.1 dB re 1 μPa^{2}s

4.2 Single location modelling

This section presents the modelling results for piling taking place at a single location, either a single pile installation or sequential pile installations. For this modelling, single strike results are relevant to both single pile and sequential pile scenarios as these use the same maximum blow energies. Single strike modelling has been undertaken for the maximum blow energy and the first pile strike in each scenario.

4.2.1 Marine mammal criteria

Table 4-3 to Table 4-14 present the modelling results in terms of the Southall *et al*. (2019) marine mammal criteria, covering the parameters as described in Section 3.2.

The largest marine mammal impact ranges are predicted for the worst case monopile and pin pile scenarios at the East modelling location. Maximum PTS injury ranges are predicted for LF cetaceans, with ranges of up to 7.0 km; VHF cetaceans show maximum PTS ranges of up to 3.3 km.

When comparing the impact ranges for a single pile installation and sequential pile installations, the overall increases for the sequential scenarios results are minimal, as by the time the subsequent piles are installed the fleeing receptor is at such a distance that the additional exposure is small. The largest increases seen in impact ranges for these scenarios are only a few hundred metres.

Additional Southall *et al*. (2019) criteria covering the non-impulsive impacts are presented in Appendix A.

4.2.1.1 East location

Table 4-3 Summary of the unweighted SPL$_{peak}$ impact ranges using the Southall et al. (2019) impulsive criteria for the monopile worst case modelling scenario at the East location

Southall *et al.* (2019) Unweighted SPL$_{peak}$		**Full energy (6,000 kJ)**				**First strike (900 kJ)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (219 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.4 km^2	680 m	660 m	670 m	0.29 km^2	310 m	310 m	310 m
	PCW (218 dB)	0.01 km^2	60 m	60 m	60 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.05 km^2	120 m	120 m	120 m	0.01 km^2	60 m	50 m	60 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	8.2 km^2	1.7 km	1.6 km	1.6 km	1.9 km^2	790 m	760 m	770 m
	PCW (212 dB)	0.06 km^2	140 m	140 m	140 m	0.01 km^2	70 m	60 m	60 m

Table 4-4 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2014) impulsive criteria for the monopile worst case modelling scenario at the East location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Single monopile installation**				**Sequential monopile installation (3 monopiles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (183 dB)	94 km^2	7.0 km	3.3 km	5.3 km	94 km^2	7.0 km	3.3 km	5.3 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	22 km^2	3.3 km	1.7 km	2.6 km	22 km^2	3.3 km	1.7 km	2.6 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	1,600 km^2	30 km	15 km	22 km	1,600 km^2	30 km	15 km	22 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	1,000 km^2	24 km	12 km	18 km	1,000 km^2	24 km	12 km	18 km
	PCW (170 dB)	160 km^2	9.0 km	4.5 km	7.0 km	160 km^2	9.0 km	4.5 km	7.0 km

Table 4-5 Summary of the unweighted SPL_{peak} impact ranges using the Southall et al. (2019) impulsive criteria for the pin pile worst case modelling scenario at the East location

Southall *et al.* (2019) Unweighted SPL_{peak}		**Full energy (4,400 kJ)**				**First strike (660 kJ)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (219 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.2 km^2	630 m	610 m	620 m	0.17 km^2	240 m	240 m	240 m
	PCW (218 dB)	0.01 km^2	50 m	50 m	50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.04 km^2	110 m	110 m	110 m	0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	7.1 km^2	1.6 km	1.5 km	1.5 km	1.1 km^2	610 m	590 m	600 m
	PCW (212 dB)	0.05 km^2	130 m	130 m	130 m	0.01 km^2	50 m	< 50 m	50 m

Table 4-6 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2014) impulsive criteria for the pin pile worst case modelling scenario at the East location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Single pin pile installation**				**Sequential pin pile installation (6 pin piles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (183 dB)	85 km^2	6.9 km	2.8 km	5.0 km	85 km^2	6.9 km	2.8 km	5.0 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	22 km^2	3.3 km	1.6 km	2.6 km	23 km^2	3.4 km	1.6 km	2.6 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	1,500 km^2	31 km	14 km	22 km	1,500 km^2	31 km	14 km	22 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	1,100 km^2	24 km	12 km	18 km	1,100 km^2	24 km	12 km	18 km
	PCW (170 dB)	180 km^2	9.3 km	4.6 km	7.3 km	180 km^2	9.5 km	4.6 km	7.4 km

4.2.1.2 South location

Table 4-7 Summary of the unweighted SPL_{peak} impact ranges using the Southall et al. (2019) impulsive criteria for the monopile worst case modelling scenario at the South location

Southall *et al.* (2019) Unweighted SPL_{peak}		**Full energy (6,000 kJ)**				**First strike (900 kJ)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (219 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.4 km^2	660 m	660 m	660 m	0.29 km^2	310 m	300 m	300 m
	PCW (218 dB)	0.01 km^2	60 m	60 m	60 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.05 km^2	120 m	120 m	120 m	0.01 km^2	60 m	50 m	60 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	1.8 km^2	760 m	750 m	760 m	1.8 km^2	760 m	750 m	760 m
	PCW (212 dB)	0.01 km^2	60 m	60 m	60 m	0.01 km^2	60 m	60 m	60 m

Table 4-8 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2014) impulsive criteria for the monopile worst case modelling scenario at the South location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Single monopile installation**				**Sequential monopile installation (3 monopiles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (183 dB)	68 km^2	5.1 km	3.7 km	4.7 km	68 km^2	5.1 km	3.7 km	4.7 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	16 km^2	2.5 km	1.9 km	2.3 km	16 km^2	2.5 km	1.9 km	2.3 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	1,300 km^2	24 km	13 km	20 km	1,300 km^2	24 km	13 km	20 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	840 km^2	19 km	12 km	16 km	840 km^2	19 km	12 km	16 km
	PCW (170 dB)	120 km^2	6.9 km	4.9 km	6.2 km	120 km^2	6.9 km	4.9 km	6.2 km

Table 4-9 Summary of the unweighted SPL_{peak} impact ranges using the Southall et al. (2019) impulsive criteria for the pin pile worst case modelling scenario at the South location

Southall *et al.* (2019) Unweighted SPL_{peak}		**Full energy (4,400 kJ)**				**First strike (660 kJ)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (219 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.2 km^2	610 m	610 m	610 m	0.17 km^2	240 m	230 m	240 m
	PCW (218 dB)	0.01 km^2	50 m	50 m	50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.04 km^2	110 m	110 m	110 m	0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	6.7 km^2	1.5 km	1.4 km	1.5 km	1.1 km^2	590 m	590 m	590 m
	PCW (212 dB)	0.05 km^2	130 m	130 m	130 m	0.01 km^2	50 m	< 50 m	50 m

Table 4-10 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2014) impulsive criteria for the pin pile worst case modelling scenario at the South location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Single pin pile installation**				**Sequential pin pile installation (6 pin piles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (183 dB)	57 km²	4.7 km	3.3 km	4.3 km	57 km²	4.7 km	3.3 km	4.3 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	16 km²	2.6 km	1.8 km	2.3 km	17 km²	2.6 km	1.8 km	2.3 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	1,200 km²	24 km	13 km	20 km	1,200 km²	24 km	13 km	20 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	880 km²	19 km	11 km	17 km	880 km²	20 km	11 km	17 km
	PCW (170 dB)	140 km²	7.3 km	5.2 km	6.6 km	140 km²	7.4 km	5.2 km	6.6 km

4.2.1.3 West location

Table 4-11 Summary of the unweighted SPL_{peak} impact ranges using the Southall et al. (2019) impulsive criteria for the monopile worst case modelling scenario at the West location

Southall *et al.* (2019) Unweighted SPL_{peak}		**Full energy (6,000 kJ)**				**First strike (900 kJ)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (219 dB)	0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.3 km²	640 m	630 m	640 m	0.27 km²	300 m	290 m	300 m
	PCW (218 dB)	0.01 km²	60 m	50 m	60 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.04 km²	120 m	120 m	120 m	0.01 km²	50 m	50 m	50 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	7.1 km²	1.5 km	1.5 km	1.5 km	1.7 km²	740 m	720 m	730 m
	PCW (212 dB)	0.06 km²	140 m	140 m	140 m	0.01 km²	60 m	60 m	60 m

Table 4-12 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2014) impulsive criteria for the monopile worst case modelling scenario at the West location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Single monopile installation**				**Sequential monopile installation (3 monopiles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (183 dB)	43 km²	4.5 km	2.7 km	3.7 km	43 km²	4.5 km	2.7 km	3.7 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	11 km²	2.2 km	1.5 km	1.9 km	11 km²	2.2 km	1.5 km	1.9 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	1,000 km²	4.5 km	2.7 km	3.7 km	1,000 km²	4.5 km	2.7 km	3.7 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	670 km²	19 km	10 km	14 km	670 km²	19 km	10 km	14 km
	PCW (170 dB)	82 km²	6.3 km	3.8 km	5.1 km	82 km²	6.3 km	3.8 km	5.1 km

Table 4-13 Summary of the unweighted SPL_{peak} impact ranges using the Southall et al. (2019) impulsive criteria for the pin pile worst case modelling scenario at the West location

Southall *et al.* (2019) Unweighted SPL_{peak}		**Full energy (4,400 kJ)**				**First strike (660 kJ)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (219 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.1 km^2	600 m	590 m	590 m	0.16 km^2	230 m	230 m	230 m
	PCW (218 dB)	0.01 km^2	50 m	50 m	50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.04 km^2	110 m	110 m	110 m	0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	6.2 km^2	1.4 km	1.4 km	1.4 km	1.0 km^2	570 m	570 m	570 m
	PCW (212 dB)	0.05 km^2	130 m	130 m	130 m	0.01 km^2	< 50 m	< 50 m	< 50 m

Table 4-14 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2014) impulsive criteria for the pin pile worst case modelling scenario at the West location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Single pin pile installation**				**Sequential pin pile installation (6 pin piles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (183 dB)	34 km^2	4.2 km	2.2 km	3.2 km	34 km^2	4.2 km	2.2 km	3.2 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	10 km^2	2.2 km	1.3 km	1.8 km	10 km^2	2.2 km	1.3 km	1.8 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	980 km^2	23 km	11 km	17 km	980 km^2	23 km	11 km	17 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	690 km^2	19 km	10 km	15 km	700 km^2	19 km	10 km	15 km
	PCW (170 dB)	89 km^2	6.7 km	3.8 km	5.3 km	91 km^2	6.8 km	3.8 km	5.3 km

4.2.2 Fish criteria

Table 4-15 to Table 4-26 present the modelled ranges using the Popper *et al*. (2014) pile driving criteria for fish covering the parameters as described in Section 3.2.

The largest recoverable injury ranges (203 dB SEL_{cum} threshold) in species of fish are predicted to be 15 km assuming a stationary receptor for both the three sequentially installed monopiles scenario and the six sequentially installed pin piles scenario. If a fleeing receptor is assumed, the impact ranges are reduced to less than 100 m. Maximum TTS ranges (186 dB SEL_{cum} threshold) are predicted up to 15 km assuming a fleeing animal, increasing to 42 km when considering a stationary animal.

When comparing the impact ranges for a single pile installation and sequential pile installations the overall increases are minimal when considering a fleeing animal, as by the time the subsequent piles are installed the fleeing receptor is at such a distance that the additional exposure is small. When considering a stationary animal, the ranges are significantly increased as the receptor is essentially receiving noise from either double or quadruple the number of pile strikes from monopiles and pin piles respectively.

4.2.2.1 East location

Table 4-15 Summary of the unweighted SPL_{peak} impact ranges using the Popper et al. (2014) pile driving criteria for the monopile worst case modelling scenario at the East location

Popper *et al.* (2019) Unweighted SPL_{peak}	**Full energy (6,000 kJ)**				**First strike (900 kJ)**			
	Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
213 dB	0.05 km^2	120 m	120 m	120 m	0.01 km^2	60 m	50 m	60 m
207 dB	0.30 km^2	310 m	310 m	310 m	0.06 km^2	140 m	140 m	140 m

Table 4-16 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the monopile worst case modelling scenario at the East location assuming both a fleeing and stationary animal

Popper *et al.* (2019) Unweighted SEL_{cum}		**Single monopile installation**				**Sequential monopile installation (3 monopiles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
Fleeing	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	430 km^2	15 km	7.0 km	11 km	430 km^2	15 km	7.0 km	11 km
Stationary	219 dB	3.9 km^2	1.2 km	1.1 km	1.1 km	15 km^2	2.3 km	2.1 km	2.2 km
	216 dB	9.2 km^2	1.8 km	1.6 km	1.7 km	34 km^2	3.5 km	3.1 km	3.3 km
	210 dB	47 km^2	4.1 km	3.6 km	3.9 km	140 km^2	7.4 km	6.0 km	6.8 km
	207 dB	97 km^2	6.0 km	5.0 km	5.6 km	260 km^2	10 km	7.4 km	9.1 km
	203 dB	230 km^2	9.4 km	7.1 km	8.5 km	530 km^2	15 km	10 km	13 km
	186 dB	2,400 km^2	33 km	21 km	28 km	3,600 km^2	42 km	25 km	34 km

Table 4-17 Summary of the unweighted SPL_{peak} impact ranges using the Popper et al. (2014) pile driving criteria for the pin pile worst case modelling scenario at the East location

Popper *et al.* (2019) Unweighted SPL_{peak}	**Full energy (4,400 kJ)**				**First strike (660 kJ)**			
	Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
213 dB	0.04 km^2	110 m	110 m	110 m	0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	0.26 km^2	290 m	290 m	290 m	0.04 km^2	110 m	110 m	110 m

Table 4-18 Summary of the unweighted SEL$_{cum}$ impact ranges using the Popper et al. (2014) pile driving criteria for the pin pile worst case modelling scenario at the East location assuming both a fleeing and stationary animal

Popper *et al.* (2019) Unweighted SEL$_{cum}$		**Single pin pile installation**				**Sequential pin pile installation (6 pin piles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
Fleeing	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	450 km^2	15 km	7.1 km	12 km	450 km^2	16 km	7.2 km	12 km
Stationary	219 dB	1.5 km^2	730 m	680 m	700 m	15 km^2	2.3 km	2.1 km	2.2 km
	216 dB	3.7 km^2	1.1 km	1.1 km	1.1 km	34 km^2	3.5 km	3.1 km	3.3 km
	210 dB	21 km^2	2.7 km	2.4 km	2.6 km	140 km^2	7.3 km	5.9 km	6.7 km
	207 dB	46 km^2	4.1 km	3.6 km	3.8 km	260 km^2	10 km	7.4 km	9.0 km
	203 dB	120 km^2	6.7 km	5.5 km	6.2 km	520 km^2	15 km	10 km	13 km
	186 dB	1,800 km^2	28 km	18 km	24 km	3,600 km^2	42 km	25 km	34 km

4.2.2.2 South location

Table 4-19 Summary of the unweighted SPL$_{peak}$ impact ranges using the Popper et al. (2014) pile driving criteria for the monopile worst case modelling scenario at the South location

Popper *et al.* (2019) Unweighted SPL$_{peak}$	**Full energy (6,000 kJ)**				**First strike (900 kJ)**			
	Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
213 dB	0.05 km^2	120 m	120 m	120 m	0.01 km^2	60 m	50 m	60 m
207 dB	0.3 km^2	310 m	310 m	310 m	0.06 km^2	140 m	140 m	140 m

Table 4-20 Summary of the unweighted SEL$_{cum}$ impact ranges using the Popper et al. (2014) pile driving criteria for the monopile worst case modelling scenario at the South location assuming both a fleeing and stationary animal

Popper *et al.* (2019) Unweighted SEL$_{cum}$		**Single monopile installation**				**Sequential monopile installation (3 monopiles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
Fleeing	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	340 km^2	12 km	7.7 km	10 km	340 km^2	12 km	7.7 km	10 km
Stationary	219 dB	3.7 km^2	1.1 km	1.1 km	1.1 km	14 km^2	2.2 km	2.1 km	2.1 km
	216 dB	8.6 km^2	1.7 km	1.6 km	1.7 km	32 km^2	3.3 km	3.1 km	3.2 km
	210 dB	44 km^2	3.9 km	3.6 km	3.7 km	130 km^2	6.9 km	5.9 km	6.5 km
	207 dB	88 km^2	5.6 km	5.0 km	5.3 km	240 km^2	9.3 km	7.5 km	8.7 km
	203 dB	210 km^2	8.7 km	7.1 km	8.1 km	480 km^2	13 km	10 km	12 km
	186 dB	2,100 km^2	29 km	18 km	25 km	3,000 km^2	36 km	20 km	31 km

Table 4-21 Summary of the unweighted SPL_{peak} impact ranges using the Popper et al. (2014) pile driving criteria for the pin pile worst case modelling scenario at the South location

Popper *et al.* (2019) Unweighted SPL_{peak}	**Full energy (4,400 kJ)**				**First strike (660 kJ)**			
	Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
213 dB	0.04 km^2	110 m	110 m	110 m	0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	0.25 km^2	290 m	280 m	290 m	0.04 km^2	110 m	110 m	110 m

Table 4-22 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the pin pile worst case modelling scenario at the South location assuming both a fleeing and stationary animal

Popper *et al.* (2019) Unweighted SEL_{cum}		**Single pin pile installation**				**Sequential pin pile installation (6 pin piles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
Fleeing	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	350 km^2	12 km	7.6 km	11 km	350 km^2	12 km	7.6 km	11 km
Stationary	219 dB	1.5 km^2	700 m	680 m	690 m	14 km^2	2.2 km	2.1 km	2.1 km
	216 dB	3.5 km^2	1.1 km	1.1 km	1.1 km	31 km^2	3.3 km	3.0 km	3.2 km
	210 dB	19 km^2	2.6 km	2.4 km	2.5 km	130 km^2	6.8 km	5.8 km	6.4 km
	207 dB	43 km^2	3.8 km	3.5 km	3.7 km	230 km^2	9.3 km	7.5 km	8.6 km
	203 dB	110 km^2	6.3 km	5.5 km	5.9 km	470 km^2	13 km	10 km	12 km
	186 dB	1,500 km^2	25 km	17 km	22 km	3,000 km^2	36 km	19 km	31 km

4.2.2.3 West location

Table 4-23 Summary of the unweighted SPL_{peak} impact ranges using the Popper et al. (2014) pile driving criteria for the monopile worst case modelling scenario at the West location

Popper *et al.* (2019) Unweighted SPL_{peak}	**Full energy (6,000 kJ)**				**First strike (900 kJ)**			
	Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
213 dB	0.04 km^2	120 m	120 m	120 m	0.01 km^2	50 m	50 m	50 m
207 dB	0.28 km^2	300 m	300 m	300 m	0.06 km^2	140 m	140 m	140 m

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

Popper *et al.* (2019) Unweighted SEL_{cum}		**Single monopile installation**				**Sequential monopile installation (3 monopiles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
Fleeing	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	230 km^2	11 km	5.9 km	8.5 km	230 km^2	11 km	5.9 km	8.5 km
Stationary	219 dB	3.4 km^2	1.1 km	1.0 km	1.0 km	13 km^2	2.1 km	1.9 km	2.0 km
	216 dB	7.9 km^2	1.6 km	1.5 km	1.6 km	28 km^2	3.1 km	2.8 km	3.0 km
	210 dB	38 km^2	3.6 km	3.3 km	3.5 km	110 km^2	6.3 km	5.4 km	6.0 km
	207 dB	77 km^2	5.2 km	4.5 km	4.9 km	190 km^2	8.5 km	7.0 km	7.9 km
	203 dB	170 km^2	7.9 km	6.6 km	7.4 km	380 km^2	12 km	9.4 km	11 km
	186 dB	1,700 km^2	28 km	17 km	23 km	2,600 km^2	35 km	20 km	29 km

Table 4-25 Summary of the unweighted SPL_{peak} impact ranges using the Popper et al. (2014) pile driving criteria for the pin pile worst case modelling scenario at the West location

Popper *et al.* (2019) Unweighted SPL_{peak}	**Full energy (4,400 kJ)**				**First strike (660 kJ)**			
	Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
213 dB	0.04 km^2	110 m	110 m	110 m	0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	0.24 km^2	280 m	280 m	280 m	0.03 km^2	110 m	100 m	110 m

Table 4-26 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the pin pile worst case modelling scenario at the West location assuming both a fleeing and stationary animal

Popper *et al.* (2019) Unweighted SEL_{cum}		**Single pin pile installation**				**Sequential pin pile installation (6 pin piles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
Fleeing	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	240 km^2	11 km	5.8 km	8.6 km	240 km^2	11 km	5.8 km	8.7 km
Stationary	219 dB	1.4 km^2	680 m	650 m	660 m	12 km^2	2.1 km	1.9 km	2.0 km
	216 dB	3.3 km^2	1.1 km	1.0 km	1.0 km	27 km^2	3.1 km	2.8 km	3.0 km
	210 dB	17 km^2	2.4 km	2.2 km	2.4 km	110 km^2	6.2 km	5.3 km	5.9 km
	207 dB	37 km^2	3.6 km	3.2 km	3.4 km	190 km^2	8.4 km	7.0 km	7.8 km
	203 dB	93 km^2	5.7 km	4.9 km	5.4 km	380 km^2	12 km	9.3 km	11 km
	186 dB	1,200 km^2	24 km	15 km	20 km	2,600 km^2	35 km	20 km	29 km

4.3 Multiple location modelling

Additional modelling has been carried out to investigate the potential impacts of two piling installations occurring simultaneously at separated foundation locations. Using the worst-case monopile and pin pile sequential piling scenarios, modelling has been carried out for simultaneous piling at the East and South locations, representing a worst case spread of locations. All modelling in this section assumes that the two piling operations start at the same time.

When considering SEL_{cum} modelling, piling from multiple sources has the ability to increase impact ranges and areas significantly as, in this case, it introduces noise from double the number of pile strikes to the water. Unlike the sequential piling investigated in the previous section, fleeing receptors can be closer to a source for more pile strikes resulting in higher cumulative exposures. Figure 4-1 shows the TTS contour for fish from Popper *et al*. (2014) (186 dB SEL_{cum}) for a fleeing receptor as an example. The blue contours show the impact from each modelling location individually (as presented in the previous section), and the red contour shows the increase in impact when both sources occur simultaneously, resulting in a contour encircling the previous two.

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

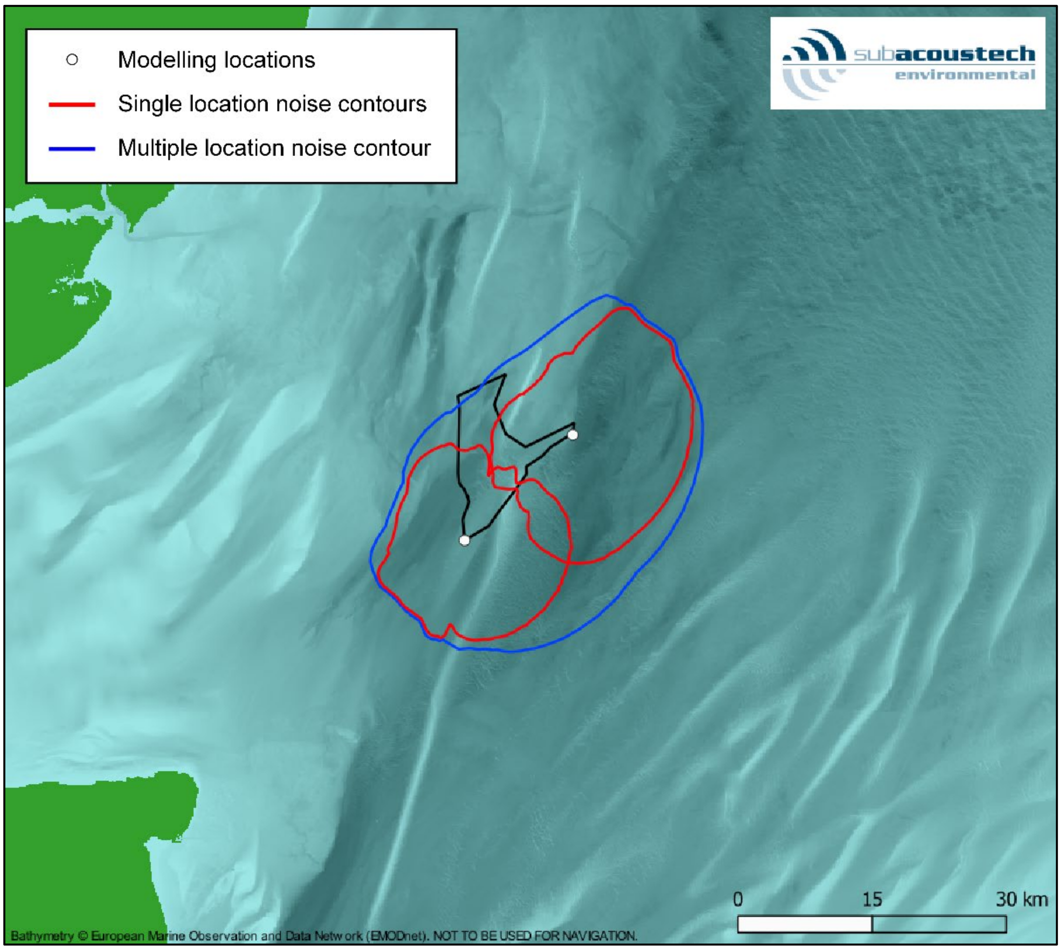


Figure 4-1 Contour plot showing the interaction between two noise sources when occurring simultaneously (TTS in fish, 186 dB SEL$_{cum}$, fleeing animal)

Sections 4.3.1 and 4.3.2 present contour plots for the multiple location piling scenarios alongside tables showing the increases in overall area. Impact ranges have not been presented in this section as there are two starting points for receptors. Fields denoted with a dash "-" show where there is no in-combination effect when piling occurs at the two locations simultaneously, generally where the individual ranges are small enough that the distant site does not produce an influencing additional exposure. Contours that are too small to be seen clearly at the scale of the figures have not been included.

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

4.3.1 Marine mammal criteria

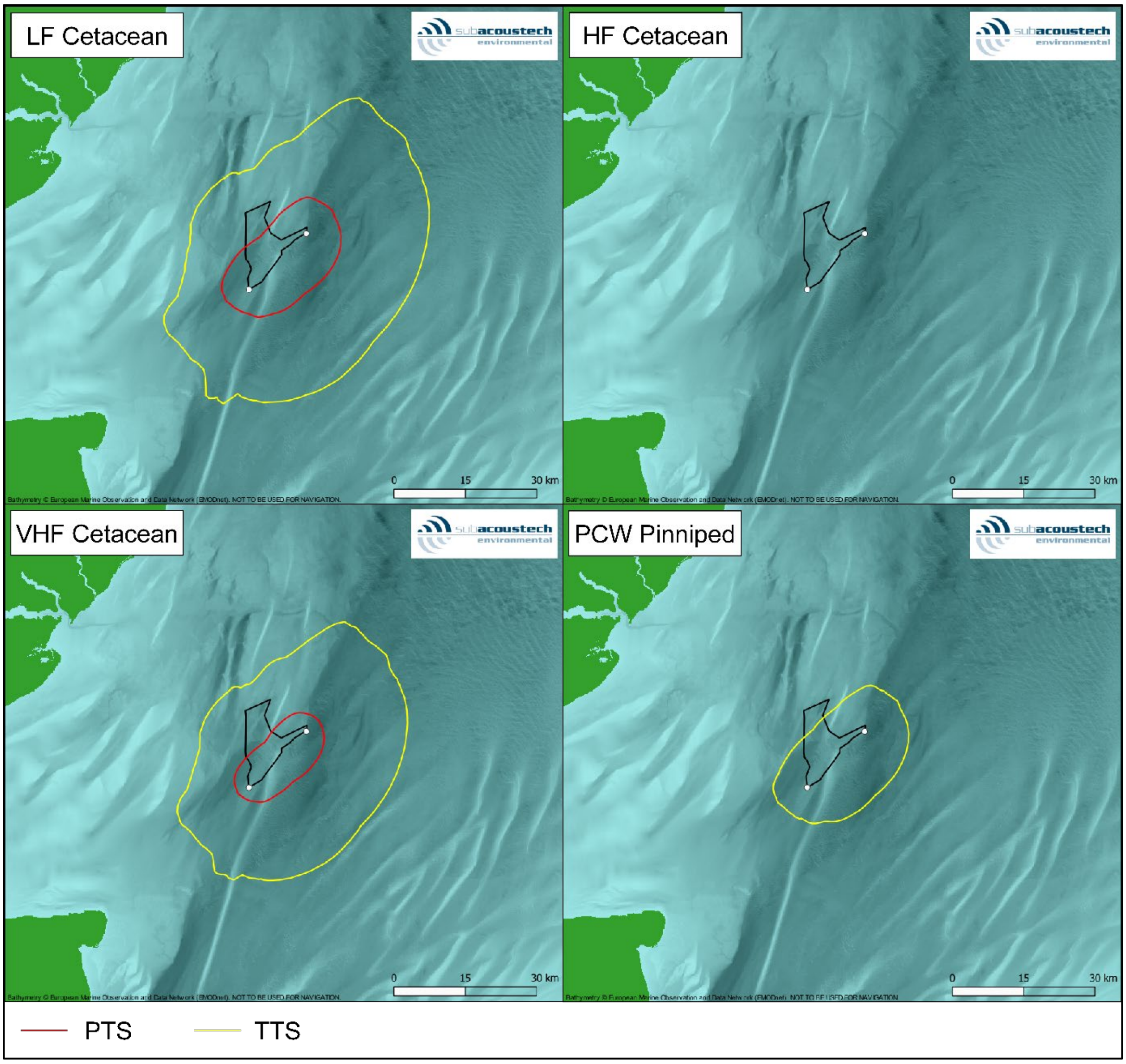


Figure 4-2 Contour plots showing the in-combination impacts of simultaneous installation of monopile foundations at the East and South modelling locations for marine mammals using the impulsive Southall et al. (2019) criteria assuming a fleeing animal

Table 4-27 Summary of the impact areas for the installation of monopile foundations using the worst case parameters at the East and South modelling locations for marine mammals using the impulsive Southall et al. (2019) SEL$_{cum}$ criteria assuming a fleeing animal

Monopile worst case Southall *et al.* (2019) Weighted SEL$_{cum}$		**East area**	**South area**	**In-combination area**
PTS (Impulsive)	LF (183 dB)	94 km^2	68 km^2	390 km^2
	HF (185 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (155 dB)	22 km^2	16 km^2	210 km^2
	PCW (185 dB)	< 0.1 km^2	< 0.1 km^2	-
TTS (Impulsive)	LF (168 dB)	1,600 km^2	1,300 km^2	2,400 km^2
	HF (170 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (140 dB)	1,000 km^2	840 km^2	1,800 km^2
	PCW (170 dB)	160 km^2	120 km^2	530 km^2

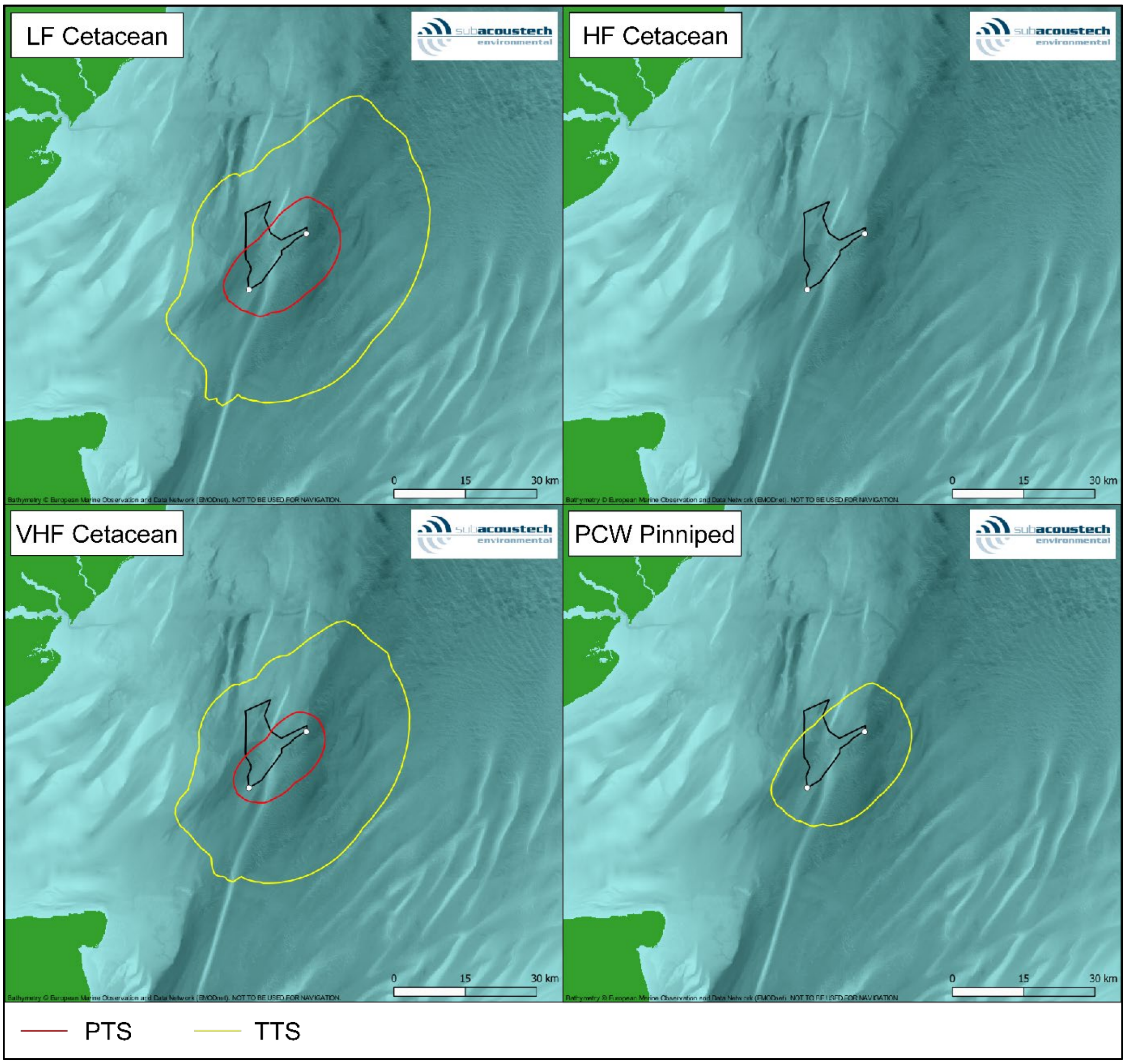


Figure 4-3 Contour plots showing the in-combination impacts of simultaneous installation of pin pile foundations at the East and South modelling locations for marine mammals using the impulsive Southall et al. (2019) criteria assuming a fleeing animal

Table 4-28 Summary of the impact areas for the installation of pin pile foundations using the worst case parameters at the East and South modelling locations for marine mammals using the impulsive Southall et al. (2019) SEL$_{cum}$ criteria assuming a fleeing animal

Pin pile worst case Southall *et al.* (2019) Weighted SEL$_{cum}$		**East area**	**South area**	**In-combination area**
PTS (Impulsive)	LF (183 dB)	85 km^2	57 km^2	380 km^2
	HF (185 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (155 dB)	23 km^2	17 km^2	230 km^2
	PCW (185 dB)	< 0.1 km^2	< 0.1 km^2	-
TTS (Impulsive)	LF (168 dB)	1,500 km^2	1,200 km^2	2,400 km^2
	HF (170 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (140 dB)	1,100 km^2	880 km^2	1,800 km^2
	PCW (170 dB)	180 km^2	140 km^2	580 km^2

4.3.2 *Fish criteria*

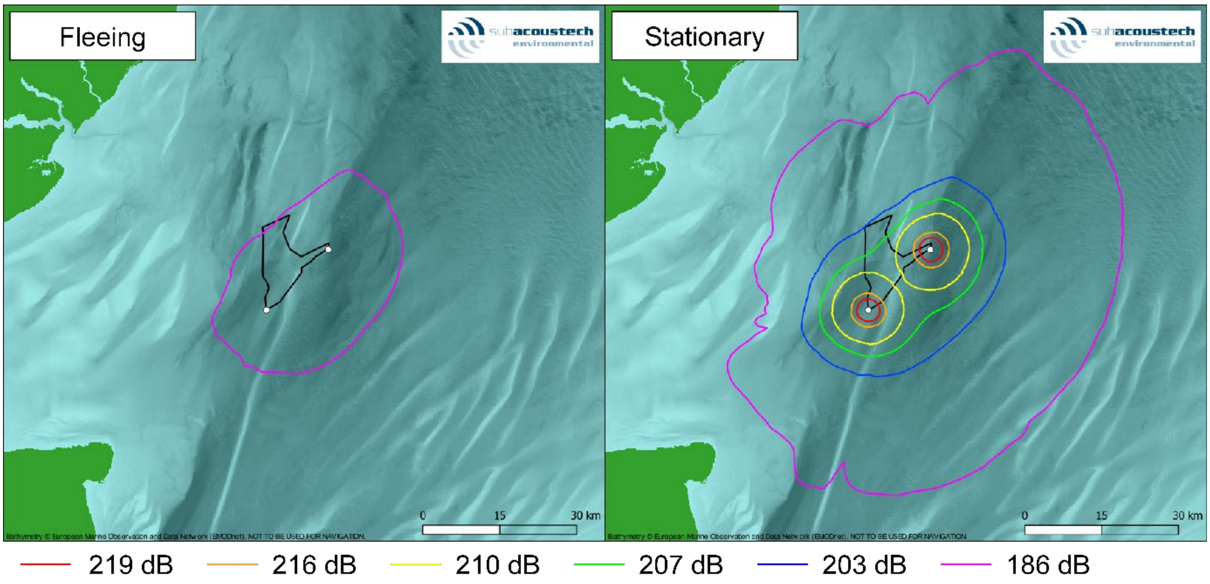


Figure 4-4 Contour plots showing the in-combination impacts of simultaneous installation of monopile foundations at the East and South modelling locations for marine mammals using the Popper et al. (2014) impact piling criteria assuming both a fleeing and stationary animal

Table 4-29 Summary of the impact areas for the installation of monopile foundations using the worst case parameters at the East and South modelling locations for fish using the Popper et al. (2014) impact piling SEL$_{cum}$ criteria assuming both a fleeing and stationary animal

Monopile worst case Popper *et al*. (2014) Unweighted SEL$_{cum}$		**East area**	**South area**	**In-combination area**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 0.1 km^2	-
	216 dB	< 0.1 km^2	< 0.1 km^2	-
	210 dB	< 0.1 km^2	< 0.1 km^2	-
	207 dB	< 0.1 km^2	< 0.1 km^2	-
	203 dB	< 0.1 km^2	< 0.1 km^2	-
	186 dB	430 km^2	340 km^2	970 km^2
Stationary	219 dB	15 km^2	14 km^2	32 km^2
	216 dB	34 km^2	32 km^2	71 km^2
	210 dB	140 km^2	130 km^2	320 km^2
	207 dB	260 km^2	240 km^2	590 km^2
	203 dB	530 km^2	480 km^2	1,000 km^2
	186 dB	3,600 km^2	3,000 km^2	4,700 km^2

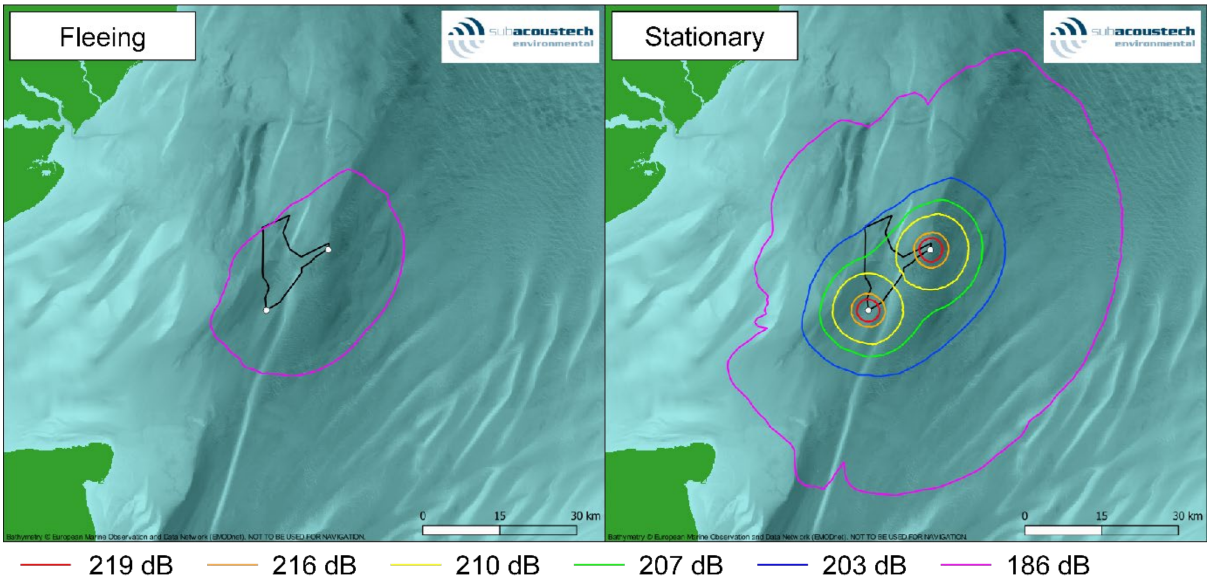


Figure 4-5 Contour plots showing the in-combination impacts of simultaneous installation of pin pile foundations at the East and South modelling locations for marine mammals using the Popper et al. (2014) impact piling criteria assuming both a fleeing and stationary animal

Table 4-30 Summary of the impact areas for the installation of pin pile foundations using the worst case parameters at the East and South modelling locations for fish using the Popper et al. (2014) impact piling SEL$_{cum}$ criteria assuming both a fleeing and stationary animal

Pin pile worst case Popper *et al*. (2014) Unweighted SEL$_{cum}$		**East area**	**South area**	**In-combination area**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 0.1 km^2	-
	216 dB	< 0.1 km^2	< 0.1 km^2	-
	210 dB	< 0.1 km^2	< 0.1 km^2	-
	207 dB	< 0.1 km^2	< 0.1 km^2	-
	203 dB	< 0.1 km^2	< 0.1 km^2	-
	186 dB	450 km^2	350 km^2	1,000 km^2
Stationary	219 dB	15 km^2	14 km^2	31 km^2
	216 dB	34 km^2	31 km^2	69 km^2
	210 dB	140 km^2	130 km^2	310 km^2
	207 dB	260 km^2	230 km^2	580 km^2
	203 dB	520 km^2	470 km^2	1,000 km^2
	186 dB	3,600 km^2	3,000 km^2	4,700 km^2

5 Other noise sources

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

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

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

Activity	Description
Cable laying	Noise from the cable laying vessel and any other associated noise during the offshore cable installation.
Dredging	Dredging may be required on site for seabed preparation work for certain foundation options, as well as for the export cable, array cables and interconnector cable installation. Suction dredging has been assumed as a worst-case.
Trenching	Plough trenching may be required during offshore cable installation.
Rock placement	Potentially required on site for installation of offshore cables (cable crossings and cable protection) and scour protection around foundation structures.
Vessel noise	Jack-up barges for piling substructure and WTG installation. Other large and medium sized vessels to carry out other construction tasks and anchor handling. Other small vessels for crew transport and maintenance on site.
Operational WTG	Noise transmitted through the water from operational WTG. The project design envelope gives WTGs with rotor diameters of either to 236 m or 337 m.
UXO clearance	There is a possibility that Unexploded Ordnance (UXO) may exist within the boundaries of North Falls, which would need to be cleared before construction can begin.

The NPL Good Practice Guide 133 for underwater noise measurements (Robinson *et al*., 2014) indicates that under certain circumstances, a simple modelling approach may be considered acceptable. Such an approach has been used for these noise sources, which are variously either quiet compared to impact piling (e.g., cable laying and dredging), or where detailed modelling would imply unjustified accuracy (e.g., where data is limited such as with large operation WTG noise or UXO detonation). The high-level overview of modelling that has been presented here is considered sufficient and there would be little benefit in using a more detailed model at this stage. The limitations of this approach are noted, including the lack of frequency or bathymetric dependence.

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

5.1 Noise making activities

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

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

Predicted apparent source levels and propagation calculations for the construction activities are presented in Table 5-2 along with a summary of the number of datasets used in each case. As previously, all SEL_{cum} criteria use the same assumptions as presented in section 2.2, and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. It should be noted that this modelling approach does not take bathymetry or any other environmental conditions into account, and as such can be applied to any location at North Falls.

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

Source	Estimated unweighted apparent source level	Approximate transmission loss	Comments
Cable laying	171 dB re 1 µPa @ 1 m (RMS)	$13\log_{10}R$ (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
Suction dredging	186 dB re 1 µPa @ 1 m (RMS)	$19\log_{10}R - 0.0009R$	Based on five datasets from suction and cutter suction dredgers
Trenching	172 dB re 1 µPa @ 1 m (RMS)	$13\log_{10}R - 0.0004R$	Based on three datasets of measurements from trenching vessels more than 100 m in length
Rock placement	172 dB re 1 µPa @ 1 m (RMS)	$12\log_{10}R - 0.0005R$	Based on four datasets from rock placement vessel '*Rollingstone*'
Vessel noise (large)	168 dB re 1 µPa @ 1 m (RMS)	$12\log_{10}R - 0.0021R$	Based on five datasets of large vessels including container ships, FPSOs and other vessels more than 100 m in length. Vessel speed assumed as 10 knots.
Vessel noise (medium)	161 dB re 1 µPa @ 1 m (RMS)	$12\log_{10}R - 0.0021R$	Based on three datasets of moderate sized vessels less than 100 m in length. Vessel speed assumed as 10 knots

All values of N and α are empirically derived and will be linked to the size and shape of the machinery and the noise source on it, the transect on which the measurements are taken and the local environment at the time.

For SEL_{cum} calculations in this section, the duration the noise is present also needs to be considered, with all sources assumed to operate constantly for 24 hours to give a worst-case assessment of the noise. Due to the low noise level of the sources considered both fleeing and stationary animals have been included for all SEL_{cum} criteria.

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

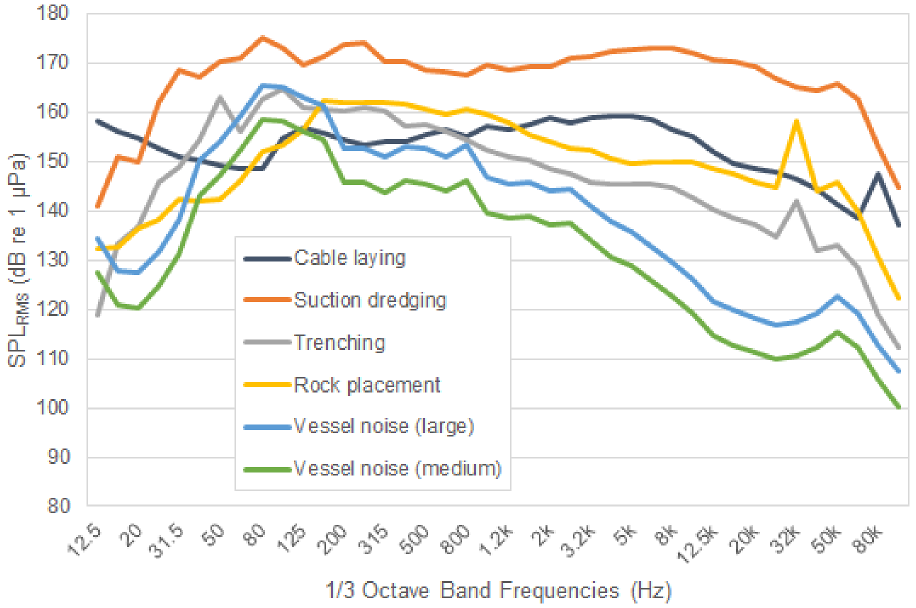


Figure 5-1 Summary of the 1/3rd octave frequency bands to which the Southall et al. (2019) weightings were applied in the simple modelling

Table 5-3 Reductions in source level for the different construction noise sources considered when the Southall et al. (2019) weightings are applied

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

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

Given the modelled impact ranges, any marine mammal would have to be closer than 100 m from the continuous noise source at the start of the activity in most cases to acquire the necessary exposure to induce PTS as per Southall *et al*. (2019). The exposure calculation assumes the same receptor swim speed as the impact piling modelling in Section 4. As explained in Section 3.3, this would only mean that the receptor reaches the 'onset' stage at these ranges, which is the minimum exposure that could potentially lead to the start of an effect and may only be marginal. In most hearing groups, the noise levels are low enough that there is a negligible risk.

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

All sources presented here result in much quieter levels than those presented for impact piling in Section 4.

Table 5-4 Summary of the impact ranges for the different construction noise sources using the non-impulsive criteria from Southall et al. (2019) for marine mammals assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Cable laying**	**Suction dredging**	**Trenching**	**Rock placement**	**Vessels (large)**	**Vessels (medium)**
PTS	199 dB (LF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	198 dB (HF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	173 dB (VHF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	201 dB (PCW)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
TTS	179 dB (LF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	178 dB (HF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	153 dB (VHF)	110 m	230 m	< 100 m	990 m	< 100 m	< 100 m
	181 dB (PCW)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-5 Summary of the impact ranges for the different construction noise sources using the non-impulsive criteria from Southall et al. (2019) for marine mammals assuming a stationary animal

Southall *et al*. (2019) Weighted SEL_{cum}		**Cable laying**	**Suction dredging**	**Trenching**	**Rock placement**	**Vessels (large)**	**Vessels (medium)**
PTS	199 dB (LF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	198 dB (HF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	173 dB (VHF)	< 100 m	570 m	< 100 m	900 m	< 100 m	< 100 m
	201 dB (PCW)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
TTS	179 dB (LF)	810 m	640 m	830 m	2.1 km	480 m	130 m
	178 dB (HF)	< 100 m	390 m	< 100 m	410 m	< 100 m	< 100 m
	153 dB (VHF)	2.3 km	4.3 km	1.9 km	13 km	140 m	< 100 m
	181 dB (PCW)	110 m	420 m	120 m	460 m	< 100 m	< 100 m

Ranges for a stationary animal are theoretical only and are expected to be over-conservative as the assumption is for the animal to remain stationary in respect to the noise source, when the source itself is moving in most cases.

Table 5-6 Summary of the impact ranges for fish from Popper et al. (2014) for shipping and continuous noise, covering the different construction noise sources

Popper *et al*. (2014) Unweighted SPL_{RMS}	**Cable laying**	**Suction dredging**	**Trenching**	**Rock placement**	**Vessels (large)**	**Vessels (medium)**
Recoverable injury 170 dB (48 hours)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
TTS 158 dB (12 hours)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m

5.2 Operational WTG noise

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

Tougaard *et al*. (2020) published a study investigating underwater noise data from 17 operational WTGs in Europe and the United Sates, from 0.2 MW to 6.15 MW nominal power output. The paper identified the nominal power output and wind speed as the two primary driving factors for underwater noise generation. Although the datasets were acquired under different conditions, the authors devised a formula based on the published data for the operational wind farms, allowing a broadband noise level to be estimated based on the application of wind speed, turbine size (by nominal power output) and distance from the turbine:

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

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

Indicative power outputs have been used to calculate impacts for this study. The smaller WTG has an indicative power output of 15 MW and the largest WTG has an indicative power output of 25 MW.

The maximum turbine sizes considered at North Falls are much larger than those used for the estimation above, so caution must be used when considering the results presented in this section. Figure 5-2 presents a level against range plot for the two turbine sizes using the Tougaard *et al.* (2020) calculation, assuming an average 6 ms^{-1} wind speed.

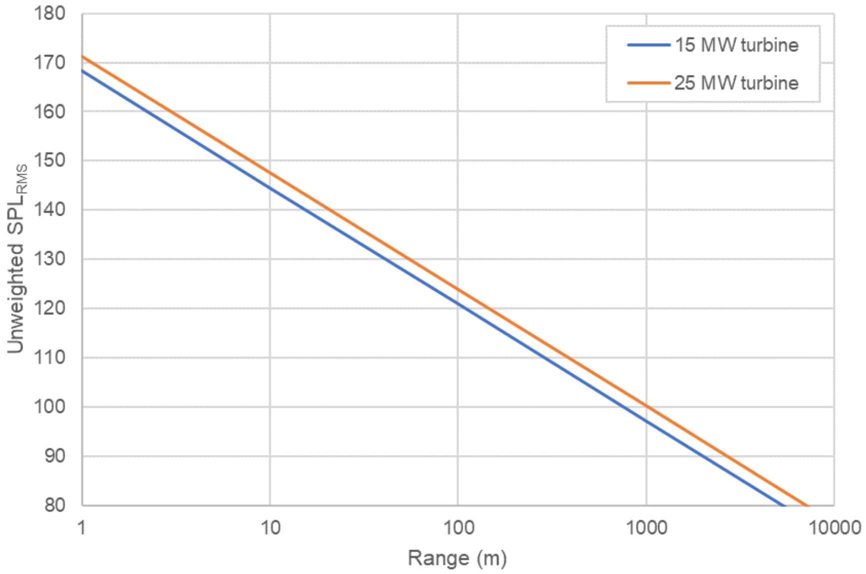


Figure 5-2 Predicted unweighted SPL$_{RMS}$ from operational WTGs with power outputs of 15 MW and 25 MW using the calculation from Tougaard et al. (2020)

Using this data, a summary of the predicted impact ranges has been produced, shown in Table 5-7 and Table 5-8. All SEL$_{cum}$ criteria use the same assumptions as presented in Section 2.2, and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. The operational WTG source is considered a non-impulsive or continuous source. For SEL$_{cum}$ calculations it has been assumed that the operational WTG noise is present 24 hours a day.

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

Southall *et al.* (2019) Weighted SEL$_{cum}$		**Operational WTG (15 MW)**	**Operational WTG (25 MW)**
PTS (non-impulsive)	199 dB (LF SEL$_{cum}$)	< 100 m	< 100 m
	198 dB (HF SEL$_{cum}$)	< 100 m	< 100 m
	173 dB (VHF SEL$_{cum}$)	< 100 m	< 100 m
	201 dB (PCW SEL$_{cum}$)	< 100 m	< 100 m
TTS (non-impulsive)	179 dB (LF SEL$_{cum}$)	< 100 m	< 100 m
	178 dB (HF SEL$_{cum}$)	< 100 m	< 100 m
	153 dB (VHF SEL$_{cum}$)	< 100 m	< 100 m
	181 dB (PCW SEL$_{cum}$)	< 100 m	< 100 m

Table 5-8 Summary of the operational WTG noise impact ranges using the continuous noise criteria from Popper et al. (2014) for fish (swim bladder involved in hearing)

Popper *et al.* (2014) Unweighted SPL_{RMS}	**Operational WTG (15 MW)**	**Operational WTG (25 MW)**
Recoverable injury 170 dB (48 hours) Unweighted SPL_{RMS}	< 50 m	< 50 m
TTS 158 dB (12 hours) Unweighted SPL_{RMS}	< 50 m	< 50 m

These results show that, for operational WTGs, injury risk is minimal. Taking the results from this and the previous section (5.1), and comparing them to the impact piling results in section 4, it is clear that noise from impact piling results in much greater noise levels and impact ranges, and hence should be considered the activity which has the potential to have the greatest effect during the construction and lifecycle of North Falls.

5.3 UXO clearance

It is possible that UXO devices with a range of charge weights (or quantity of contained explosive) are present within the boundaries of North Falls. These would need to be cleared before any construction can begin. When modelling potential noise from UXO clearance, a variety of explosive types need to be considered, with the potential that many have been subject to degradation and burying over time. Two otherwise identical explosive devices are likely to produce different blasts in the case where one has spent an extended period on the seabed. A selection of explosive sizes has been considered based on what might be present, and in each case, it has been assumed that the maximum explosive charge in each device is present and detonates with the clearance.

5.3.1 Estimation of underwater noise levels

The noise produced by the detonation of explosives is affected by several different elements, only one of which can easily be factored into a calculation: the charge weight. In this case the charge weight is based on the equivalent weight of TNT. Many other elements relating to its situation (e.g., its design, composition, age, position, orientation, whether it is covered by sediment) and exactly how they will affect the sound produced by detonation are usually unknown and cannot be directly considered in this type of assessment. This leads to a high degree of uncertainty in the estimation of the source noise level. A worst-case estimation has therefore been used for calculations, assuming the UXO to be detonated is not buried, degraded or subject to any other significant attenuation from its “as new” condition.

The consequence of this is that the noise levels produced, particularly by the larger explosives under consideration, are likely to be over-estimated as some degree of degradation would be expected.

The maximum equivalent charge weight for the potential UXO devices that could be present within the North Falls site boundary has been estimated as 750 kg, this has been modelled alongside a range of smaller devices, these are 25, 55, 120, 240 and 525 kg. In each case an additional donor weight of 0.5 kg has been included to initiate detonation. In addition, low-order deflagration has been assessed, which assumes that the donor or shaped charge (charge weight of 0.5 kg) detonates fully but without the follow-up detonation of the UXO. No mitigation has been considered for this modelling.

Estimation of the source noise level for each charge weight has been carried out in accordance with the methodology of Soloway and Dahl (2014), which follows Arons (1954) and the Marine Technical Directorate Ltd (MTD) (1996).

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 $\mathrm{SPL}_{\mathrm{peak}}$:

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

and for $\mathrm{SEL}_{\mathrm{ss}}$

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

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

These equations give a relatively simple calculation which can be used to give an indication of the range of effect. The equation does not consider variable bathymetry or seabed type, and thus calculation results will be the same regardless of where it is used. An attenuation correction can be added to the Soloway and Dahl (2014) equations for the absorption over long ranges (i.e., of the order of thousands of metres), based on measurements of high intensity noise propagation taken in the North Sea and Irish Sea in similar depths to the present at North Falls. 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, $\mathrm{SPL}_{\mathrm{peak}}$ noise levels over larger distances are difficult to predict accurately (von Benda-Beckmann *et al*., 2015). Soloway and Dahl (2014) only verify results from the equation above for small charges at ranges of less than 1 km, although the results are similar to the measurements presented by von Benda-Beckmann *et al*. (2015). At longer ranges, greater confidence is expected with the SEL calculations.

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

Additionally, an impulsive wave tends to be smoothed (i.e., the pulse becomes longer) over distance (Cudahy and Parvin, 2001), meaning the injurious potential of a wave at greater range can be even lower than just a reduction in the absolute noise level. An assessment in respect of SEL is considered preferential at long range as it considers the overall energy, and the degree of smoothing of the peak with increasing distance is less critical.

The selection of assessment criteria must also be considered in light of this. As discussed in Section 2.2.1, the smoothing of the pulse at range means that a pulse may be considered non-impulsive with distance, suggesting that, at greater ranges, it may be more appropriate to use the non-impulsive criteria. This consideration may begin at 3.5 km (Hastie *et al.*, 2019).

A summary of the unweighted UXO source levels calculated using the equations above are given in Table 5-9.

Table 5-9 Summary of the unweighted $\mathrm{SPL}_{\mathrm{peak}}$ and $\mathrm{SEL}_{\mathrm{ss}}$ source levels used for UXO clearance modelling

Charge weight	**0.5 kg**	**25 kg + donor**	**55 kg + donor**	**120 kg + donor**	**240 kg + donor**	**525 kg + donor**	**750 kg + donor**
$\mathrm{SPL}_{\mathrm{peak}}$ source level	272.1	284.9	287.5	290.0	292.3	294.8	296.0

(dB re 1 μPa @ 1 m)							
SEL$_{ss}$ source level (dB re 1 μPa^{2}s @ 1 m)	217.1	228.0	230.1	232.3	234.2	236.4	237.3

5.3.3 *Impact ranges*

Table 5-10 to Table 5-13 present the impact ranges for UXO detonation, considering various charge weights and impact criteria. It should be noted that Popper *et al.* (2014) gives specific impact criteria for explosions (Table 2-6). A UXO detonation source is defined as a single pulse, and as such the SEL$_{cum}$ criteria from Southall *et al.* (2019) have been given as SEL$_{ss}$ in the tables below. Thus, fleeing animal assumptions do not apply. As with the previous sections, ranges smaller than 50 m have not been presented.

Although the impact ranges presented 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 Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, unweighted SPL$_{peak}$ noise criteria from Southall et al. (2019) for marine mammals

Southall *et al.* (2019) Unweighted SPL$_{peak}$		**0.5 kg**	**25 kg + donor**	**55 kg + donor**	**120 kg + donor**	**240 kg + donor**	**525 kg + donor**	**750 kg + donor**
PTS	219 dB (LF)	220 m	820 m	1.0 km	1.3 km	1.7 km	2.2 km	2.5 km
	230 dB (HF)	70 m	260 m	340 m	450 m	560 m	730 m	830 m
	202 dB (VHF)	1.2 km	4.6 km	6.0 km	7.8 km	9.8 km	12 km	14 km
	218 dB (PCW)	240 m	910 m	1.1 km	1.5 km	1.9 km	2.5 km	2.8 km
TTS	213 dB (LF)	410 m	1.5 km	1.9 km	2.5 km	3.2 km	4.1 km	4.6 km
	230 dB (HF)	130 m	490 m	640 m	830 m	1.0 km	1.3 km	1.5 km
	196 dB (VHF)	2.3 km	8.5 km	11 km	14 km	18 km	23 km	26 km
	212 dB (PCW)	450 m	1.6 km	2.1 km	2.8 km	3.5 km	4.6 km	5.1 km

Table 5-11 Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, weighted SEL$_{ss}$ noise criteria from Southall et al. (2019) for marine mammals

Southall *et al.* (2019) Weighted SEL$_{ss}$		**0.5 kg**	**25 kg + donor**	**55 kg + donor**	**120 kg + donor**	**240 kg + donor**	**525 kg + donor**	**750 kg + donor**
PTS	183 dB (LF)	320 m	2.2 km	3.2 km	4.7 km	6.5 km	9.5 km	11 km
	185 dB (HF)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	50 m	60 m
	155 dB (VHF)	110 m	570 m	740 m	950 m	1.1 km	1.4 km	1.5 km
	185 dB (PCW)	60 m	390 m	570 m	830 m	1.1 km	1.6 km	2.0 km
TTS	168 dB (LF)	4.5 km	29 km	41 km	57 km	76 km	100 km	110 km
	170 dB (HF)	< 50 m	150 m	210 m	300 m	390 m	530 m	600 m
	140 dB (VHF)	930 m	2.4 km	2.8 km	3.2 km	3.5 km	4.0 km	4.2 km
	170 dB (PCW)	800 m	5.2 km	7.5 km	10 km	14 km	19 km	22 km

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

Southall *et al.* (2019) Weighted SEL$_{ss}$		**0.5 kg**	**25 kg + donor**	**55 kg + donor**	**120 kg + donor**	**240 kg + donor**	**525 kg + donor**	**750 kg + donor**
PTS	199 dB (LF)	< 50 m	130 m	190 m	280 m	390 m	570 m	680 m
	198 dB (HF)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 50 m	< 50 m	< 50 m	70 m	100 m	130 m	160 m
	201 dB (PCW)	< 50 m	< 50 m	< 50 m	< 50 m	70 m	100 m	120 m

TTS	179 dB (LF)	650 m	4.4 km	6.4 km	9.4 km	13 km	18 km	22 km
	178 dB (HF)	< 50 m	< 50 m	60 m	80 m	110 m	160 m	190 m
	153 dB (VHF)	150 m	730 m	940 m	1.1 km	1.4 km	1.7 km	1.8 km
	181 dB (PCW)	110 m	790 m	1.1 km	1.6 km	2.3 km	3.3 km	4.0 km

Table 5-13 Summary of the impact ranges for UXO detonation using the unweighted SPL_{peak} explosion noise criteria from Popper et al. (2014) for species of fish

Popper *et al.* (2014) Unweighted SPL_{peak}		**0.5 kg**	**25 kg + donor**	**55 kg + donor**	**120 kg + donor**	**240 kg + donor**	**525 kg + donor**	**750 kg + donor**
Mortality & potential mortal injury	234 dB	< 50 m	170 m	230 m	300 m	370 m	490 m	550 m
	229 dB	80 m	290 m	380 m	490 m	620 m	810 m	910 m

5.3.4 Summary

The maximum PTS range calculated for UXO is 14 km for the VHF cetacean category, based on the unweighted SPL_{peak} criteria. For SEL_{ss} criteria, the largest PTS range is calculated for LF cetaceans with a predicted impact of 11 km using the impulsive noise criteria. As explained earlier, this assumes no degradation of the UXO and no smoothing of the pulse over that distance, which is very precautionary. Although an assumption of non-pulse could under-estimate the potential impact (Martin *et al*. 2020) (the equivalent range based on LF cetacean non-pulse criteria is 680 m), it is likely that the long-range smoothing of the pulse peak would reduce its potential harm and the maximum ‘impulsive’ range for all species is very precautionary.

6 Summary and conclusions

Subacoustech Environmental have undertaken a study on behalf of HaskoningDHV UK Ltd. to assess the potential underwater noise and its effects during the construction and operation of the proposed North Falls Offshore Wind Farm, located in the southern North Sea adjacent to the existing Greater Gabbard and Galloper Offshore Wind Farms.

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

Four representative modelling locations were chosen to give spatial variation as well as account for changes in water depth around the site. At each location, two modelling scenarios were considered:

- A monopile worst case scenario, installing a 17 m diameter pile with a maximum blow energy of 6,000 kJ; and
- A pin pile worst case scenario, installing a 6 m diameter pile with a maximum blow energy of 4,400 kJ.

It is expected that up to 3 monopiles or 6 pin piles could be installed in a 24-hour period.

The loudest levels of noise and greatest impact ranges have been largely predicted for the piling scenarios at the East location. Smaller ranges are predicted at the other locations due to shallower water near these locations and the proximity to the coastline.

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 aid biological assessments.

For marine mammals, maximum PTS ranges were predicted for LF cetaceans, with ranges of up to 7.0 km based on the worst case monopile scenario. For fish, the largest recoverable injury ranges (203 dB SEL_{cum}) were predicted to be less than 100 m for a fleeing receptor, increasing to 15 km for a stationary receptor.

When comparing impact ranges for a single pile installation and sequential pile installations the overall increases are negligible when considering a fleeing animal.

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

UXO clearance has also been considered at the North Falls site, and for the expected UXO clearance noise, there is a risk of PTS up to 14 km for the largest, 750 kg, UXO device considered, using the unweighted SPL_{peak} criteria for VHF cetaceans. However, this is likely to be precautionary as the impact range is based on a worst case criterion and calculation methodology that does not account for any smoothing of the pulse over long ranges, which would reduce the pulse peak and other characteristics of the sound that cause injury.

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

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Appendix A Additional modelling results

Following from the Southall *et al*. (2019) modelled impact piling ranges presented in Section 4 of the main report, the modelling results for non-impulsive criteria from impact piling noise at North Falls, as discussed in Section 2.2.1, is presented below. The predicted ranges here fall well below the impulsive criteria presented in the main report.

A.1 Single location modelling

Table A 1 to Table A 6 present the modelling results considering single locations for the non-impulsive Southall *et al*. (2019) criteria.

Table A 1 Summary of the unweighted SEL$_{cum}$ impact ranges using the Southall et al. (2019) non-impulsive criteria for the monopile worst case modelling scenario at the East location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		**Single monopile installation**				**Sequential monopile installation (3 monopiles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	280 km^2	12 km	5.7 km	9.2 km	280 km^2	12 km	5.7 km	9.2 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	52 km^2	5.0 km	2.7 km	4.0 km	52 km^2	5.1 km	2.7 km	4.0 km
	PCW (181 dB)	< 0.1 km^2	200 m	100 m	150 m	< 0.1 km^2	200 m	100 m	150 m

Table A 2 Summary of the weighted SEL$_{cum}$ impact ranges using the Southall et al. (2019) non-impulsive criteria for the pin pile worst case modelling scenario at the East location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		**Single pin pile installation**				**Sequential pin pile installation (6 pin piles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	270 km^2	12 km	5.3 km	9.0 km	270 km^2	12 km	5.3 km	9.0 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	55 km^2	5.2 km	2.6 km	4.1 km	55 km^2	5.3 km	2.6 km	4.1 km
	PCW (181 dB)	< 0.1 km^2	150 m	< 100 m	120 m	< 0.1 km^2	150 m	< 100 m	120 m

Table A 3 Summary of the unweighted SEL$_{cum}$ impact ranges using the Southall et al. (2019) non-impulsive criteria for the monopile worst case modelling scenario at the South location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		**Single monopile installation**				**Sequential monopile installation (3 monopiles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	220 km^2	9.3 km	6.5 km	8.3 km	220 km^2	9.3 km	6.5 km	8.3 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	39 km^2	3.9 km	2.9 km	3.5 km	39 km^2	3.9 km	2.9 km	3.5 km
	PCW (181 dB)	< 0.1 km^2	150 m	< 100 m	130 m	< 0.1 km^2	150 m	< 100 m	130 m

Table A 4 Summary of the weighted SEL$_{cum}$ impact ranges using the Southall et al. (2019) non-impulsive criteria for the pin pile worst case modelling scenario at the South location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		**Single pin pile installation**				**Sequential pin pile installation (6 pin piles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	200 km^2	9.2 km	6.1 km^2	8.0 km	200 km^2	9.2 km^2	6.1 km	8.0 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	42 km^2	4.1 km	2.9 km	3.6 km	42 km^2	4.1 km	2.9 km	3.7 km
	PCW (181 dB)	< 0.1 km^2	130 m	< 100 m	< 100 m	< 0.1 km^2	130 m	< 100 m	< 100 m

Table A 5 Summary of the unweighted SEL$_{cum}$ impact ranges using the Southall et al. (2019) non-impulsive criteria for the monopile worst case modelling scenario at the West location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		**Single monopile installation**				**Sequential monopile installation (3 monopiles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	150 km^2	8.6 km	4.8 km	6.8 km	150 km^2	8.6 km	4.8 km	6.8 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	27 km^2	3.5 km	2.3 km	2.9 km	27 km^2	3.5 km	2.3 km	2.9 km
	PCW (181 dB)	< 0.1 km^2	130 m	< 100 m	110 m	< 0.1 km^2	130 m	< 100 m	110 m

Table A 6 Summary of the weighted SEL$_{cum}$ impact ranges using the Southall et al. (2019) non-impulsive criteria for the pin pile worst case modelling scenario at the West location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL$_{cum}$		**Single pin pile installation**				**Sequential pin pile installation (6 pin piles)**			
		Area	**Max**	**Min**	**Mean**	**Area**	**Max**	**Min**	**Mean**
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	130 km^2	8.4 km^2	4.3 km	6.4 km	130 km^2	8.4 km	4.3 km	6.4 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	28 km^2	3.6 km	2.1 km	3.0 km	28 km^2	3.6 km	2.1 km	3.0 km
	PCW (181 dB)	< 0.1 km^2	100 m	< 100 m	< 100 m	< 0.1 km^2	100 m	< 100 m	< 100 m

A.2 Multiple location modelling

Figure A 1 and Figure A 2, Table A 7 and Table A 8 expand on the results presented in Section 4.3 for multiple location piling, covering the non-impulsive criteria from Southall *et al*. (2019) for marine mammals. As before, contours too small to be seen at this scale have not been included, impact ranges have not been presented as there are two starting points for receptors, and fields denoted with a dash "-" show where there is no in-combination effect when the two piles are installed simultaneously.

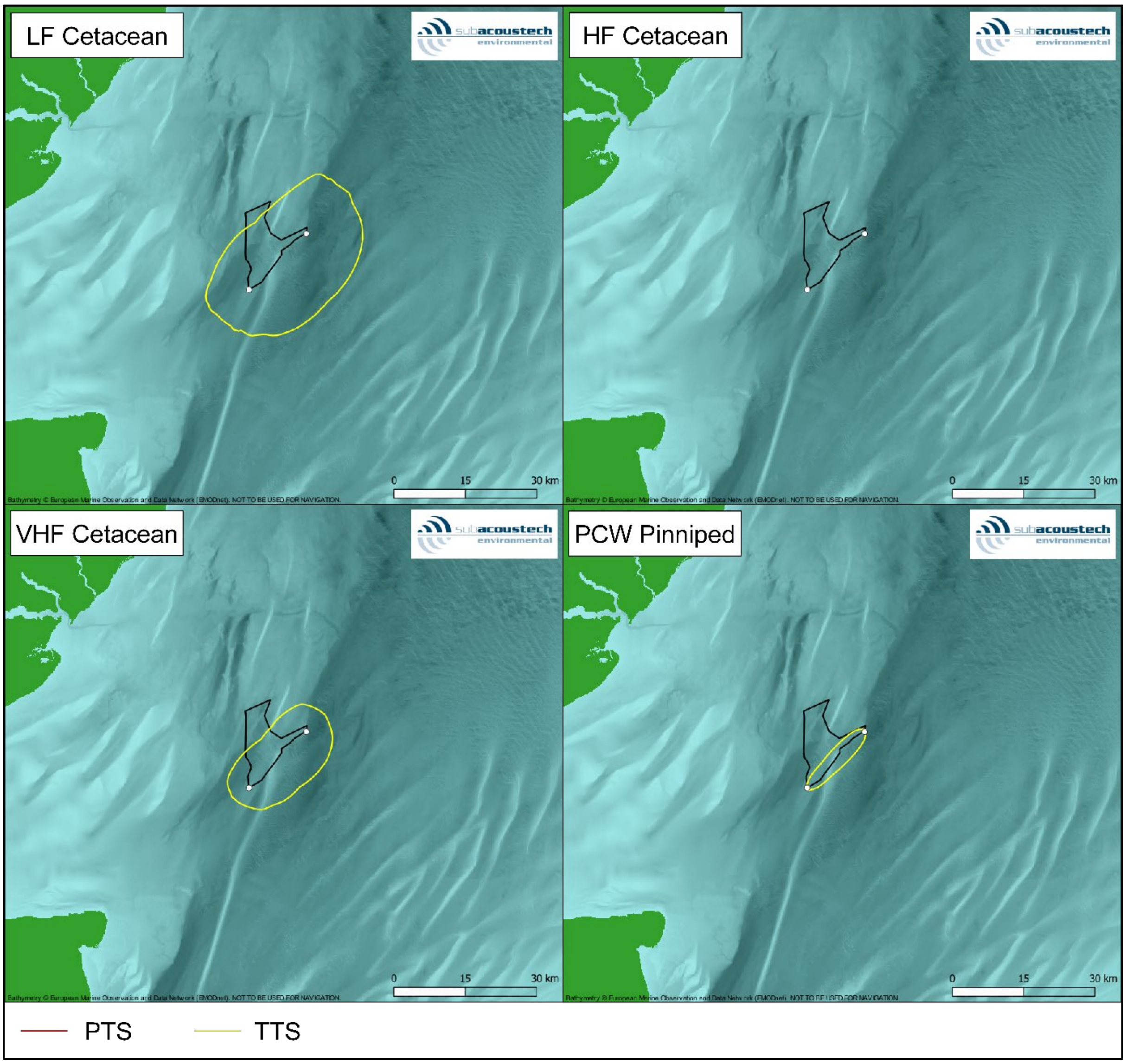

Figure A 1 Contour plots showing the in-combination impacts of simultaneous installation of monopile foundations at the East and South modelling locations for marine mammals using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal

Table A 7 Summary of the impact areas for the installation of monopile foundations using the worst case parameters at the East and South modelling locations for marine mammals using the non-impulsive Southall et al. (2019) SEL$_{cum}$ criteria assuming a fleeing animal

Monopile worst case Southall *et al.* (2019) Weighted SEL$_{cum}$		**East area**	**South area**	**In-combination area**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 0.1 km^2	-
	HF (198 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (173 dB)	< 0.1 km^2	< 0.1 km^2	-
	PCW (201 dB)	< 0.1 km^2	< 0.1 km^2	-
TTS (Non-impulsive)	LF (179 dB)	280 km^2	220 km^2	730 km^2
	HF (178 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (153 dB)	52 km^2	39 km^2	300 km^2
	PCW (181 dB)	< 0.1 km^2	< 0.1 km^2	55 km^2

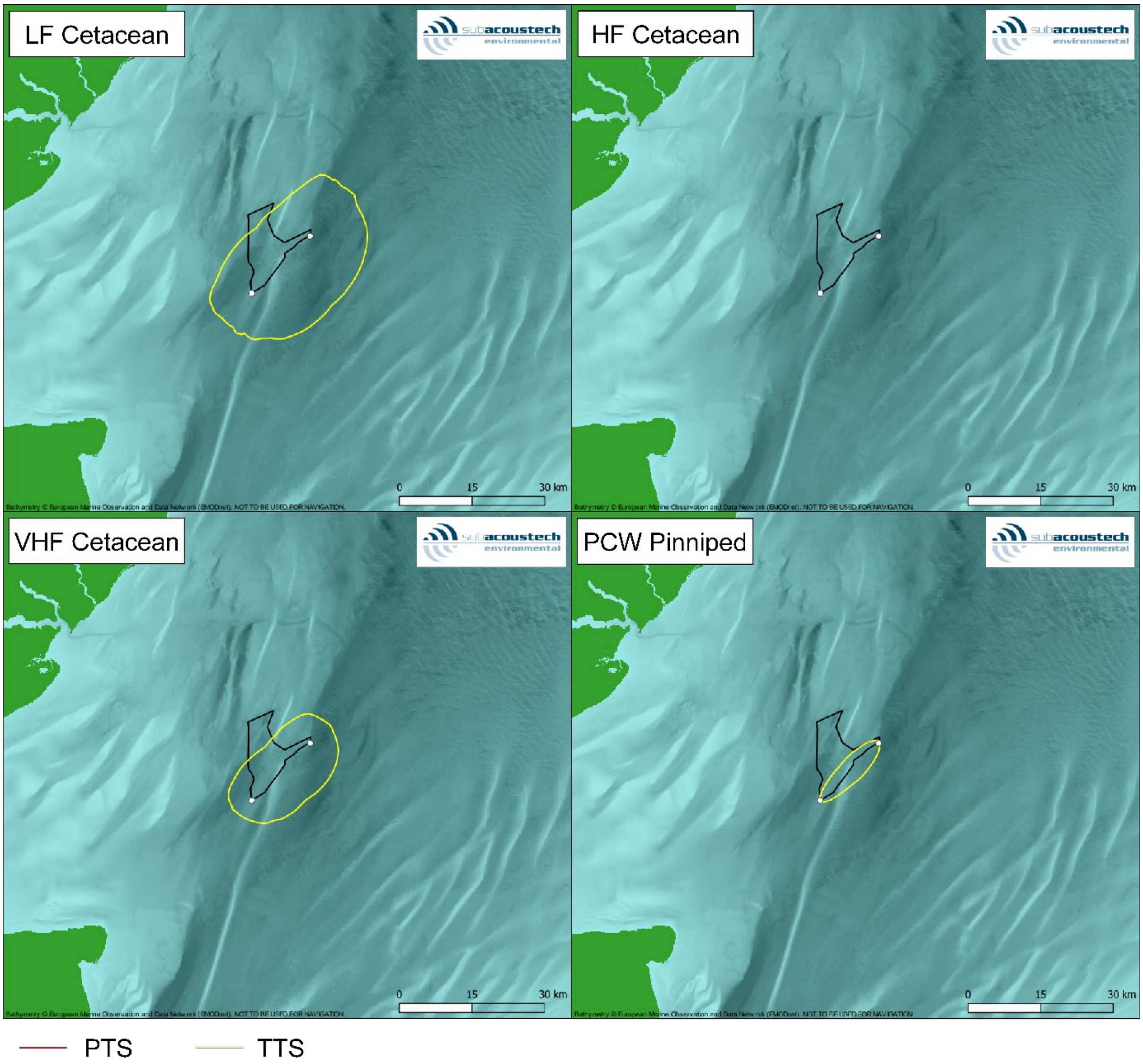

Figure A 2 Contour plots showing the in-combination impacts of simultaneous installation of pin pile foundations at the East and South modelling locations for marine mammals using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal

Table A 8 Summary of the impact areas for the installation of pin pile foundations using the worst case parameters at the East and South modelling locations for marine mammals using the non-impulsive Southall et al. (2019) SEL_{cum} criteria assuming a fleeing animal

Pin pile worst case Southall *et al.* (2019) Weighted SEL_{cum}		**East area**	**South area**	**In-combination area**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 0.1 km^2	-
	HF (198 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (173 dB)	< 0.1 km^2	< 0.1 km^2	-
	PCW (201 dB)	< 0.1 km^2	< 0.1 km^2	-
TTS (Non-impulsive)	LF (179 dB)	270 km^2	200 km^2	710 km^2
	HF (178 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (153 dB)	55 km^2	42 km^2	320 km^2
	PCW (170 dB)	< 0.1 km^2	< 0.1 km^2	63 km^2

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