Dudgeon and Sheringham Shoal Offshore Wind Farm Extensions

Preliminary Environmental Information Report

Volume 3

Appendix 12.2 - Underwater Noise Modelling Report

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Sheringham Extension Project and Dudgeon Extension Project: Underwater noise assessment

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Glossary

Term	Definition
Decibel	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 $10\log_{10}\left(\frac{actual}{reference}\right)$, where $\left(\frac{actual}{reference}\right)$ is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is $20\log_{10}\left(\frac{actual\ pressure}{reference\ pressure}\right)$. The standard reference for underwater sound pressure is 1 micropascal (µPa). The dB symbol is followed by a second symbol identifying the specific reference value (i.e. 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 is 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 ear, and thus a permanent reduction of hearing acuity.
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 Pressure Level (SPL)	The sound pressure level or SPL is an expression of the sound pressure using the decibel (dB) scale, and the standard reference pressures of 1 µPa for water and 20 µPa for air.
Temporary Threshold Shift (TTS)	Temporary reduction of hearing acuity as a result of exposure to sound over time. Exposure to high levels of sound over relatively short time periods could cause the same amount 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.

1 Introduction

The Sheringham Extension Project (SEP) and the Dudgeon Extension Project (DEP) are proposed extensions to the existing Sheringham Shoal and Dudgeon offshore wind farms in the North Sea, off the coast of Norfolk, England. 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 for the two wind farm sites.

SEP is located immediately to the north and east of the existing Sheringham Shoal offshore wind farm, approximately 17.5 km from the shore at its closest point, with an expected capacity of up to 317 MW from between 14 and 27 wind turbine generators (WTGs). DEP covers two areas situated immediately to the north and southeast of the existing Dudgeon offshore wind farm, approximately 31 km from the shore at its closest point and with an expected capacity of 402 MW from between 18 and 34 WTGs. The locations of the two wind farm sites are shown in Figure 1-1.

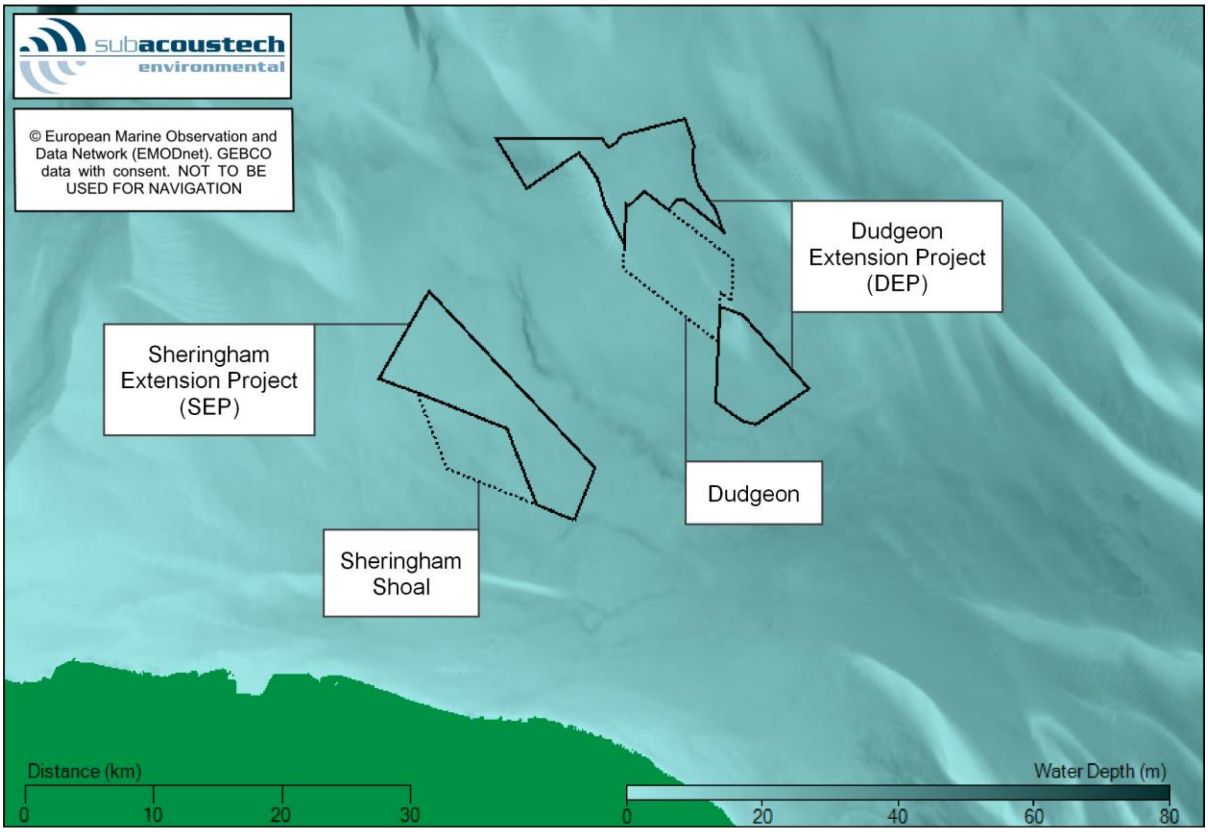

Figure 1-1 Overview map showing the SEP and DEP site boundaries (solid lines) as well as the original Sheringham Shoal and Dudgeon offshore wind farms (dotted lines)

This report presents a detailed assessment of the potential underwater noise and its effects during construction and operation of the SEP and DEP wind farms, and covers the following:

- A review of background information on 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 noise modelling undertaken (Section 3);
- Presentation and interpretation of the detailed subsea noise modelling for impact piling with regards to the effects in marine mammals and fish using various metrics and criteria (Section 4);
- Noise modelling of the other noise sources expected around construction and operation of the wind farms including cable laying, trenching, rock placement, drilling, dredging, vessel noise, operational WTG noise and UXO detonation (Section 5); and
- Summary and conclusions (Section 6).

Further modelling results for single strike noise levels are provided in Appendix A of this report.

2 Background to underwater noise metrics

2.1 Underwater noise

2.1.1 Background

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. As an example, background noise levels in the sea of 130 dB re 1 µPa for UK coastal waters are not uncommon (Nedwell *et al*. 2003 and 2007).

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

2.1.2 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, for instance, an increase of 6 dB can be interpreted as "twice as much as…" (although this is a simplistic description). 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.

A refinement is that the scale, when used with sound pressure, is applied to the pressure squared rather than just the pressure. If this were not the case, when the acoustic power level of a source rose by 10 dB the sound pressure would rise by 20 dB. So that variations in the units agree, the sound pressure must be specified as units of Root Mean Square (RMS) pressure squared. This is equivalent to expressing the sound as:

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

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

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

2.1.2.1 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).

2.1.2.2 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 2.1.2).

2.1.2.3 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 and 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 has to 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).

2.2 Analysis of environmental effects

2.2.1 Background

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 at the SEP and DEP wind farm sites.

2.2.2 Criteria to be used

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 noise exposure criteria;
- Lucke *et al*. (2009) TTS and behavioural thresholds for harbour porpoise; and
- Popper *et al*. (2014) sound exposure guidelines for fishes.

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

2.2.2.1 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 categories of similar species and applies filters to the unweighted noise to approximate the hearing sensitivities of the receptor. The hearing groups given in 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 also given, but these have not been used for this study as those species are not commonly found in the North Sea.

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)

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

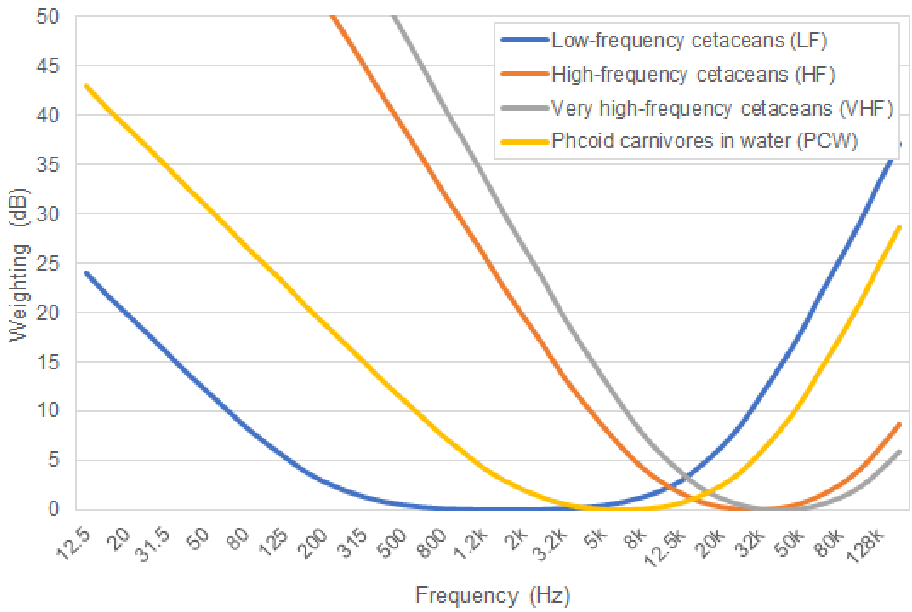

Figure 2-1 Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al., 2019)

Southall *et al*. (2019) also gives individual criteria based on whether the noise source is considered impulsive or non-impulsive. Southall *et al*. 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 (i.e. more than a single sound impulse) weighted sound exposure criteria (SEL_{cum}) for both permanent threshold shift (PTS), where unrecoverable hearing damage may occur, and temporary threshold shift (TTS), where a temporary reduction in hearing sensitivity may occur in individual receptors.

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 this. 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. However, 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. To provide as much detail as possible, both impulsive and non-impulsive criteria from Southall *et al.* (2019) have been included in this study.

Table 2-2 and Table 2-3 present the Southall *et al*. (2019) criteria for the onset of PTS and TTS risk for each of the key marine mammal hearing groups considering impulsive and non-impulsive sources.

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

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

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

Where SEL_{cum} 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. For this, 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. The fleeing animal model and the assumptions related to it are discussed in more detail in section 3.3.3.

It is worth noting that, with regards to the criteria from NMFS (2018), although numerically identical to Southall *et al.* (2019), the guidance applies different names to the marine mammal groups and weightings. 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 describe different species depending on which study is being used.

Additionally, unweighted impulsive single-strike criteria from Lucke *et al*. (2009) have also been included as part of this study covering TTS and behavioural thresholds for harbour porpoise, which are based on impulsive seismic airgun stimuli. The criteria are given as unweighted peak-to-peak SPLs and unweighted single strike SELs.

- TTS in harbour porpoise at 199.7 dB re 1 µPa ($SPL_{peak\text{-}to\text{-}peak}$), and 164.3 dB re 1 µPa^{2}s (SEL_{ss}); and
- Aversive behavioural reaction in harbour porpoise at 174 dB re 1 µPa ($SPL_{peak\text{-}to\text{-}peak}$), and 145 dB re 1 µPa^{2}s (SEL_{ss})

2.2.2.2 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), 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. A further set of criteria also exists for turtles, which have not been included as part of this study as they are not expected to be present at the site.

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.

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

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	Impairment	
	Recoverable injury	TTS
Fish: swim bladder involved in hearing	170 dB RMS for 48 hrs	158 dB RMS For 12 hrs

Table 2-5 Criteria for recoverable injury and TTS in species of fish from continuous noise sources (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 involving in hearing	229 – 234 dB peak
Eggs and larvae	> 13 mm s^{-1} peak velocity

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

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.

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 involving in hearing	See Table 2-4	See Table 2-4	(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate
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 2-7 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	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 involving 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
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 2-8 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	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 involving in hearing	(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

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)

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 fishes 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.

3 Modelling methodology

3.1 Introduction

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

The modelling of impact piling has been undertaken using the INSPIRE noise model. The INSPIRE model (currently version 5.1) is a semi-empirical underwater noise propagation model based around a combination of numerical modelling 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 SEP and DEP. 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 content to ensure accurate results are produced specific to the location and nature of the piling operation. It should also be noted that the results presented in this study 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 the lifecycle of SEP and DEP. These are discussed in section 5.

3.2 Modelling confidence

Previous iterations of the INSPIRE model have endeavoured to give a conservative estimate of underwater noise levels from impact piling. There is always some variability with underwater noise measurements, even when considering measurements of pile strikes at the same blow energy taken at the same range. For example, there can be big variations in noise level, sometimes up to 5 or even 10 dB, as seen in Bailey *et al*. (2010) and the data shown in Figure 3-1. When using a such an approach, conservatism can be compounded and create overcautious predictions; for example, calculating SEL_{cum}. With this in mind, the current version of the INSPIRE model attempts to calculate an average fit to the measured noise levels at all ranges.

The current version of INSPIRE 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, giving a database of single strike noise levels referenced to a specific blow energy at a specific range. This re-analysis showed that the previous versions of INSPIRE could overestimate the change in noise level with higher blow energies and underestimate levels at lower blow energies, which in some cases led to overestimations in predicted levels.

As INSPIRE is semi-empirical, 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, a average fit is used. This is the same process that has been used for previous iterations of INSPIRE, and with each new version more measurement data is included.

In addition, INSPIRE is also validated by comparing the noise levels outputted from the model with measurements and modelling undertaken by third parties.

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 average fit to data, with the INSPIRE modelled data points sitting, more or less, in the middle of the measured noise levels at each range.

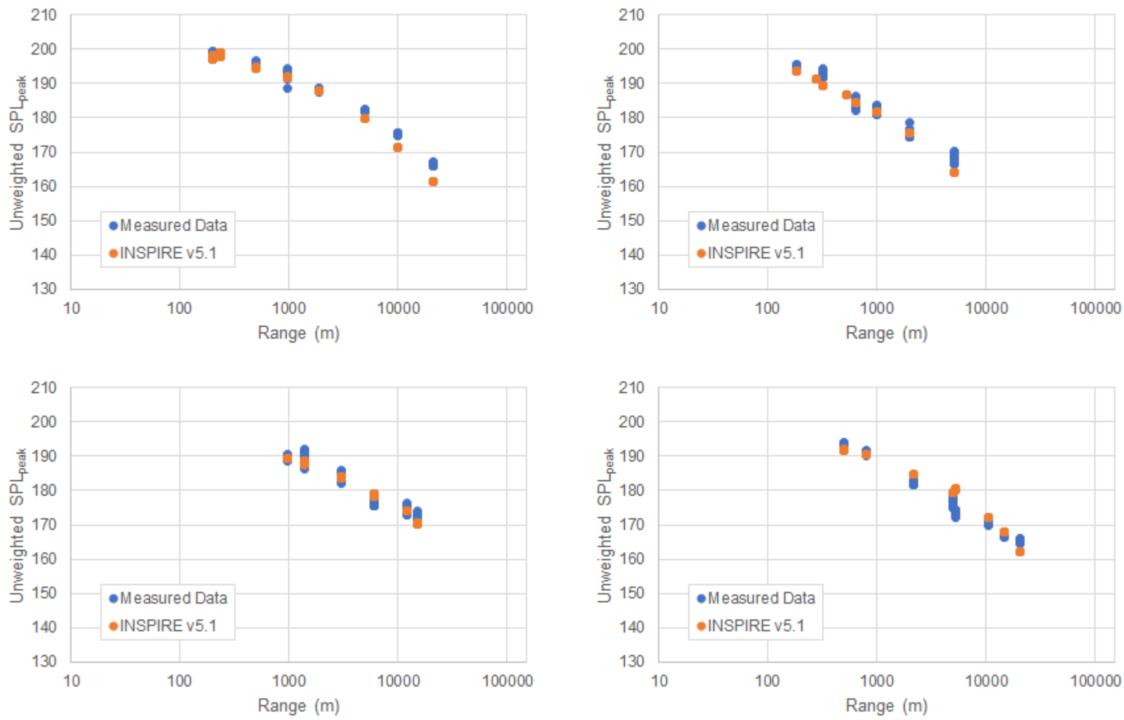

Figure 3-1 Comparison between example measured data (blue points) and modelled data using INSPIRE version 5.0 (orange points)

3.3 Modelling parameters

3.3.1 Modelling locations

Modelling has been undertaken at four representative locations, covering the extents of the SEP and DEP sites, with two positions modelled at each site. The eastern and northern corners were chosen for the SEP and the north eastern corner of the north part of the DEP and the south eastern corner of the southern part of the DEP were chosen for modelling. These locations are summarised in Table 3-1 and illustrated in Figure 3-2.

Modelling locations	SEP		DEP	
	East (E)	North (N)	North east (NE)	South east (SE)
Latitude	53.1219°N	53.2446° N	53.3657°N	53.1775°N
Longitude	001.2841°E	001.0920°E	001.3897°E	001.5335°E
Water depth (mean tide)	21.3 m	18.6 m	23.2 m	25.5 m

Table 3-1 Summary of the underwater noise modelling locations at the SEP and DEP sites

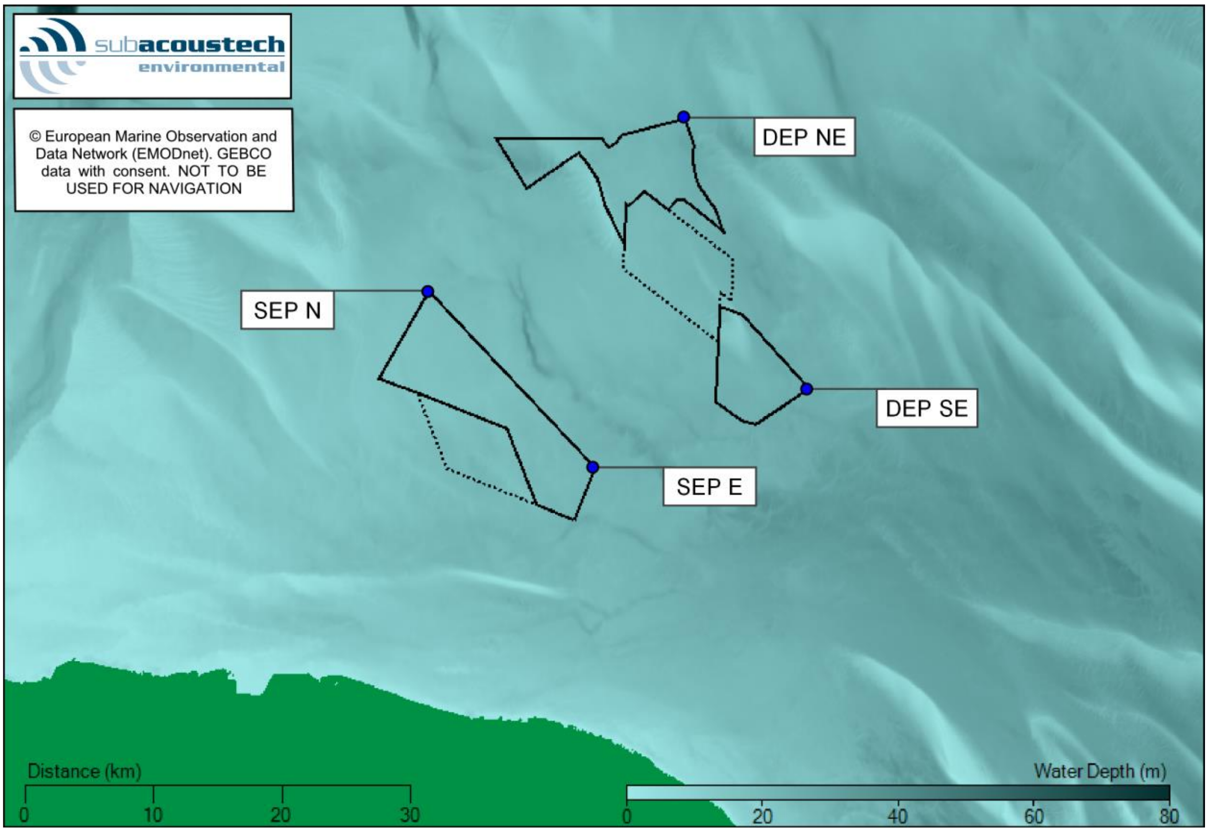

Figure 3-2 Approximate positions of the modelling locations at the SEP and DEP sites

3.3.2 Impact piling parameters

A selection of piling scenarios have been modelled including monopile and pin pile foundations for WTGs, covering both worst case and most likely installation scenarios. The worst case installation scenarios consider the maximum possible piling durations and blow energies at the end of ramp up, which may prove to be highly unrealistic due to hammer capacity or pile fatigue. The most likely scenarios use more realistic blow energies and durations, which have been chosen based on what has been seen at other wind farm installations. The modelled scenarios include:

- Monopile worst case – up to 16 m in diameter, installed using a maximum blow energy of 5,500 kJ;
- Worst case pin pile – up to 3.5 m in diameter, installed using a maximum blow energy of 3,000 kJ; and
- Most likely monopile – up to 16 m in diameter, installed using a maximum blow energy of 4,500 kJ.

A most likely pin pile scenario has not been included following discussions with SEP and DEP engineers after receipt of the worst case pin pile results.

For SEL_{cum}, the soft start and ramp up of blow energies along with the total duration and strike rate must also be considered; these vary for the worst case and most likely scenarios. The soft start and ramp up scenarios for this modelling are summarised in Table 3-2 to Table 3-4. The main difference between the worst case and most likely scenarios are that the most likely scenario uses lower blow energies and utilises a soft start procedure whereby single blows of the piling hammer occur at low energy, interspersed with pauses of several minutes before commencing a more continuous strike rate, before ramping up to maximum energy.

The modelled scenarios contain a total of 9,250 strikes over 4 hours for the worst case monopile scenario, 6,600 strikes over 3 hours for the worst case pin piles, and 7,004 strikes over 3 hours and 10 minutes.

Monopile worst case	**1,000 kJ**	**1,500 kJ**	**2,500 kJ**	**3,500 kJ**	**4,500 kJ**	**5,500 kJ**
Number of strikes	1,350	2,400	1,600	1,200	1,350	1,350
Duration	30 mins	40 mins	40 mins	40 mins	45 mins	45 mins
Strikes per minute	45 str/min	60 str/min	40 str/min	30 str/min	30 str/min	30 str/min

Table 3-2 Summary of the worst case ramp up scenario used for calculating SEL_{cum} for monopiles

Pin pile worst case	**400 kJ**	**920 kJ**	**1,440 kJ**	**1,960 kJ**	**2,480 kJ**	**3,000 kJ**
Number of strikes	1,200	1,200	1,200	1,200	900	900
Duration	30 mins	30 mins	30 mins	30 mins	30 mins	30 mins
Strikes per minute	40 str/min	40 str/min	40 str/min	40 str/min	30 str/min	30 str/min

Table 3-3 Summary of the worst case ramp up scenario used for calculating SEL_{cum} for pin piles

Monopile most likely	**600 kJ**	**600 kJ**	**1,500 kJ**	**2,500 kJ**	**3,500 kJ**	**4,500 kJ**
Number of strikes	4	900	2,400	1,600	1,200	900
Duration	20 mins	20 mins	40 mins	40 mins	40 mins	30 mins
Strike rate	1 strike per 5 mins	45 str/min	60 str/min	40 str/min	30 str/min	30 str/min

Table 3-4 Summary of the most likely ramp up scenario used for calculating SEL_{cum} for monopiles

3.3.2.1 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 a single point, as it will appear at a distance. The source level is estimated based on the pile diameter and the blow energy imparted on the pile by the hammer. This is then adjusted depending on the water depth at the modelling location to allow for the length of pile 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} source levels estimated for this study are provided in Table 3-5 and Table 3-6. In general, the source levels for the different locations do not show much differentiation, due to the relative uniformity of all the water depths at the source locations (Table 3-1; 18.6 m to 25.5 m).

SPL_{peak} source levels (dB re 1 µPa @ 1 m)	**Site**	**Location**	**Monopile**	**Pin pile**
Worst case Monopile: 16 m / 5,500 kJ Pin pile: 3.5 m / 3,000 kJ	SEP	E	242.9	241.4
		N	242.9	241.4
	DEP	NE	242.9	241.5
		SE	242.9	241.5
Most Likely Monopile: 16 m / 4,500 kJ	SEP	E	242.6	
		N	242.6	
	DEP	NE	242.6	
		SE	242.6	

Table 3-5 Summary of the unweighted SPL_{peak} source levels used for modelling

SEL_{ss} source levels (dB re 1 µPa²s @ 1 m)	Site	Location	Monopile	Pin pile
Worst case Monopile: 16 m / 5,500 kJ Pin pile: 3.5 m / 3,000 kJ	SEP	E	224.1	222.1
		N	224.1	222.0
	DEP	NE	224.1	222.1
		SE	224.1	222.2
Most Likely Monopile: 16 m / 4,500 kJ	SEP	E	223.7	
		N	223.7	
	DEP	NE	223.7	
		SE	223.7	

Table 3-6 Summary of the unweighted SEL_{ss} source levels used for modelling

3.3.2.2 Environmental conditions

With the inclusion of measured 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 water as well as the sediment type surrounding the site. Data from the European Marine Observation and Data Network (EMODnet) geology study show that the seabed surrounding the SEP and DEP sites are generally made up of sand and sandy gravel.

Digital bathymetry, also from the EMODnet, has been used for this modelling; mean tidal depth has been used throughout.

3.3.3 Cumulative SELs and fleeing receptors

Expanding on the information in section 2.2.2 regarding SEL_{cum} and the fleeing animal model used for modelling, it is important to understand what the results presented in the following sections mean.

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 receptor. For example, if a receptor starting at a position denoted on a PTS contour began to flee, in a straight line, away from the noise source, 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 2.1.2.3, the SEL_{cum} is a measure of the total received noise over the whole piling operation; in the case of the Southall *et al*. (2019) and Popper *et al*. (2014) criteria this covers any piling a 24-hour period.

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

For a fleeing animal, the receptor's distance from the noise source while fleeing needs to be considered. To model this, a starting point close to the source is chosen, and then the received noise level for each pile strike while the receptor is fleeing is noted. If, for example, a pile strike occurs every 6 seconds and an animal is fleeing at a rate of 1.5 ms^{-1}, it is 9 m further from the source at a subsequent pile strike, resulting in a slightly reduced received noise level with each strike. These values are then aggregated into an SEL_{cum} over the entire piling period. The faster an animal is fleeing the greater distance travelled between each pile strike. The impact range outputted by the model for this situation is the distance the receptor must be at the start of piling to exactly meet the exposure threshold.

The graphs in Figure 3-3 and Figure 3-4 show the difference in the SELs received by a stationary receptor and a fleeing receptor travelling at a constant speed of 1.5 ms^{-1}, using the worst case monopile parameters (Table 3-2). This was carried out at the SEP East location as an example.

The received SEL_{ss} from a 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 is reduced, resulting in progressively lower received noise levels. For example, after the first 30 minutes where the blow energy is 1,000 kJ, the fleeing receptor will have already moved 2.7 km away. After the full piling duration of 4 hours the receptor will be over 21 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 219.2 dB re 1 µPa²s. If the receptor were to remain stationary throughout the 4 hours of piling it would receive a cumulative received level of 262.0 dB re 1 µPa²s, whereas fleeing at 1.5 ms^{-1} over the same piling scenario would result in a cumulative received level of just 221.9 dB re 1 µPa²s.

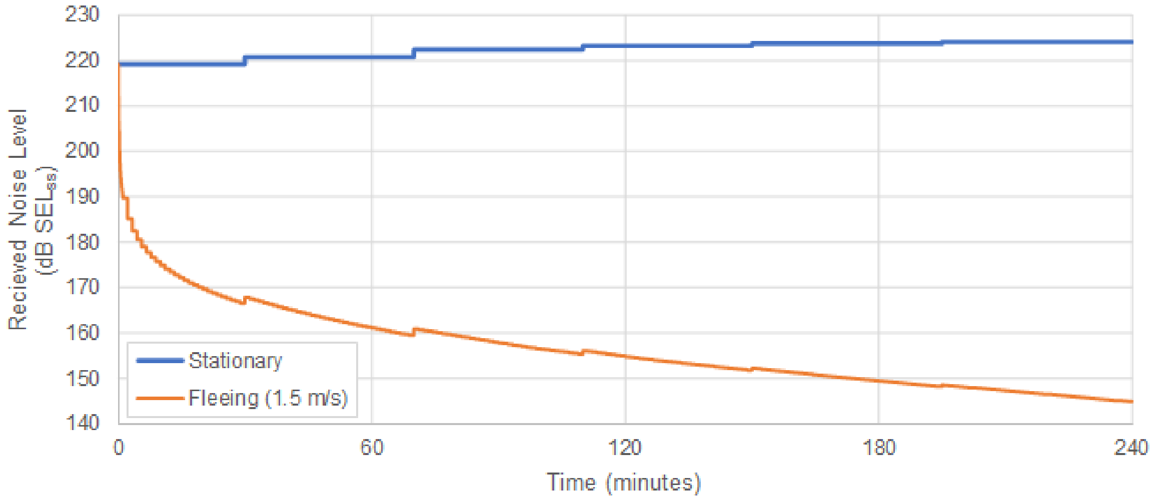

Figure 3-3 Received single-strike noise levels (SEL_{ss}) for receptors during the worst case monopile piling parameters assuming both a stationary and a fleeing receptor starting at a location 1 m from the noise source

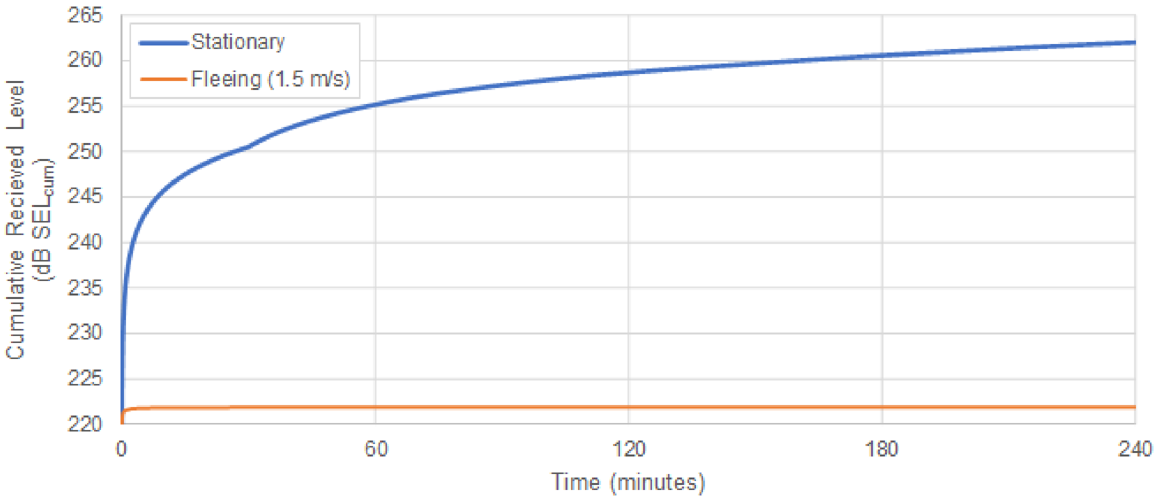

Figure 3-4 Cumulative received noise levels (SEL_{cum}) for receptors during the worst case monopile piling parameters assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source

The outputted SEL_{cum} values, and ranges presented in section 4, represent the position from where a receptor must begin fleeing at the start of piling in order to exactly receive the noise exposure criterion at the end of the modelled piling event. 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.

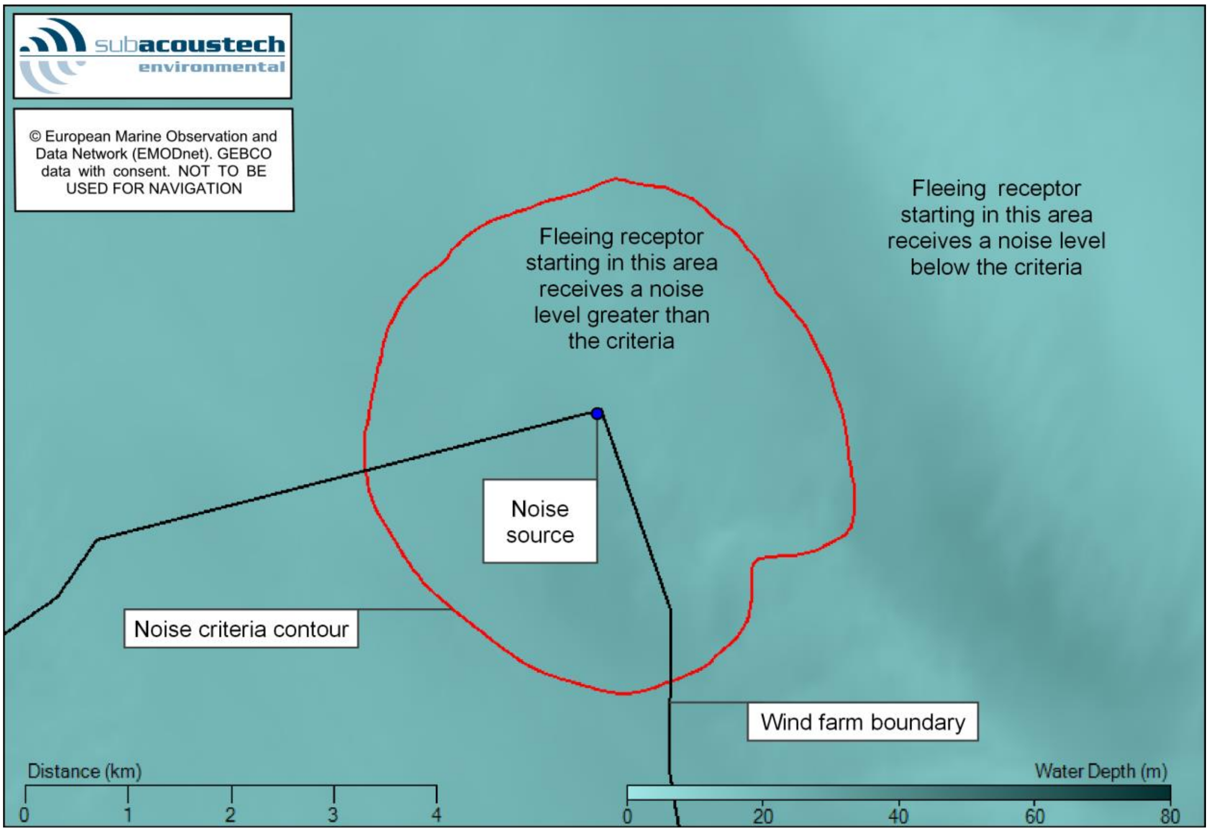

Figure 3-5 Example plot showing a fleeing animal SEL_{cum} criteria contour and the areas where the cumulative received level will exceed the criteria

Some modelling approaches include the effects of Acoustic Deterrent Devices (ADDs) that cause receptors to flee area certain distance before the piling activity commences. Subacoustech's modelling approach does not include this, but 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 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.

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

As discussed in section 3.3.2, parameters such as water depth, 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 energies 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 three modelled cumulative scenarios, showing how the monopile scenarios reach a higher blow energy over a greater total duration.

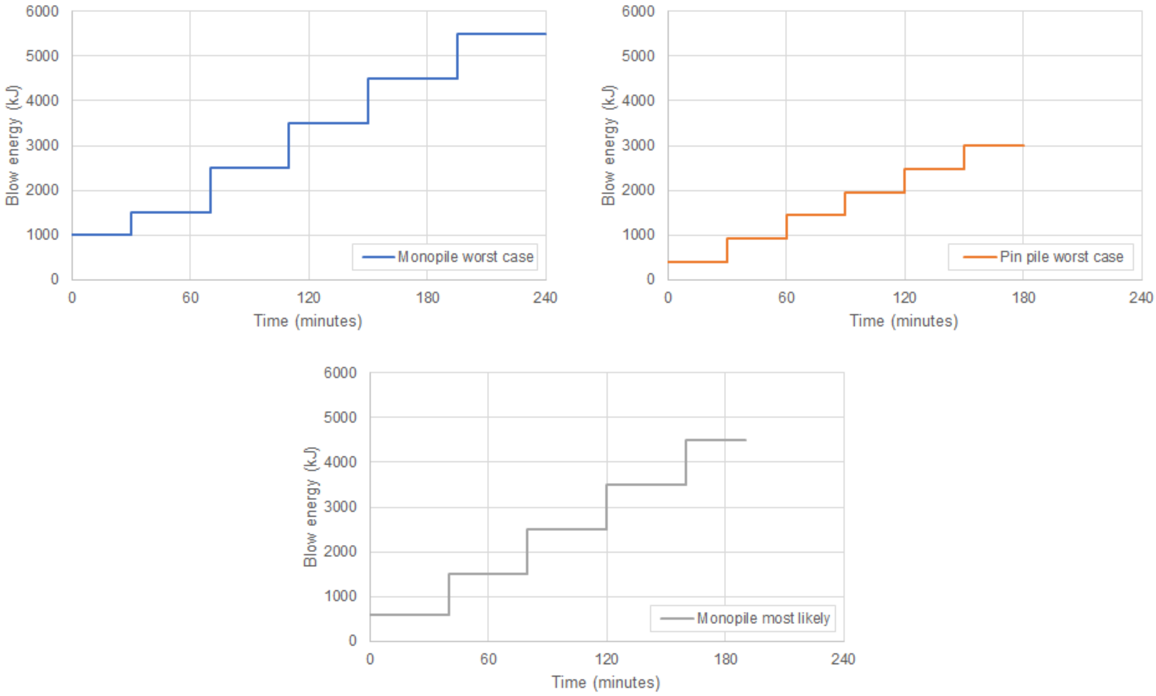

Figure 3-6 Graphical representation of the three modelled ramp up scenarios

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 shows the strike rate against time for the three modelled scenarios, with the fastest strike rates being achieved for the monopile scenarios as well as the slow "one strike every five minutes" period at the start of the monopile most likely scenario. The total duration of piling is less important when considering a fleeing animal as the additional pile strikes at the end of piling occur when the receptor has travelled to a greater distance, where noise levels will have reduced to a relatively low level. This can be seen in Figure 3-3 and Figure 3-4 in the previous section.

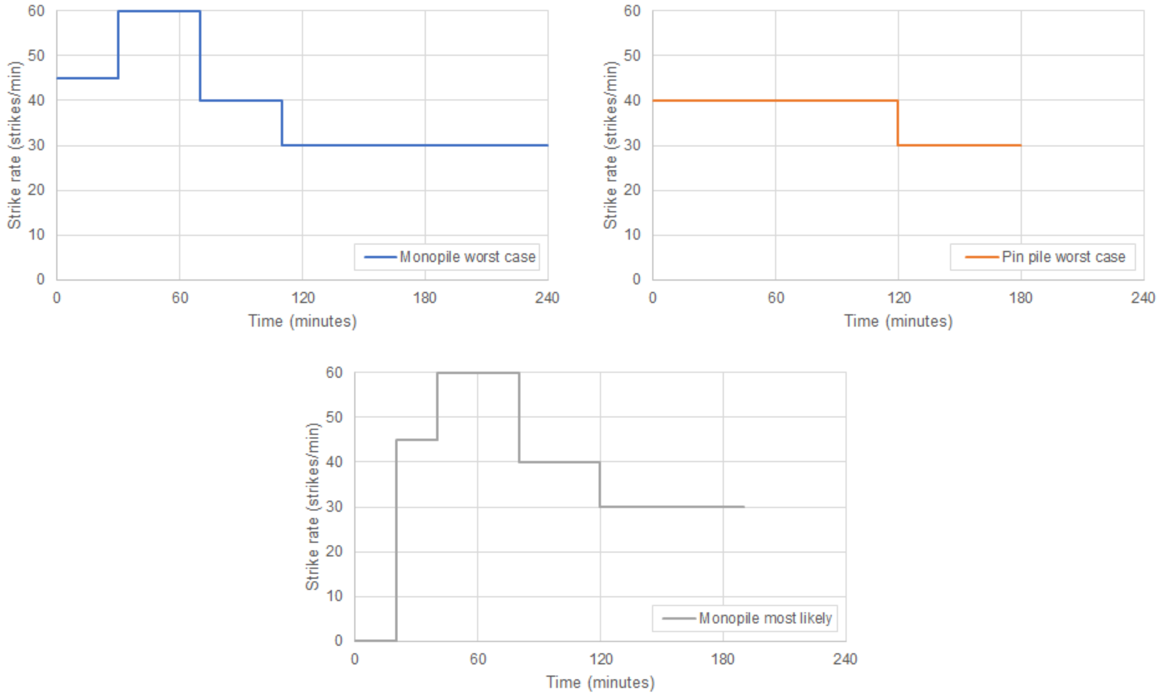

Figure 3-7 Graphical representation of the strike rate for the three modelled ramp up scenarios

4 Modelling results

The following sections present the modelled impact ranges for the parameters detailed in section 3.3 and the criteria outlined in section 2.2.2, split into the worst case parameters (section 4.1) and the most likely parameters (section 4.2). To aid navigation Table 4-1 and Table 4-34 contain a list of all the impact range tables for the worst case and most likely parameters, respectively. Further modelling has also been completed covering single strike noise criteria, and the noise from the first pile strike, these results are presented in Appendix A.

For the results presented in this section, 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. This close to the noise source, the modelling processes are unable to model a sufficient level of accuracy due to acoustic effects near the pile.

The largest ranges are predicted for the worst case monopile scenario, with smaller ranges predicted for the most likely monopile scenarios, and smaller ranges still for the pin pile scenarios. The SE location at the DEP resulted in the largest ranges due to the deeper water at, and surrounding, that location.

4.1 Worst case parameters

Table 4-2 to Table 4-33 present the worst case monopile results, covering the Southall *et al*. (2019) criteria for marine mammals and the Popper *et al*. (2014) criteria for fish, as discussed in section 2.2.2. These predicted impact ranges show that, for the worst case parameters, impact ranges for monopiles are greater than those predicted for pin piles.

Maximum PTS injury ranges in marine mammals of 8.3 km for LF cetaceans and 4.9 km for VHF cetaceans are predicted using the impulsive SEL_{cum} Southall *et al*. (2019) criteria at the SE location of the DEP. A maximum behavioural impact range of 25 km is predicted for aversive behavioural reaction in harbour porpoise using the Lucke *et al*. (2009) SEL criteria. For fish, a maximum fleeing range of 12 km (19 km stationary) is predicted for TTS using the Popper *et al*. (2014) criteria at the same location.

Lower ranges are predicted at the SEP site, with maximum ranges predicted of 6.2 km for PTS in LF cetaceans, 4.1 km for PTS in VHF cetaceans and 9.6 km for TTS in fleeing fish (16 km for stationary receptors), all at the deeper E location.

<table>
<tr><th>Table (page)</th><th colspan="3">Parameters</th><th colspan="2">Criteria</th></tr>
<tr><td>Table 4-2 (p21)</td><td>SEP</td><td rowspan="32">Worst case</td><td rowspan="10">Monopiles</td><td rowspan="6">Southall et al. (2019)</td><td rowspan="2">Unweighted SPL_{peak}</td></tr>
<tr><td>Table 4-3 (p22)</td><td>DEP</td></tr>
<tr><td>Table 4-4 (p22)</td><td>SEP</td><td rowspan="2">Weighted SEL_{cum} (impulsive)</td></tr>
<tr><td>Table 4-5 (p22)</td><td>DEP</td></tr>
<tr><td>Table 4-6 (p22)</td><td>SEP</td><td rowspan="2">Weighted SEL_{cum} (non-impulsive)</td></tr>
<tr><td>Table 4-7 (p23)</td><td>DEP</td></tr>
<tr><td>Table 4-8 (p23)</td><td>SEP</td><td rowspan="4">Lucke et al. (2009)</td><td rowspan="2">Unweighted $SPL_{peak\text{-}to\text{-}peak}$</td></tr>
<tr><td>Table 4-9 (p23)</td><td>DEP</td></tr>
<tr><td>Table 4-10 (p23)</td><td>SEP</td><td rowspan="2">Unweighted SEL_{ss}</td></tr>
<tr><td>Table 4-11 (p23)</td><td>DEP</td></tr>
<tr><td>Table 4-12 (p24)</td><td>SEP</td><td rowspan="10">Pin piles</td><td rowspan="6">Southall et al. (2019)</td><td rowspan="2">Unweighted SPL_{peak}</td></tr>
<tr><td>Table 4-13 (p24)</td><td>DEP</td></tr>
<tr><td>Table 4-14 (p24)</td><td>SEP</td><td rowspan="2">Weighted SEL_{cum} (impulsive)</td></tr>
<tr><td>Table 4-15 (p24)</td><td>DEP</td></tr>
<tr><td>Table 4-16 (p25)</td><td>SEP</td><td rowspan="2">Weighted SEL_{cum} (non-impulsive)</td></tr>
<tr><td>Table 4-17 (p25)</td><td>DEP</td></tr>
<tr><td>Table 4-18 (p25)</td><td>SEP</td><td rowspan="4">Lucke et al. (2009)</td><td rowspan="2">Unweighted $SPL_{peak\text{-}to\text{-}peak}$</td></tr>
<tr><td>Table 4-19 (p25)</td><td>DEP</td></tr>
<tr><td>Table 4-20 (p25)</td><td>SEP</td><td rowspan="2">Unweighted SEL_{ss}</td></tr>
<tr><td>Table 4-21 (p26)</td><td>DEP</td></tr>
<tr><td>Table 4-22 (p26)</td><td>SEP</td><td rowspan="6">Monopiles</td><td rowspan="12">Popper et al. (2014)</td><td rowspan="2">Unweighted SPL_{peak}</td></tr>
<tr><td>Table 4-23 (p26)</td><td>DEP</td></tr>
<tr><td>Table 4-24 (p26)</td><td>SEP</td><td rowspan="2">Unweighted SEL_{cum} (fleeing)</td></tr>
<tr><td>Table 4-25 (p26)</td><td>DEP</td></tr>
<tr><td>Table 4-26 (p27)</td><td>SEP</td><td rowspan="2">Unweighted SEL_{cum} (stationary)</td></tr>
<tr><td>Table 4-27 (p27)</td><td>DEP</td></tr>
<tr><td>Table 4-28 (p27)</td><td>SEP</td><td rowspan="6">Pin piles</td><td rowspan="2">Unweighted SPL_{peak}</td></tr>
<tr><td>Table 4-29 (p27)</td><td>DEP</td></tr>
<tr><td>Table 4-30 (p27)</td><td>SEP</td><td rowspan="2">Unweighted SEL_{cum} (fleeing)</td></tr>
<tr><td>Table 4-31 (p28)</td><td>DEP</td></tr>
<tr><td>Table 4-32 (p28)</td><td>SEP</td><td rowspan="2">Unweighted SEL_{cum} (stationary)</td></tr>
<tr><td>Table 4-33 (p28)</td><td>DEP</td></tr>
</table>

Table 4-1 Summary of the worst case modelling results tables presented in this section

4.1.1 Marine mammals

<table>
<tr><th colspan="2" rowspan="3">Southall et al. (2019)
Unweighted SPL_{peak}</th><th colspan="8">Worst case monopiles</th></tr>
<tr><th colspan="4">SEP E</th><th colspan="4">SEP N</th></tr>
<tr><th>Area</th><th>Max</th><th>Min</th><th>Mean</th><th>Area</th><th>Max</th><th>Min</th><th>Mean</th></tr>
<tr><td rowspan="4">PTS</td><td>219 dB (LF)</td><td>< 0.01 km^2</td><td>< 50 m</td><td>< 50 m</td><td>< 50 m</td><td>< 0.01 km^2</td><td>< 50 m</td><td>< 50 m</td><td>< 50 m</td></tr>
<tr><td>230 dB (HF)</td><td>< 0.01 km^2</td><td>< 50 m</td><td>< 50 m</td><td>< 50 m</td><td>< 0.01 km^2</td><td>< 50 m</td><td>< 50 m</td><td>< 50 m</td></tr>
<tr><td>202 dB (VHF)</td><td>0.82 km^2</td><td>510 m</td><td>510 m</td><td>510 m</td><td>0.68 km^2</td><td>470 m</td><td>460 m</td><td>470 m</td></tr>
<tr><td>218 dB (PCW)</td><td>< 0.01 km^2</td><td>< 50 m</td><td>< 50 m</td><td>< 50 m</td><td>< 0.01 km^2</td><td>50 m</td><td>50 m</td><td>50 m</td></tr>
<tr><td rowspan="4">TTS</td><td>213 dB (LF)</td><td>0.03 km^2</td><td>100 m</td><td>100 m</td><td>100 m</td><td>0.03 km^2</td><td>100 m</td><td>90 m</td><td>100 m</td></tr>
<tr><td>224 dB (HF)</td><td>< 0.01 km^2</td><td>< 50 m</td><td>< 50 m</td><td>< 50 m</td><td>< 0.01 km^2</td><td>< 50 m</td><td>< 50 m</td><td>< 50 m</td></tr>
<tr><td>196 dB (VHF)</td><td>4.2 km^2</td><td>1.2 km</td><td>1.1 km</td><td>1.2 km</td><td>3.4 km^2</td><td>1.1 km</td><td>1.0 km</td><td>1.0 km</td></tr>
<tr><td>212 dB (PCW)</td><td>0.04 km^2</td><td>120 m</td><td>120 m</td><td>120 m</td><td>0.04 km^2</td><td>110 m</td><td>110 m</td><td>110 m</td></tr>
</table>

Table 4-2 Summary of impact ranges from worst case monopile modelling at the SEP site using the Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al*. (2019) Unweighted SPL_{peak}		Worst case monopiles							
		DEP NE				**DEP SE**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS	219 dB (LF)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	230 dB (HF)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	202 dB (VHF)	0.91 km²	550 m	540 m	540 m	1.0 km²	570 m	570 m	570 m
	218 dB (PCW)	< 0.01 km²	50 m	50 m	50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS	213 dB (LF)	0.03 km²	110 m	100 m	110 m	0.04 km²	110 m	110 m	110 m
	224 dB (HF)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	196 dB (VHF)	4.7 km²	1.3 km	1.2 km	1.2 km	5.3 km²	1.3 km	1.3 km	1.3 km
	212 dB (PCW)	0.05 km²	120 m	120 m	120 m	0.05 km²	130 m	130 m	130 m

Table 4-3 Summary of impact ranges from worst case monopile modelling at the DEP site using the Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al*. (2019) Weighted SEL_{cum}		Worst case monopiles							
		SEP E				**SEP N**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	92 km²	6.2 km	4.8 km	5.4 km	55 km²	4.8 km	3.6 km	4.2 km
	185 dB (HF)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	155 dB (VHF)	43 km²	4.1 km	3.4 km	3.7 km	29 km²	3.4 km	2.8 km	3.1 km
	185 dB (PCW)	0.84 km²	600 m	500 m	500 m	0.52 km²	500 m	400 m	400 m
TTS (Impulsive)	168 dB (LF)	720 km²	20 km	12 km	15 km	470 km²	15 km	8.3 km	12 km
	170 dB (HF)	0.33 km²	400 m	300 m	300 m	0.27 km²	400 m	300 m	300 m
	140 dB (VHF)	530 km²	16 km	11 km	13 km	370 km²	13 km	7.8 km	11 km
	170 dB (PCW)	140 km²	7.7 km	6.0 km	6.8 km	91 km²	6.1 km	4.5 km	5.4 km

Table 4-4 Summary of impact ranges from worst case monopile modelling at the SEP site using the impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		Worst case monopiles							
		DEP NE				**DEP SE**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	100 km²	6.7 km	4.9 km	5.7 km	150 km²	8.3 km	5.7 km	6.9 km
	185 dB (HF)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	155 dB (VHF)	47 km²	4.4 km	3.6 km	3.9 km	61 km²	4.9 km	4.0 km	4.4 km
	185 dB (PCW)	1.1 km²	700 m	600 m	600 m	1.4 km²	700 m	600 m	700 m
TTS (Impulsive)	168 dB (LF)	750 km²	20 km	11 km	15 km	1100 km²	25 km	14 km	18 km
	170 dB (HF)	0.44 km²	400 m	400 m	400 m	0.44 km²	400 m	400 m	400 m
	140 dB (VHF)	540 km²	16 km	9.7 km	13 km	750 km²	19 km	12 km	15 km
	170 dB (PCW)	150 km²	8.1 km	6.0 km	7.0 km	220 km²	9.7 km	6.8 km	8.3 km

Table 4-5 Summary of impact ranges from worst case monopile modelling at the DEP site using the impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		Worst case monopiles							
		SEP E				**SEP N**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	0.24 km²	300 m	300 m	300 m	0.16 km²	300 m	200 m	200 m
	198 dB (HF)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	173 dB (VHF)	< 0.1 km²	200 m	100 m	100 m	< 0.1 km²	200 m	100 m	100 m
	201 dB (PCW)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	179 dB (LF)	190 km²	9.2 km	6.7 km	7.8 km	120 km²	7.0 km	5.1 km	6.1 km
	178 dB (HF)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	153 dB (VHF)	70 km²	5.2 km	4.3 km	4.7 km	47 km²	4.3 km	3.4 km	3.9 km
	181 dB (PCW)	5.8 km²	1.5 km	1.3 km	1.4 km	3.5 km²	1.2 km	1.0 km	1.1 km

Table 4-6 Summary of impact ranges from worst case monopile modelling at the SEP site using the non-impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Worst case monopiles							
		DEP NE				**DEP SE**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	0.28 km^2	400 m	300 m	300 m	0.37 km^2	400 m	300 m	300 m
	198 dB (HF)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	173 dB (VHF)	< 0.1 km^2	200 m	100 m	100 m	< 0.1 km^2	200 m	100 m	100 m
	201 dB (PCW)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	179 dB (LF)	200 km^2	9.7 km	6.6 km	8.0 km	300 km^2	12 km	7.6 km	9.8 km
	178 dB (HF)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	153 dB (VHF)	74 km^2	5.5 km	4.4 km	4.9 km	98 km^2	6.3 km	4.9 km	5.6 km
	181 dB (PCW)	7.2 km^2	1.7 km	1.4 km	1.5 km	9.6 km^2	1.9 km	1.7 km	1.8 km

Table 4-7 Summary of impact ranges from worst case monopile modelling at the DEP site using the non-impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing animal

Lucke *et al.* (2009) Unweighted $SPL_{peak\text{-}to\text{-}peak}$	Worst case monopiles							
	SEP E				**SEP N**			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (199.7 dB)	0.25 km^2	290 m	280 m	290 m	0.29 km^2	310 m	300 m	310 m
Behavioural (174 dB)	96 km^2	6.0 km	5.2 km	5.5 km	130 km^2	7.0 km	6.1 km	6.5 km

Table 4-8 Summary of impact ranges from worst case monopile modelling at the SEP site using the Lucke et al. (2009) unweighted $SPL_{peak\text{-}to\text{-}peak}$ criteria for harbour porpoise

Lucke *et al.* (2009) Unweighted $SPL_{peak\text{-}to\text{-}peak}$	Worst case monopiles							
	DEP NE				**DEP SE**			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (199.7 dB)	0.33 km^2	330 m	320 m	330 m	0.35 km^2	340 m	330 m	340 m
Behavioural (174 dB)	140 km^2	7.5 km	6.2 km	6.7 km	170 km^2	8.0 km	6.9 km	7.4 km

Table 4-9 Summary of impact ranges from worst case monopile modelling at the DEP site using the Lucke et al. (2009) unweighted $SPL_{peak\text{-}to\text{-}peak}$ criteria for harbour porpoise

Lucke *et al.* (2009) Unweighted SEL_{ss}	Worst case monopiles							
	SEP E				**SEP N**			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (164.3 dB)	66 km^2	4.9 km	4.3 km	4.6 km	90 km^2	5.7 km	5.1 km	5.4 km
Behavioural (145 dB)	700 km^2	17 km	10 km	15 km	980 km^2	21 km	15 km	18 km

Table 4-10 Summary of impact ranges from worst case monopile modelling at the SEP site using the Lucke et al. (2009) unweighted SEL_{ss} criteria for harbour porpoise

Lucke *et al.* (2009) Unweighted SEL_{ss}	Worst case monopiles							
	DEP NE				**DEP SE**			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (164.3 dB)	100 km^2	6.2 km	5.3 km	5.6 km	120 km^2	6.5 km	5.9 km	6.2 km
Behavioural (145 dB)	1000 km^2	22 km	13 km	18 km	1400 km^2	25 km	16 km	21 km

Table 4-11 Summary of impact ranges from worst case monopile modelling at the DEP site using the Lucke et al. (2009) unweighted SEL_{ss} criteria for harbour porpoise

Southall *et al.* (2019) Unweighted SPL_{peak}		Worst case pin piles							
		SEP E				**SEP N**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS	219 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	230 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	202 dB (VHF)	0.54 km^2	420 m	420 m	420 m	0.45 km^2	380 m	380 m	380 m
	218 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	213 dB (LF)	0.02 km^2	80 m	80 m	80 m	0.02 km^2	80 m	80 m	80 m
	224 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	196 dB (VHF)	2.9 km^2	960 m	950 m	960 m	2.3 km^2	870 m	840 m	860 m
	212 dB (PCW)	0.03 km^2	100 m	90 m	100 m	0.02 km^2	90 m	90 m	90 m

Table 4-12 Summary of impact ranges from worst case pin pile modelling at the SEP site using the Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al.* (2019) Unweighted SPL_{peak}		Worst case pin piles							
		DEP NE				**DEP SE**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS	219 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	230 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	202 dB (VHF)	0.6 km^2	440 m	440 m	440 m	0.67 km^2	470 m	460 m	460 m
	218 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	213 dB (LF)	0.02 km^2	90 m	80 m	90 m	0.02 km^2	90 m	90 m	90 m
	224 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	196 dB (VHF)	3.2 km^2	1.0 km	1.0 km	1.0 km	3.7 km^2	1.1 km	1.1 km	1.1 km
	212 dB (PCW)	0.03 km^2	100 m	100 m	100 m	0.03 km^2	100 m	100 m	100 m

Table 4-13 Summary of impact ranges from worst case pin pile modelling at the DEP site using the Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al.* (2019) Weighted SEL_{cum}		Worst case pin piles							
		SEP E				**SEP N**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	18 km^2	2.7 km	2.1 km	2.4 km	9.6 km^2	2.0 km	1.6 km	1.8 km
	185 dB (HF)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	155 dB (VHF)	8.5 km^2	1.8 km	1.5 km	1.6 km	5.5 km^2	1.5 km	1.2 km	1.3 km
	185 dB (PCW)	< 0.1 km^2	200 m	100 m	100 m	< 0.1 km^2	200 m	100 m	100 m
TTS (Impulsive)	168 dB (LF)	370 km^2	14 km	9.1 km	11 km	230 km^2	10 km	6.5 km	8.5 km
	170 dB (HF)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	200 m	100 m	100 m
	140 dB (VHF)	300 km^2	12 km	8.4 km	9.7 km	200 km^2	9.2 km	6.0 km	8.0 km
	170 dB (PCW)	55 km^2	4.8 km	3.8 km	4.2 km	32 km^2	3.7 km	2.8 km	3.2 km

Table 4-14 Summary of impact ranges from worst case pin pile modelling at the SEP site using the impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Worst case pin piles							
		DEP NE				**DEP SE**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	22 km^2	3.1 km	2.4 km	2.6 km	33 km^2	3.8 km	2.8 km	3.2 km
	185 dB (HF)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	155 dB (VHF)	9.9 km^2	2.0 km	1.7 km	1.8 km	13 km^2	2.3 km	1.9 km	2.0 km
	185 dB (PCW)	< 0.1 km^2	200 m	200 m	200 m	< 0.1 km^2	200 m	200 m	200 m
TTS (Impulsive)	168 dB (LF)	390 km^2	14 km	8.4 km	11 km	590 km^2	18 km	10 km	14 km
	170 dB (HF)	< 0.1 km^2	200 m	100 m	100 m	< 0.1 km^2	200 m	100 m	100 m
	140 dB (VHF)	310 km^2	12 km	7.5 km	9.9 km	440 km^2	15 km	9.3 km	12 km
	170 dB (PCW)	62 km^2	5.2 km	3.9 km	4.4 km	90 km^2	6.3 km	4.5 km	5.3 km

Table 4-15 Summary of impact ranges from worst case pin pile modelling at the DEP site using the impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Worst case pin piles							
		SEP E				SEP N			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	198 dB (HF)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	173 dB (VHF)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	201 dB (PCW)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	179 dB (LF)	55 km^2	4.8 km	3.7 km	4.2 km	31 km^2	3.6 km	2.7 km	3.1 km
	178 dB (HF)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	153 dB (VHF)	18 km^2	2.6 km	2.2 km	2.4 km	11 km^2	2.1 km	1.7 km	1.9 km
	181 dB (PCW)	0.57 km^2	500 m	400 m	500 m	0.33 km^2	400 m	300 m	300 m

Table 4-16 Summary of impact ranges from worst case pin pile modelling at the SEP site using the non-impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Worst case pin piles							
		DEP NE				DEP SE			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	198 dB (HF)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	173 dB (VHF)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	201 dB (PCW)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	179 dB (LF)	63 km^2	5.3 km	3.9 km	4.5 km	96 km^2	6.8 km	4.6 km	5.5 km
	178 dB (HF)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	153 dB (VHF)	20 km^2	2.9 km^2	2.3 km	2.5 km	27 km^2	3.3 km	2.6 km	2.9 km
	181 dB (PCW)	0.73 km^2	600 m	500 m	500 m	1.0 km^2	600 m	500 m	600 m

Table 4-17 Summary of impact ranges from worst case pin pile modelling at the DEP site using the non-impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing animal

Lucke *et al.* (2009) Unweighted $SPL_{peak\text{-}to\text{-}peak}$	Worst case pin piles							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (199.7 dB)	0.17 km^2	240 m	230 m	240 m	0.2 km^2	260 m	250 m	260 m
Behavioural (174 dB)	77 km^2	5.3 km	4.7 km	5.0 km	110 km^2	6.3 km	5.5 km	5.8 km

Table 4-18 Summary of impact ranges from worst case pin pile modelling at the SEP site using the Lucke et al. (2009) unweighted $SPL_{peak\text{-}to\text{-}peak}$ criteria for harbour porpoise

Lucke *et al.* (2009) Unweighted $SPL_{peak\text{-}to\text{-}peak}$	Worst case pin piles							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (199.7 dB)	0.22 km^2	270 m	260 m	270 m	0.24 km^2	280 m	270 m	280 m
Behavioural (174 dB)	120 km^2	6.8 km	5.6 km	6.1 km	140 km^2	7.2 km	6.4 km	6.7 km

Table 4-19 Summary of impact ranges from worst case pin pile modelling at the DEP site using the Lucke et al. (2009) unweighted $SPL_{peak\text{-}to\text{-}peak}$ criteria for harbour porpoise

Lucke *et al.* (2009) Unweighted SEL_{ss}	Worst case pin piles							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (164.3 dB)	46 km^2	4.1 km	3.6 km	3.8 km	63 km^2	4.7 km	4.3 km	4.5 km
Behavioural (145 dB)	590 km^2	16 km	9.9 km	14 km	820 km^2	19 km	14 km	16 km

Table 4-20 Summary of impact ranges from worst case pin pile modelling at the SEP site using the Lucke et al. (2009) unweighted SEL_{ss} criteria for harbour porpoise

Lucke *et al*. (2009) Unweighted SEL_{ss}	Worst case pin piles							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (164.3 dB)	71 km²	5.1 km	4.5 km	4.8 km	84 km²	5.4 km	5.0 km	5.2 km
Behavioural (145 dB)	850 km²	20 km	12 km	16 km	1100 km²	23 km	15 km	19 km

Table 4-21 Summary of impact ranges from worst case pin pile modelling at the DEP site using the Lucke et al. (2009) unweighted SEL_{ss} criteria for harbour porpoise

4.1.2 Fish

Popper *et al*. (2014) Unweighted SPL_{peak}	Worst case monopiles							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
213 dB	0.03 km²	100 m	100 m	100 m	0.03 km²	100 m	90 m	100 m
207 dB	0.19 km²	250 m	250 m	250 m	0.16 km²	230 m	230 m	230 m

Table 4-22 Summary of impact ranges from worst case monopile modelling at the SEP site using the Popper et al. (2014) unweighted SPL_{peak} criteria for fish

Popper *et al*. (2014) Unweighted SPL_{peak}	Worst case monopiles							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
213 dB	0.03 km²	110 m	100 m	110 m	0.04 km²	110 m	110 m	110 m
207 dB	0.21 km²	260 m	260 m	260 m	0.23 km²	270 m	270 m	270 m

Table 4-23 Summary of impact ranges from worst case monopile modelling at the DEP site using the Popper et al. (2014) unweighted SPL_{peak} criteria for fish

Popper *et al*. (2014) Unweighted SEL_{cum}	Worst case monopiles							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB (fleeing)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
216 dB (fleeing)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
210 dB (fleeing)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
207 dB (fleeing)	< 0.1 km²	200 m	200 m	200 m	< 0.1 km²	200 m	200 m	200 m
203 dB (fleeing)	1.1 km²	600 m	600 m	600 m	0.62 km²	500 m	400 m	500 m
186 dB (fleeing)	210 km²	9.6 km	7.2 km	8.3 km	140 km²	7.5 km	5.3 km	6.5 km

Table 4-24 Summary of impact ranges from worst case monopile modelling at the SEP site using the Popper et al. (2014) unweighted SEL_{cum} criteria for fish assuming a fleeing animal

Popper *et al*. (2014) Unweighted SEL_{cum}	Worst case monopiles							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB (fleeing)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
216 dB (fleeing)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
210 dB (fleeing)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	200 m	100 m	100 m
207 dB (fleeing)	0.16 km²	300 m	200 m	200 m	0.16 km²	300 m	200 m	200 m
203 dB (fleeing)	1.4 km²	800 m	600 m	700 m	1.9 km²	900 m	800 m	800 m
186 dB (fleeing)	230 km²	10 km	6.9 km	8.5 km	330 km²	12 km	8.1 km	10 km

Table 4-25 Summary of impact ranges from worst case monopile modelling at the DEP site using the Popper et al. (2014) unweighted SEL_{cum} criteria for fish assuming a fleeing animal

Popper *et al*. (2014) Unweighted SEL_{cum}	Worst case monopiles							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB (stationary)	1.2 km^2	700 m	600 m	600 m	1.0 km^2	600 m	600 m	600 m
216 dB (stationary)	2.7 km^2	1.0 km	900 m	900 m	2.1 km^2	900 m	800 m	800 m
210 dB (stationary)	12 km^2	2.0 km	1.9 km	2.0 km	9.4 km^2	1.8 km	1.7 km	1.7 km
207 dB (stationary)	24 km^2	2.8 km	2.7 km	2.8 km	19 km^2	2.6 km	2.3 km	2.4 km
203 dB (stationary)	55 km^2	4.4 km	4.1 km	4.2 km	42 km^2	3.9 km	3.5 km	3.6 km
186 dB (stationary)	620 km^2	16 km	12 km	14 km	450 km^2	13 km	9.2 km	12 km

Table 4-26 Summary of impact ranges from worst case monopile modelling at the SEP site using the Popper et al. (2014) unweighted SEL_{cum} criteria for fish assuming a stationary animal

Popper *et al*. (2014) Unweighted SEL_{cum}	Worst case monopiles							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB (stationary)	1.3 km^2	700 m	600 m	700 m	1.4 km^2	700 m	700 m	700 m
216 dB (stationary)	3.0 km^2	1.0 km	1.0 km	1.0 km	3.3 km^2	1.1 km	1.0 km	1.0 km
210 dB (stationary)	14 km^2	2.2 km	2.0 km	2.1 km	15 km^2	2.3 km	2.2 km	2.2 km
207 dB (stationary)	28 km^2	3.2 km	2.8 km	3.0 km	31 km^2	3.3 km	3.1 km	3.2 km
203 dB (stationary)	63 km^2	4.8 km	4.3 km	4.5 km	72 km^2	5.0 km	4.7 km	4.8 km
186 dB (stationary)	640 km^2	17 km	11 km	14 km	840 km^2	19 km	13 km	16 km

Table 4-27 Summary of impact ranges from worst case monopile modelling at the DEP site using the Popper et al. (2014) unweighted SEL_{cum} criteria for fish assuming a stationary animal

Popper *et al*. (2014) Unweighted SPL_{peak}	Worst case pin piles							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
213 dB	0.02 km^2	80 m	80 m	80 m	0.02 km^2	80 m	80 m	80 m
207 dB	0.12 km^2	200 m	200 m	200 m	0.11 km^2	190 m	180 m	180 m

Table 4-28 Summary of impact ranges from worst case pin pile modelling at the SEP site using the Popper et al. (2014) unweighted SPL_{peak} criteria for fish

Popper *et al*. (2014) Unweighted SPL_{peak}	Worst case pin piles							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
213 dB	0.02 km^2	90 m	80 m	90 m	0.02 km^2	90 m	90 m	90 m
207 dB	0.14 km^2	210 m	210 m	210 m	0.15 km^2	220 m	220 m	220 m

Table 4-29 Summary of impact ranges from worst case pin pile modelling at the DEP site using the Popper et al. (2014) unweighted SPL_{peak} criteria for fish

Popper *et al*. (2014) Unweighted SEL_{cum}	Worst case pin piles							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB (fleeing)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
216 dB (fleeing)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
210 dB (fleeing)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
207 dB (fleeing)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
203 dB (fleeing)	< 0.1 km^2	200 m	100 m	100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
186 dB (fleeing)	75 km^2	5.7 km	4.3 km	4.9 km	42 km^2	4.3 km	3.0 km	3.6 km

Table 4-30 Summary of impact ranges from worst case pin pile modelling at the SEP site using the Popper et al. (2014) unweighted SEL_{cum} criteria for fish assuming a fleeing animal

Popper *et al*. (2014) Unweighted SEL_{cum}	Worst case pin piles							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB (fleeing)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
216 dB (fleeing)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
210 dB (fleeing)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
207 dB (fleeing)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
203 dB (fleeing)	< 0.1 km²	200 m	100 m	100 m	< 0.1 km²	200 m	100 m	100 m
186 dB (fleeing)	84 km²	6.2 km	4.4 km	5.2 km	130 km²	7.8 km	5.1 km	6.4 km

Table 4-31 Summary of impact ranges from worst case pin pile modelling at the DEP site using the Popper et al. (2014) unweighted SEL_{cum} criteria for fish assuming a fleeing animal

Popper *et al*. (2014) Unweighted SEL_{cum}	Worst case pin piles							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB (stationary)	0.44 km²	400 m	400 m	400 m	0.33 km²	400 m	300 m	300 m
216 dB (stationary)	0.86 km²	600 m	500 m	500 m	0.71 km²	500 m	500 m	500 m
210 dB (stationary)	4.3 km²	1.2 km	1.2 km	1.2 km	3.4 km²	1.1 km	1.0 km	1.0 km
207 dB (stationary)	9.2 km²	1.8 km	1.7 km	1.7 km	7.1 km²	1.6 km	1.5 km	1.5 km
203 dB (stationary)	23 km²	2.8 km	2.7 km	2.7 km	18 km²	2.5 km	2.3 km	2.4 km
186 dB (stationary)	400 km²	12 km	10 km	11 km	280 km²	10 km	7.9 km	9.5 km

Table 4-32 Summary of impact ranges from worst case pin pile modelling at the SEP site using the Popper et al. (2014) unweighted SEL_{cum} criteria for fish assuming a stationary animal

Popper *et al*. (2014) Unweighted SEL_{cum}	Worst case pin piles							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB (stationary)	0.44 km²	400 m	400 m	400 m	0.44 km²	400 m	400 m	400 m
216 dB (stationary)	1.0 km²	600 m	600 m	600 m	1.0 km²	600 m	600 m	600 m
210 dB (stationary)	4.9 km²	1.3 km	1.2 km	1.2 km	5.5 km²	1.4 km	1.3 km	1.3 km
207 dB (stationary)	11 km²	2.0 km	1.8 km	1.8 km	12 km²	2.0 km	2.0 km	2.0 km
203 dB (stationary)	27 km²	3.1 km	2.8 km	2.9 km	31 km²	3.2 km	3.1 km	3.2 km
186 dB (stationary)	410 km²	13 km	10 km	11 km	540 km²	15 km	11 km	13 km

Table 4-33 Summary of impact ranges from worst case pin pile modelling at the DEP site using the Popper et al. (2014) unweighted SEL_{cum} criteria for fish assuming a stationary animal

4.2 Most likely parameters

Table 4-35 to Table 4-50 present the impact ranges for monopile foundations using the most likely parameters as described in section 3.3 and the marine mammal and fish impact criteria detailed in section 2.2.2.

Compared to the worst case parameters, reductions in impact ranges for the most likely parameters with maximum PTS ranges injury ranges in marine mammals of 4.1 km for LF cetaceans and 3.0 km for VHF cetaceans are predicted using the impulsive SEL_{cum} Southall *et al*. (2019) criteria at the SE location of the DEP. For fish, the maximum fleeing range was 10 km for TTS using the Popper *et al*. (2014) criteria at the same location. It should be noted that these most likely ranges for monopile foundations are still in excess of those predicted for the worst case pin pile parameters. Again, lower ranges are predicted at the SEP site, with maximum ranges predicted of 1.9 km for PTS in LF cetaceans, 2.2 km for PTS in VHF cetaceans and 7.7 km for TTS in fish at the E location.

Table (page)	Parameters			Criteria	
Table 4-35 (p29)	SEP	Most likely	Monopiles	Southall *et al.* (2019)	Unweighted SPL_{peak}
Table 4-36 (p29)	DEP				
Table 4-37 (p30)	SEP				Weighted SEL_{cum} (impulsive)
Table 4-38 (p30)	DEP				
Table 4-39 (p30)	SEP				Weighted SEL_{cum} (non-impulsive)
Table 4-40 (p30)	DEP				
Table 4-41 (p31)	SEP			Lucke *et al.* (2009)	Unweighted $SPL_{peak\text{-}to\text{-}peak}$
Table 4-42 (p31)	DEP				
Table 4-43 (p31)	SEP				Unweighted SEL_{ss}
Table 4-44 (p31)	DEP				
Table 4-45 (p31)	SEP			Popper *et al.* (2014)	Unweighted SPL_{peak}
Table 4-46 (p31)	DEP				
Table 4-47 (p32)	SEP				Unweighted SEL_{cum} (fleeing)
Table 4-48 (p32)	DEP				
Table *4-49* (p32)	SEP				Unweighted SEL_{cum} (stationary)
Table 4-50 (p32)	DEP				

Table 4-34 Summary of the most likely modelling results tables presented in this section

4.2.1 Marine mammals

Southall *et al.* (2019) Unweighted SPL_{peak}		Most likely monopiles							
		SEP E				SEP N			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS	219 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	230 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	202 dB (VHF)	0.76 km^2	490 m	490 m	490 m	0.63 km^2	450 m	440 m	450 m
	218 dB (PCW)	< 0.01 km^2	50 m	50 m	50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	213 dB (LF)	0.03 km^2	100 m	100 m	100 m	0.03 km^2	90 m	90 m	90 m
	224 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	196 dB (VHF)	3.9 km^2	1.1 km	1.1 km	1.1 km	3.1 km^2	1.0 km	980 m	1.0 km
	212 dB (PCW)	0.04 km^2	110 m	110 m	110 m	0.03 km^2	110 m	110 m	110 m

Table 4-35 Summary of impact ranges from most likely monopile modelling at the SEP site using the Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al.* (2019) Unweighted SPL_{peak}		Most likely monopiles							
		DEP NE				DEP SE			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS	219 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	230 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	202 dB (VHF)	0.84 km^2	530 m	510 m	520 m	0.93 km^2	550 m	550 m	550 m
	218 dB (PCW)	< 0.01 km^2	50 m	50 m	50 m	< 0.1 km^2	50 m	50 m	50 m
TTS	213 dB (LF)	0.03 km^2	100 m	100 m	100 m	0.03 km^2	110 m	100 m	110 m
	224 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	196 dB (VHF)	4.4 km^2	1.2 km	1.2 km	1.2 km	5.0 km^2	1.3 km	1.3 km	1.3 km
	212 dB (PCW)	0.04 km^2	120 m	120 m	120 m	0.05 km^2	120 m	120 m	120 m

Table 4-36 Summary of impact ranges from most likely monopile modelling at the DEP site using the Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al.* (2019) Weighted SEL_{cum}		Most likely monopiles							
		SEP E				SEP N			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	4.3 km²	1.9 km	400 m	1.1 km	< 0.1 km²	400 m	< 100 m	100 m
	185 dB (HF)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	155 dB (VHF)	10 km²	2.2 km	1.5 km	1.8 km	4.0 km²	1.5 km	800 m	1.1 km
	185 dB (PCW)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	168 dB (LF)	380 km²	16 km	8.0 km	11 km	200 km²	11 km	3.9 km	7.8 km
	170 dB (HF)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	140 dB (VHF)	390 km²	14 km	9.2 km	11 km	260 km²	11 km	5.7 km	9.0 km
	170 dB (PCW)	75 km²	5.7 km	4.2 km	4.9 km	39 km²	4.3 km	2.7 km	3.5 km

Table 4-37 Summary of impact ranges from most likely monopile modelling at the SEP site using the impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Most likely monopiles							
		DEP NE				DEP SE			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	6.2 km²	2.4 km	500 m	1.3 km	24 km²	4.1 km	1.3 km	2.6 km
	185 dB (HF)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	155 dB (VHF)	12 km²	2.5 km	1.6 km	2.0 km	20 km²	3.0 km	2.1 km	2.5 km
	185 dB (PCW)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	168 dB (LF)	400 km²	16 km	6.3 km	11 km	650 km²	21 km	9.4 km	14 km
	170 dB (HF)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	140 dB (VHF)	400 km²	14 km	7.7 km	11 km	580 km²	17 km	10 km	13 km
	170 dB (PCW)	82 km²	6.2 km	4.1 km	5.1 km	130 km²	7.7 km	4.9 km	6.4 km

Table 4-38 Summary of impact ranges from most likely monopile modelling at the DEP site using the impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Most likely monopiles							
		SEP E				SEP N			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	198 dB (HF)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	173 dB (VHF)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	201 dB (PCW)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	179 dB (LF)	39 km²	5.0 km	2.4 km	3.5 km	11 km²	2.7 km	500 m	1.7 km
	178 dB (HF)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	153 dB (VHF)	25 km²	3.3 km	2.4 km	2.8 km	12 km²	2.4 km	1.5 km	2.0 km
	181 dB (PCW)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m

Table 4-39 Summary of impact ranges from most likely monopile modelling at the SEP site using the non-impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Most likely monopiles							
		DEP NE				DEP SE			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	198 dB (HF)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	173 dB (VHF)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	201 dB (PCW)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	179 dB (LF)	44 km²	5.5 km	2.1 km	3.7 km	100 km²	7.9 km	3.3 km	5.5 km
	178 dB (HF)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m
	153 dB (VHF)	28 km²	3.6 km	2.5 km	3.0 km	43 km²	4.4 km	2.9 km	3.7 km
	181 dB (PCW)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²	< 100 m	< 100 m	< 100 m

Table 4-40 Summary of impact ranges from most likely monopile modelling at the DEP site using the non-impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing animal

Lucke *et al*. (2009) Unweighted $SPL_{peak-to-peak}$	Most likely monopiles							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (199.7 dB)	0.24 km^2	280 m	270 m	280 m	0.27 km^2	300 m	290 m	300 m
Behavioural (174 dB)	92 km^2	5.9 km	5.1 km	5.4 km	130 km^2	6.9 km	5.9 km	6.4 km

Table 4-41 Summary of impact ranges from most likely monopile modelling at the SEP site using the Lucke et al. (2009) unweighted $SPL_{peak-to-peak}$ criteria for harbour porpoise

Lucke *et al*. (2009) Unweighted $SPL_{peak-to-peak}$	Most likely monopiles							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (199.7 dB)	0.31 km^2	320 m	300 m	310 m	0.33 km^2	330 m	320 m	330 m
Behavioural (174 dB)	140 km^2	7.4 km	6.1 km	6.6 km	170 km^2	7.9 km	6.8 km	7.3 km

Table 4-42 Summary of impact ranges from most likely monopile modelling at the DEP site using the Lucke et al. (2009) unweighted $SPL_{peak-to-peak}$ criteria for harbour porpoise

Lucke *et al*. (2009) Unweighted SEL_{ss}	Most likely monopiles							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (164.3 dB)	62 km^2	4.8 km	4.2 km	4.5 km	85 km^2	5.5 km	5.0 km	5.2 km
Behavioural (145 dB)	680 km^2	17 km	10 km	15 km	950 km^2	21 km	15 km	17 km

Table 4-43 Summary of impact ranges from most likely monopile modelling at the SEP site using the Lucke et al. (2009) unweighted SEL_{ss} criteria for harbour porpoise

Lucke *et al*. (2009) Unweighted SEL_{ss}	Most likely monopiles							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (164.3 dB)	94 km^2	6.0 km	5.1 km	5.5 km	110 km^2	6.3 km	5.7 km	6.0 km
Behavioural (145 dB)	970 km^2	21 km	13 km	18 km	13 km^2	25 km	16 km	20 km

Table 4-44 Summary of impact ranges from most likely monopile modelling at the DEP site using the Lucke et al. (2009) unweighted SEL_{ss} criteria for harbour porpoise

4.2.2 Fish

Popper *et al*. (2014) Unweighted SPL_{peak}	Most likely monopiles							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
213 dB	0.03 km^2	100 m	100 m	100 m	0.03 km^2	90 m	90 m	90 m
207 dB	0.18 km^2	240 m	240 m	240 m	0.15 km^2	220 m	220 m	220 m

Table 4-45 Summary of impact ranges from most likely monopile modelling at the SEP site using the Popper et al. (2014) unweighted SPL_{peak} criteria for fish

Popper *et al*. (2014) Unweighted SPL_{peak}	Most likely monopiles							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
213 dB	0.03 km^2	100 m	100 m	100 m	0.03 km^2	110 m	100 m	110 m
207 dB	0.19 km^2	250 m	250 m	250 m	0.21 km^2	260 m	260 m	260 m

Table 4-46 Summary of impact ranges from most likely monopile modelling at the DEP site using the Popper et al. (2014) unweighted SPL_{peak} criteria for fish

Popper *et al*. (2014) Unweighted SEL_{cum}	Most likely monopiles							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB (fleeing)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
216 dB (fleeing)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
210 dB (fleeing)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
207 dB (fleeing)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
203 dB (fleeing)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
186 dB (fleeing)	130 km^2	7.7 km	5.4 km	6.4 km	69 km^2	5.7 km	3.3 km	4.7 km

Table 4-47 Summary of impact ranges from most likely monopile modelling at the SEP site using the Popper et al. (2014) unweighted SEL_{cum} criteria for fish assuming a fleeing animal

Popper *et al*. (2014) Unweighted SEL_{cum}	Most likely monopiles							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB (fleeing)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
216 dB (fleeing)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
210 dB (fleeing)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
207 dB (fleeing)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
203 dB (fleeing)	< 0.1 km^2	< 100 m	< 100 m	< 100 m	< 0.1 km^2	< 100 m	< 100 m	< 100 m
186 dB (fleeing)	140 km^2	8.3 km	5.0 km	6.6 km	220 km^2	10 km	6.2 km	8.3 km

Table 4-48 Summary of impact ranges from most likely monopile modelling at the DEP site using the Popper et al. (2014) unweighted SEL_{cum} criteria for fish assuming a fleeing animal

Popper *et al*. (2014) Unweighted SEL_{cum}	Most likely monopiles							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB (stationary)	0.86 km^2	600 m	500 m	500 m	0.71 km^2	500 m	500 m	500 m
216 dB (stationary)	1.9 km^2	800 m	800 m	800 m	1.4 km^2	700 m	700 m	700 m
210 dB (stationary)	8.6 km^2	1.7 km	1.6 km	1.7 km	6.8 km^2	1.6 km	1.4 km	1.5 km
207 dB (stationary)	17 km^2	2.4 km	2.3 km	2.4 km	14 km^2	2.2 km	2.0 km	2.1 km
203 dB (stationary)	42 km^2	3.8 km	3.5 km	3.7 km	32 km^2	3.4 km	3.1 km	3.2 km
186 dB (stationary)	540 km^2	15 km	11 km	13 km	390 km^2	12 km	8.8 km	11 km

Table 4-49 Summary of impact ranges from most likely monopile modelling at the SEP site using the Popper et al. (2014) unweighted SEL_{cum} criteria for fish assuming a stationary animal

Popper *et al*. (2014) Unweighted SEL_{cum}	Most likely monopiles							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB (stationary)	0.86 km^2	600 m	500 m	500 m	1.0 km^2	600 m	600 m	600 m
216 dB (stationary)	2.0 km^2	900 m	800 m	800 m	2.4 km^2	900 m	900 m	900 m
210 dB (stationary)	9.8 km^2	1.9 km	1.7 km	1.8 km	11 km^2	1.9 km	1.9 km	1.9 km
207 dB (stationary)	20 km^2	2.7 km	2.4 km	2.5 km	23 km^2	2.8 km	2.7 km	2.7 km
203 dB (stationary)	48 km^2	4.2 km	3.7 km	3.9 km	55 km^2	4.3 km	4.1 km	4.2 km
186 dB (stationary)	560 km^2	15 km	11 km	13 km	730 km^2	18 km	13 km	15 km

Table 4-50 Summary of impact ranges from most likely monopile modelling at the DEP site using the Popper et al. (2014) unweighted SEL_{cum} criteria for fish assuming a stationary animal

5 Other noise sources

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

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

Activity	Description
Cable laying	Noise from the cable laying vessel and any other associated noise during the offshore cable installation.
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.
Drilling	Necessary in case of impact piling refusal.
Suction dredging (seabed preparation)	Trailer suction hopper dredging may be required on site for seabed preparation work for certain foundation options, as well as for the export cable, array cable and interconnector cable installation.
Vessel noise	Jack-up barges for piling substructure and WTG installation. Other large and medium sized vessels on site to carry out other construction tasks, and anchor handing. Other small vessel for crew transport and maintenance on site.
Operational WTG	Noise transmitted through the water from operation WTG. The project design envelope gives turbines with capacities of up to 18 MW.
UXO detonation	Unexploded Ordnance (UXO) has been identified with the boundaries of the SEP and DEP sites, which need to be cleared before construction can begin.

Table 5-1 Summary of the possible noise making activities at the SEP and DEP other than impact piling

The NPL Good Practice Guide 133 for underwater noise measurements (Robinson *et al*., 2014) indicated 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. drilling and cable laying) or where detailed modelling would imply unjustified accuracy (e.g. where data is limited such as with large operational 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.

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 measured data from Subacoustech Environmental's own underwater noise measurement database, scaled to relevant parameters for the site and 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 on transects around these sources by Subacoustech. 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:

$$Source\ level\ (SL) - N \log R - \alpha R$$

Predicted source levels and propagation calculations for the construction activities are presented in Table 5-2 along with a summary of the number of datasets used in each case. As previously, all SEL_{cum}

criteria use the same assumptions as presented in 2.2.2, 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 other environmental conditions into account, and as such can be applied to any location in either the SEP or DEP areas. Noise from operational WTGs has been reviewed separately in section 5.2, and UXO detonation is covered in section 5.3.

Source	Estimated unweighted source level	Approximate transmission loss	Comments
Cable laying	171 dB re 1 µPa @ 1 m (RMS)	$13 \log R$ (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.
Trenching	172 dB re 1 µPa @ 1 m (RMS)	$13 \log R - 0.0004R$	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)	$12 \log R - 0.0005R$	Based on four datasets from rock placement vessel 'Rollingstone.'
Drilling	169 dB re 1 µPa @ 1 m (RMS)	$16 \log R - 0.0006R$	Based on seven datasets of offshore drilling using a variety of drill sizes and powers. Modelling assumes a 200 kW drilling rig.
Suction dredging	186 dB re 1 µPa @ 1 m (RMS)	$19 \log R - 0.0009R$	Based on five datasets from suction and cutter suction dredgers.
Vessel noise (large)	168 dB re 1 µPa @ 1 m (RMS)	$12 \log R - 0.0021R$	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)	$12 \log R - 0.0021R$	Based on three datasets of moderate sized vessels less than 100 m in length. Vessel speed assumed as 10 knots.

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

For SEL_{cum} calculations, the duration the noise is present is also considered, with all sources operating for a worst case 12 hours in any given 24-hour period apart from vessel noise which is assumed to be present for 24 hours a day.

To account for the weightings required for modelling using the Southall *et al*. (2019) criteria (section 2.2.2.1), reductions in source level have been applied to the various noise sources. Figure 5-1 shows the representative noise measurements used, adjusted for the source levels in Table 5-2. Table 5-3 presents details of the reductions in source levels for each of the weightings used for modelling.

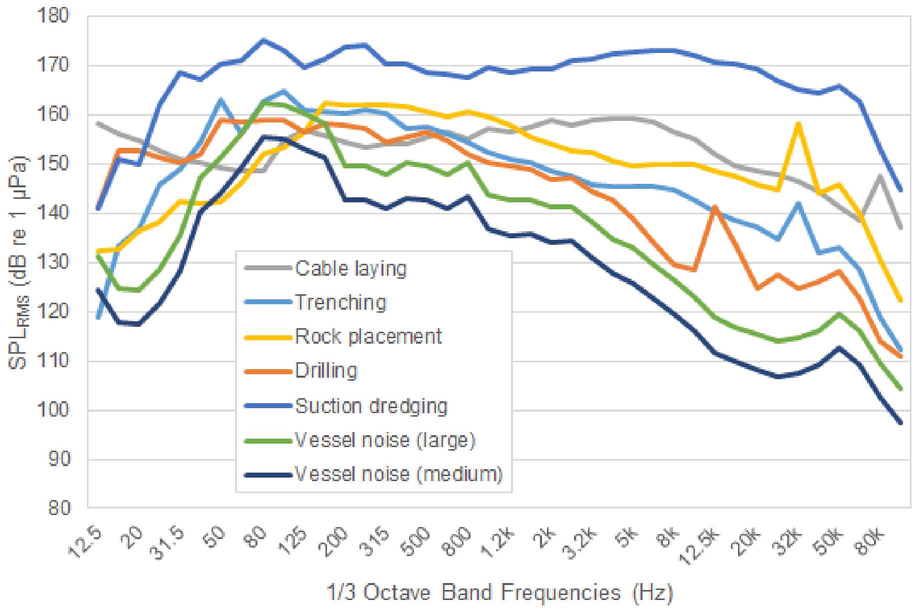

Figure 5-1 Summary of the 1/3 octave frequency bands used as a basis for the Southall et al. (2019) weightings used in the simple modelling

Source	**Reduction in source level from the unweighted level**			
	LF	**HF**	**VHF**	**PCW**
Cable laying	3.6 dB	22.9 dB	23.9 dB	13.2 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
Drilling	4.0 dB	25.8 dB	28.4 dB	13.2 dB
Suction dredging	2.5 dB	7.9 dB	9.6 dB	4.2 dB
Vessel noise	5.5 dB	34.4 dB	38.6 dB	17.4 dB

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

Table 5-4 and Table 5-5 summarise the predicted impact ranges for these noise sources. It is worth noting that Southall *et al*. (2019) and Popper *et al*. (2014) give different criteria for non-impulsive or continuous noise sources compared to impulsive noise (see section 2.2.2); all sources in this section are considered non-pulse or continuous.

Given the modelled impact ranges, any marine mammal would have to be less 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 3.3.3, it should also be noted that this would only mean that the receptor reaches the ‘onset’ stage, which is the minimum exposure that could potentially lead to the start of an effect, and may only be marginal. In most hearing groups, the noise levels are low enough that there is negligible risk.

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

All sources presented here are much quieter than those presented for impact piling in section 4.

Southall *et al*. (2019) Weighted SEL_{cum}		Cable laying	Trenching	Rock placement	Drilling	Suction dredging	Vessels (large)	Vessels (medium)
PTS	199 dB (LF)	< 100 m	< 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	< 100 m
	173 dB (VHF)	< 100 m	< 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	< 100 m
TTS	179 dB (LF)	< 100 m	< 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	< 100 m
	153 dB (VHF)	< 100 m	< 100 m	1.0 km	< 100 m	200 m	< 100 m	< 100 m
	181 dB (PCW)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m

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

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

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

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 turbines, which is transmitted into the sea through the structure of the turbine tower, pile and foundations (Nedwell *et al*., 2003). Noise levels generated above the water surface are low enough that no significant airborne sound will pass from the air to the water.

A summary of operational WTG where measurements have been collected is given in Table 5-6.

Wind farm	Lynn	Inner Dowsing	Gunfleet Sands 1 & 2	Gunfleet Sands 3
Type of turbine used	Siemens SWT-3.6-107	Siemens SWT-3.6-107	Siemens SWT-3.6-107	Siemens SWT-6.0-120
Number of turbines	27	27	48	2
Power rating	3.6 MW	3.6 MW	3.6 MW	6.0 MW
Rotor diameter	107 m	107 m	107 m	120 m
Water depths	6 to 8 m	6 to 14 m	0 to 15 m	5 to 12 m
Representative sediment type	Sandy gravel / muddy sandy gravel	Sandy gravel / muddy sandy gravel	Sand / muddy sand / muddy sandy gravel	Sand / muddy sand / muddy sandy gravel
Turbine separation	500 m	500 m	890 m	435 m

Table 5-6 Characteristics of measured operational wind farms used as a basis for modelling

The estimation of the effects of operational WTG noise in these situations has two features that make it harder to predict compared with noise sources such as impact piling. Primarily, the problem is one of level; noise measurements made at many operational wind farms have demonstrated that the operational noise produced was at such a low level that it was difficult to measure relative to background noise at distances of a few hundred metres (Cheesman, 2016). Secondly, the multiple turbines of an offshore wind farm could be considered as an extended, distributed noise source, as opposed to a “point source,” as would be appropriate for piling driving at a single location for example. The measurement techniques used at the sites above have dealt with issues by considering the operational WTG noise spectra in terms of levels within and on the edge of the wind farm (but relatively close to the turbines, so that some noise above background can be detected).

The considered turbine sizes for modelling at SEP and DEP are larger than those for which data is available (with turbines between 14-26 MW being considered). The SEP and DEP sites are also situated in greater water depths, and as such, estimations of a scaling factor must be conservative to minimise the risk of underestimating the noise. However, it is recognised that the available data on which to base the scaling factor is limited and the extrapolation that must be made is significant.

The operational source levels (as SPL_{RMS}) for the measured sites are given in Table 5-7 (Cheesman, 2016), with an estimated source level for SEP and DEP in the bottom row. To predict operational WTG noise levels at SEP and DEP, the extrapolated source level from the measured data at each of the sites has been taken and then a linear correction factor has been included to scale up the source levels (Figure 5-2). A linear fit was applied to the data to keep conservatism in the extrapolation and to take account of the deeper water depths, leading to the highest, and thus worst case, estimation of source level noise from the larger turbines. This resulted in estimated source levels of 157.1 dB re 1 µPa (SPL_{RMS}) @ 1 m for a 14 MW WTG and 173.8 dB re 1 µPa (SPL_{RMS}) @ 1 m for 26 MW WTGs; 11.1 and 27.8 dB higher, respectively, than the 6.0 MW turbines for which measurements are available.

Site	Unweighted source level
Lynn (3.6 MW)	141 dB re 1 µPa (SPL_{RMS}) @ 1 m
Inner Dowsing (3.6 MW)	142 dB re 1 µPa (SPL_{RMS}) @ 1 m
Gunfleet Sands 1 & 2 (3.6 MW)	145 dB re 1 µPa (SPL_{RMS}) @ 1 m
Gunfleet Sands 3 (6.0 MW)	146 dB re 1 µPa (SPL_{RMS}) @ 1 m
SEP and DEP (14 MW)	157.1 dB re 1 µPa (SPL_{RMS}) @ 1 m
SEP and DEP (26 MW)	173.8 dB re 1 µPa (SPL_{RMS}) @ 1 m

Table 5-7 Measured operational WTG noise taken at operational wind farms, and the predicted source level for the turbine sizes considered at SEP and DEP

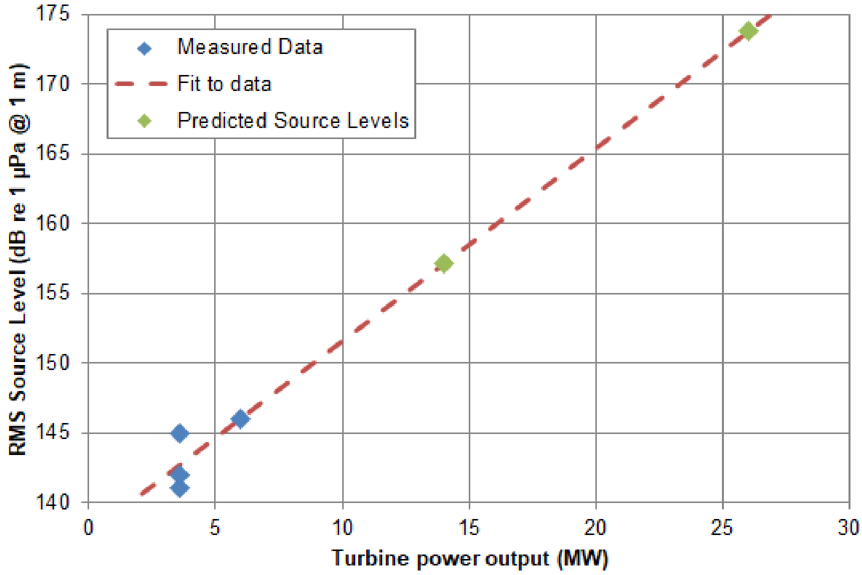

Figure 5-2 Extrapolated source levels from operational WTGs plotted with a linear fit to estimate the source level for 14 to 26 MW WTGs

It is acknowledged that this fit is speculative: the available data is very limited. Newer, larger, direct-drive (gearbox-less) designs tend to be more efficient and losses (e.g. in energy which produce noise and vibration) are significantly reduced. It is anticipated that an alternative but more likely extrapolation would produce an increase of between 3 – 6 dB per doubling of power, which would lead to estimated SPL_{RMS} source levels of up to 155.3 dB for a 14 MW WTG and 160.7 dB for 26 MW WTGs, 1.8 and 13.1 dB lower than the estimates used above. Thus, the linear extrapolation represents a considerably greater noise output and can be considered conservative.

A summary of the predicted impact ranges are given in Table 5-8 and Table 5-9. All SEL_{cum} criteria use the same assumptions as presented in section 2.2.2, 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 sound by Southall *et al*. (2019) and a continuous source by Popper *et al*. (2014). For SEL_{cum} calculations it has been assumed that the operational WTG noise is present 24 hours a day.

Southall *et al*. (2019)		**Operational WTG (14 MW)**	**Operational WTG (26 MW)**
PTS	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	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 impact ranges for the proposed operational WTGs using the non-impulsive noise criteria from Southall et al (2019) for marine mammals

Popper *et al*. (2014)	**Operational WTG (14 MW)**	**Operational WTG (26 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

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

These results show that, for operational WTGs, injury risk is minimal. Taking the results from this and the previous section (5.2), 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 SEP and DEP.

5.3 UXO detonation

Several UXO devices with a range of charge weights (or quantity of contained explosive) have been identified within the boundaries of the SEP and DEP sites. These need to be cleared before any construction can begin. There are expected to be a variety of explosive types, many of which 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 site surveys 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 in 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 range of equivalent charge weights for the potential UXO devices that could be present within the SEP and DEP site boundaries have been estimated as 25, 55, 120, 240 and 525 kg. 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 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 SPL_{peak}:

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

and for SEL_{ss}

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

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

These equations give a relatively simple calculation which can be used to give an indication of the range of effect. The equation does not consider variable bathymetry or seabed type, and thus calculation results will be the same regardless 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 and Irish Seas in similar depths to the present at SEP and DEP.

Despite this attenuation correction, the resulting noise levels still need to be considered carefully. For example, SPL_{peak} noise levels over larger distances are difficult to predict accurately (von Benda-Beckmann *et al*., 2015). Soloway and Dahl (2014) only verify results from the equation above for small charges at ranges of less than 1 km, although the results do agree with 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 smoothing of the peak is less critical.

The selection of assessment criteria must also be considered in light of this. As discussed in section 2.2.2.1, the smoothing of the pulse at range means that a pulse may be considered a non-pulse at greater distance. This study has presented impact ranges for both impulsive and non-impulsive criteria at greater ranges, suggesting that, at greater ranges, it may be more appropriate to use the non-pulse criteria.

A summary of the unweighted UXO source levels calculated using the equations above are given in Table 5-10.

Charge weight	25 kg	55 kg	120 kg	240 kg	525 kg
SPL_{peak} source level (dB re 1 µPa @ 1 m)	284.9	287.4	290.0	292.2	294.8
SEL_{ss} source level (dB re 1 µPa²s @ 1 m)	227.9	230.1	232.3	234.2	236.4

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

5.3.3 Impact ranges

Table 5-11 to Table 5-14 present the impact ranges for UXO detonation, considering various charge weights and impact criteria. It should be noted that Popper *et al*. (2014) gives specific impact criteria for explosions (Table 2-6). A UXO detonation source is defined as a single pulse, and as such the SEL_{cum} criteria from Southall *et al*. (2019) have been given as SEL_{ss} in the tables below, thus, fleeing animal assumptions do not apply.

As with the previous sections, ranges smaller than 50 m have not been presented.

Although the impact ranges presented in the following tables 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.

Southall *et al*. (2019) Unweighted SPL_{peak}		**25 kg**	**55 kg**	**120 kg**	**240 kg**	**525 kg**
PTS	219 dB (LF)	810 m	1.0 km	1.3 km	1.7 km	2.2 km
	230 dB (HF)	260 m	340 m	450 m	560 m	730 m
	202 dB (VHF)	4.6 km	6.0 km	7.7 km	9.8 km	13 km
	218 dB (PCW)	900 m	1.1 km	1.5 km	1.9 km	2.5 km
TTS	213 dB (LF)	1.5 km	1.9 km	2.5 km	3.2 km	4.1 km
	224 dB (HF)	490 m	640 m	830 m	1.0 km	1.3 km
	196 dB (VHF)	8.5 km	11 km	14 km	18 km	23 km
	212 dB (PCW)	1.6 km	2.1 km	2.8 km	3.5 km	4.6 km

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

Southall *et al*. (2019) Weighted SEL_{ss}		**25 kg**	**55 kg**	**120 kg**	**240 kg**	**525 kg**
PTS (Impulsive)	183 dB (LF)	2.1 km	3.2 km	4.6 km	6.5 km	9.5 km
	185 dB (HF)	< 50 m	< 50 m	< 50 m	< 50 m	50 m
	155 dB (VHF)	560 m	740 m	950 m	1.1 km	1.4 km
	185 dB (PCW)	380 m	560 m	830 m	1.1 km	1.6 km
TTS (Impulsive)	168 dB (LF)	29 km	41 km	57 km	76 km	103 km
	170 dB (HF)	150 m	210 m	300 m	390 m	530 m
	140 dB (VHF)	2.4 km	2.8 km	3.2 km	3.5 km	4.0 km
	170 dB (PCW)	5.2 km	7.4 km	11 km	14 km	20 km

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

Southall *et al*. (2019) Weighted SEL_{ss}		**25 kg**	**55 kg**	**120 kg**	**240 kg**	**525 kg**
PTS (Non-impulsive)	199 dB (LF)	120 m	190 m	280 m	390 m	570 m
	198 dB (HF)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 50 m	< 50 m	70 m	100 m	130 m
	201 dB (PCW)	< 50 m	< 50 m	< 50 m	70 m	100 m
TTS (Non-impulsive)	179 dB (LF)	4.4 km	6.4 km	9.3 km	13 km	19 km
	178 dB (HF)	< 50 m	60 m	80 m	110 m	160 m
	153 dB (VHF)	730 m	940 m	1.1 km	1.4 km	1.7 km
	181 dB (PCW)	780 m	1.1 km	1.6 km	2.3 km	3.3 km

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

Popper *et al*. (2014) Unweighted SPL_{peak}	**25 kg**	**55 kg**	**120 kg**	**240 kg**	**525 kg**
234 dB (Mortality and potential mortal injury)	170 m	230 m	290 m	370 m	490 m
229 dB (Mortality and potential mortal injury)	290 m	380 m	490 m	620 m	810 m

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

The maximum PTS range calculated here for the . UXO is 13 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 9.5 km using the impulsive SEL_{ss} 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 570 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 Equinor to assess the potential underwater noise, and its effects, during construction and operation of the proposed Sheringham Extension Project (SEP) and Dudgeon Extension Project (DEP) offshore wind farms.

The level of underwater noise from the installation of monopile and pin pile 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 locations were chosen, two at the SEP and two at the DEP, to give spatial variation as well as account for changes in water depth around the site. At each location, three sets of modelling parameters were considered:

- Worst case monopile – a 16 m diameter pile installed with a maximum blow energy of 5,500 kJ;
- Worst case pin pile – a 3.5 m diameter pile installed with a maximum blow energy of 3,000 kJ; and
- Most likely monopile – a 16 m diameter pile installed with a maximum blow energy of 4,500 kJ.

The loudest levels of noise and greatest impact ranges have been predicted for the worst case monopile parameters, with reduced ranges for the most likely monopile parameters and the smallest ranges overall for the worst case pin pile parameters. Also, the deeper SE location at DEP resulted in larger ranges than the three other, shallower, locations.

The modelling results were analysed in terms of relevant noise metrics and criteria to assess the impacts of the impact piling noise on marine mammals (Southall *et al*., 2019 and Lucke *et al*., 2009) 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 of 8.3 km and for VHF cetaceans of 4.9 km, for the worst case monopile parameters at the SE DEP modelling location. These ranges are reduced when considering the most likely monopile parameters, pin pile parameters and the other modelling locations. A maximum behavioural impact range of 25 km was predicted for aversive behavioural reaction in harbour porpoise using the Lucke *et al*. (2009) SEL criteria. For fish, the largest TTS ranges were predicted using the worst case monopile parameters with a maximum range of 12 km for fleeing receptors at the SE DEP location. Ranges were smaller for the most likely monopile parameters, the worst case pin pile parameters and the other modelling locations.

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 when very close to the source of the noise.

UXO detonation has also been considered at the SEP and DEP sites, and for the expected UXO detonation noise, there is a risk of PTS up to 13 km for the largest UXO considered, a 525 kg device using the unweighted SPL_{peak} Southall *et al*. (2019) criteria for VHF cetaceans. However, this is likely to be very precautionary as the impact range is based on worst case criteria that do not account for any smoothing of the pulse over long ranges, which reduces 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 Single strike modelling results

This appendix presents single strike impact piling modelling results that were calculated in addition to the results presented in section 4. It should be noted that the SEL_{ss} parameters presented in this appendix are not part of the Southall *et al*. (2019) and Popper *et al*. (2014) criteria but have been included to give an idea as to the levels of noise present for the first pile strike and at full energy at the end of the piling operations. The results for the worst case parameters are given in section A.1 and the results for the most likely parameters are given in section A.2.

As with the previous modelling for single strikes, predicted ranges smaller than 50 m and areas less than 0.01 km^2 have not been presented as the modelling processes are unable to specify that level of accuracy with confidence due to acoustic effects near the source and other noise processes at close ranges.

A.1 Worst case parameters

<table>
<tr><th>Table (page)</th><th colspan="3">Parameters</th><th colspan="2">Criteria</th></tr>
<tr><td>Table A 2 (p47)</td><td>SEP</td><td rowspan="28">Worst case</td><td rowspan="10">Monopiles</td><td rowspan="6">Southall et al. (2019)</td><td rowspan="2">Unweighted SPL_{peak} (First strike)</td></tr>
<tr><td>Table A 3 (p47)</td><td>DEP</td></tr>
<tr><td>Table A 4 (p48)</td><td>SEP</td><td rowspan="2">Weighted SEL_{ss} (impulsive) (First strike)</td></tr>
<tr><td>Table A 5 (p48)</td><td>DEP</td></tr>
<tr><td>Table A 6 (p48)</td><td>SEP</td><td rowspan="2">Weighted SEL_{ss} (non-impulsive) (First strike)</td></tr>
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<tr><td>Table A 8 (p49)</td><td>SEP</td><td rowspan="4">Lucke et al. (2009)</td><td rowspan="2">Unweighted $SPL_{peak\text{-}to\text{-}peak}$</td></tr>
<tr><td>Table A 9 (p49)</td><td>DEP</td></tr>
<tr><td>Table A 10 (p49)</td><td>SEP</td><td rowspan="2">Unweighted SEL_{ss}</td></tr>
<tr><td>Table A 11 (p49)</td><td>DEP</td></tr>
<tr><td>Table A 12 (p49)</td><td>SEP</td><td rowspan="10">Pin piles</td><td rowspan="6">Southall et al. (2019)</td><td rowspan="2">Unweighted SPL_{peak} (First strike)</td></tr>
<tr><td>Table A 13 (p49)</td><td>DEP</td></tr>
<tr><td>Table A 14 (p50)</td><td>SEP</td><td rowspan="2">Weighted SEL_{ss} (impulsive) (First strike)</td></tr>
<tr><td>Table A 15 (p50)</td><td>DEP</td></tr>
<tr><td>Table A 16 (p50)</td><td>SEP</td><td rowspan="2">Weighted SEL_{ss} (non-impulsive) (First strike)</td></tr>
<tr><td>Table A 17 (p50)</td><td>DEP</td></tr>
<tr><td>Table A 18 (p51)</td><td>SEP</td><td rowspan="4">Lucke et al. (2009)</td><td rowspan="2">Unweighted $SPL_{peak\text{-}to\text{-}peak}$</td></tr>
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<tr><td>Table A 20 (p51)</td><td>SEP</td><td rowspan="2">Unweighted SEL_{ss}</td></tr>
<tr><td>Table A 21 (p51)</td><td>DEP</td></tr>
<tr><td>Table A 22 (p51)</td><td>SEP</td><td rowspan="4">Mono-piles</td><td rowspan="8">Southall et al. (2019)</td><td rowspan="2">Weighted SEL_{ss} (impulsive) (Full energy)</td></tr>
<tr><td>Table A 23 (p52)</td><td>DEP</td></tr>
<tr><td>Table A 24 (p52)</td><td>SEP</td><td rowspan="2">Weighted SEL_{ss} (non-impulsive) (Full energy)</td></tr>
<tr><td>Table A 25 (p52)</td><td>DEP</td></tr>
<tr><td>Table A 26 (p52)</td><td>SEP</td><td rowspan="4">Pin piles</td><td rowspan="2">Weighted SEL_{ss} (impulsive) (Full energy)</td></tr>
<tr><td>Table A 27 (p53)</td><td>DEP</td></tr>
<tr><td>Table A 28 (p53)</td><td>SEP</td><td rowspan="2">Weighted SEL_{ss} (non-impulsive) (Full energy)</td></tr>
<tr><td>Table A 29 (p53)</td><td>DEP</td></tr>
</table>

Table (page)	Parameters			Criteria	
Table A 30 (p53)	SEP	Worst case	Mono-piles	Popper *et al*. (2014)	Unweighted SPL_{peak} (First strike)
Table A 31 (p54)	DEP				
Table A 32 (p54)	SEP				Unweighted SEL_{ss} (First strike)
Table A 33 (p54)	DEP				
Table A 34 (p54)	SEP		Pin piles		Unweighted SPL_{peak} (First strike)
Table A 35 (p54)	DEP				
Table A 36 (p54)	SEP				Unweighted SEL_{ss} (First strike)
Table A 37 (p55)	DEP				
Table A *38* (p55)	SEP		Mono-piles		Unweighted SEL_{ss} (Full energy)
Table A 39 (p55)	DEP				
Table A 40 (p55)	SEP		Pin piles		
Table A 41 (p56)	DEP				

Table A 1 Summary of the worst case, single strike modelling results tables presented in this section

A.1.1 Marine mammals

First strike

Southall *et al*. (2019) Unweighted SPL_{peak}		Worst case monopiles (first strike)							
		SEP E				SEP N			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS	219 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	230 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	202 dB (VHF)	0.22 km^2	270 m	270 m	270 m	0.19 km^2	250 m	250 m	250 m
	218 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	213 dB (LF)	< 0.01 km^2	50 m	50 m	50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	224 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	196 dB (VHF)	1.3 km^2	630 m	630 m	630 m	1.0 km^2	580 m	570 m	570 m
	212 dB (PCW)	< 0.01 km^2	60 m	60 m	60 m	< 0.1 km^2	60 m	60 m	60 m

Table A 2 Summary of the first strike impact ranges from worst case monopile modelling at the SEP site using the Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al*. (2019) Unweighted SPL_{peak}		Worst case monopiles (first strike)							
		DEP NE				DEP SE			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS	219 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	230 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	202 dB (VHF)	0.24 km^2	280 m	280 m	280 m	0.27 km^2	290 m	290 m	290 m
	218 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	213 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	60 m	50 m	60 m
	224 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	196 dB (VHF)	1.4 km^2	680 m	660 m	670 m	1.6 km^2	710 m	700 m	710 m
	212 dB (PCW)	< 0.01 km^2	60 m	60 m	60 m	< 0.01 km^2	60 m	60	60 m

Table A 3 Summary of the first strike impact ranges from worst case monopile modelling at the DEP site using the Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al.* (2019) Weighted SEL_{ss}		Worst case monopiles (first strike)							
		SEP E				SEP N			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	0.09 km^2	170 m	170 m	170 m	0.07 km^2	160 m	150 m	150 m
	185 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	155 dB (VHF)	0.03 km^2	100 m	100 m	100 m	0.03 km^2	90 m	90 m	90 m
	185 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	168 dB (LF)	7.1 km^2	1.5 km	1.5 km	1.5 km	5.5 km^2	1.4 km	1.3 km	1.3 km
	170 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	140 dB (VHF)	1.4 km^2	680 m	680 m	680 m	1.3 km^2	650 m	640 m	640 m
	170 dB (PCW)	0.05 km^2	130 m	130 m	130 m	0.05 km^2	120 m	120 m	120 m

Table A 4 Summary of the first strike impact ranges from worst case monopile modelling at the SEP site using the impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al.* (2019) Weighted SEL_{ss}		Worst case monopiles (first strike)							
		DEP NE				DEP SE			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	0.1 km^2	180 m	180 m	180 m	0.11 km^2	190 m	190 m	190 m
	185 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	155 dB (VHF)	0.03 km^2	100 m	100 m	100 m	0.03 km^2	100 m	100 m	100 m
	185 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	168 dB (LF)	8.2 km^2	1.7 km	1.6 km	1.6 km	9.4 km^2	1.7 km	1.7 km	1.7 km
	170 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	140 dB (VHF)	1.5 km^2	710 m	700 m	700 m	1.6 km^2	730 m	720 m	730 m
	170 dB (PCW)	0.06 km^2	140 m	140 m	140 m	0.06 km^2	140 m	140 m	140 m

Table A 5 Summary of the first strike impact ranges from worst case monopile modelling at the DEP site using the impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al.* (2019) Weighted SEL_{ss}		Worst case monopiles (first strike)							
		SEP E				SEP N			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	198 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	201 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	179 dB (LF)	0.3 km^2	310 m	310 m	310 m	0.25 km^2	280 m	280 m	280 m
	178 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	153 dB (VHF)	0.05 km^2	130 m	120 m	130 m	0.05 km^2	120 m	120 m	120 m
	181 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A 6 Summary of the first strike impact ranges from worst case monopile modelling at the SEP site using the non-impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al.* (2019) Weighted SEL_{ss}		Worst case monopiles (first strike)							
		DEP NE				DEP SE			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	198 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	201 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	179 dB (LF)	0.34 km^2	330 m	330 m	330 m	0.38 km^2	350 m	350 m	350 m
	178 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	153 dB (VHF)	0.05 km^2	130 m	130 m	130 m	0.05 km^2	130 m	130 m	130 m
	181 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A 7 Summary of the first strike impact ranges from worst case monopile modelling at the DEP site using the non-impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Lucke *et al*. (2009) Unweighted $SPL_{peak-to-peak}$	Worst case monopiles (first strike)							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (199.7 dB)	0.08 km^2	160 m	150 m	160 m	0.09 km^2	170 m	160 m	170 m
Behavioural (174 dB)	48 km^2	4.2 km	3.7 km	3.9 km	65 km^2	4.8 km	4.3 km	4.5 km

Table A 8 Summary of the first strike impact ranges from worst case monopile modelling at the SEP site using the Lucke et al. (2009) unweighted $SPL_{peak-to-peak}$ criteria for harbour porpoise

Lucke *et al*. (2009) Unweighted $SPL_{peak-to-peak}$	Worst case monopiles (first strike)							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (199.7 dB)	0.09 km^2	180 m	160 m	170 m	0.1 km^2	180 m	170 m	180 m
Behavioural (174 dB)	72 km^2	5.2 km	4.5 km	4.8 km	84 km^2	5.4 km	5.0 km	5.2 km

Table A 9 Summary of the first strike impact ranges from worst case monopile modelling at the DEP site using the Lucke et al. (2009) unweighted $SPL_{peak-to-peak}$ criteria for harbour porpoise

Lucke *et al*. (2009) Unweighted SEL_{ss}	Worst case monopiles (first strike)							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (164.3 dB)	27 km^2	3.1 km	2.8 km	2.9 km	35 km^2	3.4 km	3.2 km	3.3 km
Behavioural (145 dB)	450 km^2	13 km	9.2 km	12 km	620 km^2	16 km	12 km	14 km

Table A 10 Summary of the first strike impact ranges from worst case monopile modelling at the SEP site using the Lucke et al. (2009) unweighted $SPL_{peak-to-peak}$ criteria for harbour porpoise

Lucke *et al*. (2009) Unweighted SEL_{ss}	Worst case monopiles (first strike)							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (164.3 dB)	40 km^2	3.8 km	3.4 km	3.6 km	46 km^2	3.9 km	3.7 km	3.8 km
Behavioural (145 dB)	640 km^2	17 km	11 km	14 km	850 km^2	19 km	13 km	16 km

Table A 11 Summary of the first strike impact ranges from worst case monopile modelling at the DEP site using the Lucke et al. (2009) unweighted $SPL_{peak-to-peak}$ criteria for harbour porpoise

Southall *et al*. (2019) Unweighted SPL_{peak}		Worst case pin piles (first strike)							
		SEP E				SEP N			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS	219 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	230 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	202 dB (VHF)	0.04 km^2	120 m	110 m	120 m	0.04 km^2	110 m	110 m	110 m
	218 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	213 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	224 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	196 dB (VHF)	0.25 km^2	280 m	280 m	280 m	0.21 km^2	260 m	260 m	260 m
	212 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A 12 Summary of the first strike impact ranges from worst case pin pile modelling at the SEP site using the Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al*. (2019) Unweighted SPL_{peak}		Worst case pin piles (first strike)							
		DEP NE				DEP SE			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS	219 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	230 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	202 dB (VHF)	0.04 km^2	120 m	120 m	120 m	0.05 km^2	130 m	120 m	130 m
	218 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	213 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	224 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	196 dB (VHF)	0.27 km^2	300 m	290 m	300 m	0.3 km^2	310 m	310 m	310 m
	212 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A 13 Summary of the first strike impact ranges from worst case pin pile modelling at the DEP site using the Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al*. (2019) Weighted SEL_{ss}		Worst case pin piles (first strike)							
		SEP E				**SEP N**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	0.02 km^2	70 m	70 m	70 m	< 0.01 km^2	70 m	60 m	70 m
	185 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	155 dB (VHF)	< 0.01 km^2	50 m	50 m	50 m	< 0.01 km^2	50 m	50 m	50 m
	185 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	168 dB (LF)	1.5 km^2	700 m	700 m	700 m	1.2 km^2	630 m	610 m	620 m
	170 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	140 dB (VHF)	0.4 km^2	360 m	360 m	360 m	0.36 km^2	340 m	340 m	340 m
	170 dB (PCW)	0.02 km^2	80 m	70 m	70 m	0.02 km^2	70 m	70 m	70 m

Table A 14 Summary of the first strike impact ranges from worst case pin pile modelling at the SEP site using the impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al*. (2019) Weighted SEL_{ss}		Worst case pin piles (first strike)							
		DEP NE				**DEP SE**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	0.02 km^2	70 m	70 m	70 m	0.02 km^2	80 m	80 m	80 m
	185 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	155 dB (VHF)	< 0.01 km^2	50 m	50 m	50 m	< 0.01 km^2	50 m	50 m	50 m
	185 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	168 dB (LF)	1.8 km^2	760 m	740 m	750 m	2.0 km^2	810 m	800 m	800 m
	170 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	140 dB (VHF)	0.43 km^2	370 m	370 m	370 m	0.45 km^2	380 m	380 m	380 m
	170 dB (PCW)	0.02 km^2	80 m	80 m	80 m	0.02 km^2	80 m	80 m	80 m

Table A 15 Summary of the first strike impact ranges from worst case pin pile modelling at the DEP site using the impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al*. (2019) Weighted SEL_{ss}		Worst case pin piles (first strike)							
		SEP E				**SEP N**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	198 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	201 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	179 dB (LF)	0.05 km^2	130 m	130 m	130 m	0.04 km^2	120 m	120 m	120 m
	178 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	153 dB (VHF)	< 0.01 km^2	70 m	60 m	70 m	< 0.01 km^2	60 m	60 m	60 m
	181 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A 16 Summary of the first strike impact ranges from worst case pin pile modelling at the SEP site using the non-impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al*. (2019) Weighted SEL_{ss}		Worst case pin piles (first strike)							
		DEP NE				**DEP SE**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	198 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	201 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	179 dB (LF)	0.06 km^2	140 m	140 m	140 m	0.07 km^2	150 m	150 m	150 m
	178 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	153 dB (VHF)	< 0.01 km^2	70 m	70 m	70 m	< 0.01 km^2	70 m	70 m	70 m
	181 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A 17 Summary of the first strike impact ranges from worst case pin pile modelling at the DEP site using the non-impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Lucke *et al*. (2009) Unweighted $SPL_{peak\text{-}to\text{-}peak}$	**Worst case pin piles (first strike)**							
	SEP E				**SEP N**			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (199.7 dB)	0.02 km^2	80 m	70 m	80 m	0.02 km^2	80 m	70 m	80 m
Behavioural (174 dB)	16 km^2	2.4 km	2.2 km	2.3 km	21 km^2	2.7 km	2.5 km	2.6 km

Table A 18 Summary of the first strike impact ranges from worst case pin pile modelling at the SEP site using the Lucke et al. (2009) unweighted $SPL_{peak\text{-}to\text{-}peak}$ criteria for harbour porpoise

Lucke *et al*. (2009) Unweighted $SPL_{peak\text{-}to\text{-}peak}$	**Worst case pin piles (first strike)**							
	DEP NE				**DEP SE**			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (199.7 dB)	0.02 km^2	80 m	70 m	80 m	0.02 km^2	80 m	70 m	80 m
Behavioural (174 dB)	25 km^2	3.0 km	2.7 km	2.8 km	28 km^2	3.0 km	3.0 km	3.0 km

Table A 19 Summary of the first strike impact ranges from worst case pin pile modelling at the DEP site using the Lucke et al. (2009) unweighted $SPL_{peak\text{-}to\text{-}peak}$ criteria for harbour porpoise

Lucke *et al*. (2009) Unweighted SEL_{ss}	**Worst case pin piles (first strike)**							
	SEP E				**SEP N**			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (164.3 dB)	7.6 km^2	1.6 km	1.5 km	1.6 km	9.8 km^2	1.8 km	1.7 km	1.8 km
Behavioural (145 dB)	240 km^2	9.7 km	7.5 km	8.8 km	340 km^2	11 km	9.6 km	10 km

Table A 20 Summary of the first strike impact ranges from worst case pin pile modelling at the SEP site using the Lucke et al. (2009) unweighted $SPL_{peak\text{-}to\text{-}peak}$ criteria for harbour porpoise

Lucke *et al*. (2009) Unweighted SEL_{ss}	**Worst case pin piles (first strike)**							
	DEP NE				**DEP SE**			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (164.3 dB)	11 km^2	2.0 km	1.8 km	1.9 km	13 km^2	2.1 km	2.0 km	2.0 km
Behavioural (145 dB)	350 km^2	12 km	9.4 km	11 km	470 km^2	14 km	10 km	12 km

Table A 21 Summary of the first strike impact ranges from worst case pin pile modelling at the DEP site using the Lucke et al. (2009) unweighted $SPL_{peak\text{-}to\text{-}peak}$ criteria for harbour porpoise

Full energy

Southall *et al*. (2019) Weighted SEL_{ss}		**Worst case monopiles (full energy)**							
		SEP E				**SEP N**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	0.38 km^2	350 m	350 m	350 m	0.31 km^2	320 m	310 m	320 m
	185 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	155 dB (VHF)	0.1 km^2	180 m	180 m	180 m	0.1 km^2	180 m	170 m	180 m
	185 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	168 dB (LF)	22 km^2	2.7 km	2.6 km	2.7 km	17 km^2	2.4 km	2.2 km	2.3 km
	170 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	140 dB (VHF)	4.7 km^2	1.2 km	1.2 km	1.2 km	4.2 km^2	1.2 km	1.1 km	1.2 km
	170 dB (PCW)	0.11 km^2	190 m	190 m	190 m	0.1 km^2	180 m	180 m	180 m

Table A 22 Summary of the full energy single strike impact ranges from worst case monopile modelling at the SEP site using the impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al.* (2019) Weighted SEL_{ss}		Worst case monopiles (full energy)							
		DEP NE				**DEP SE**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	0.43 km^2	370 m	370 m	370 m	0.48 km^2	390 m	390 m	390 m
	185 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	155 dB (VHF)	0.11 km^2	190 m	190 m	190 m	0.11 km^2	190 m	190 m	190 m
	185 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	168 dB (LF)	26 km^2	3.0 km	2.8 km	2.9 km	30 km^2	3.1 km	3.1 km	3.1 km
	170 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	140 dB (VHF)	5.1 km^2	1.3 km	1.3 km	1.3 km	5.5 km^2	1.3 km	1.3 km	1.3 km
	170 dB (PCW)	0.12 km^2	200 m	200 m	200 m	0.13 km^2	210 m	200 m	210 m

Table A 23 Summary of the full energy single strike impact ranges from worst case monopile modelling at the DEP site using the impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al.* (2019) Weighted SEL_{ss}		Worst case monopiles (full energy)							
		SEP E				**SEP N**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	198 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	201 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	179 dB (LF)	1.3 km^2	640 m	630 m	630 m	1.0 km^2	570 m	560 m	570 m
	178 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	153 dB (VHF)	0.18 km^2	240 m	240 m	240 m	0.16 km^2	230 m	230 m	230 m
	181 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A 24 Summary of the full energy single strike impact ranges from worst case monopile modelling at the SEP site using the non-impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al.* (2019) Weighted SEL_{ss}		Worst case monopiles (full energy)							
		DEP NE				**DEP SE**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	198 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	201 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	179 dB (LF)	1.4 km^2	680 m	670 m	680 m	1.6 km^2	720 m	720 m	720 m
	178 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	153 dB (VHF)	0.18 km^2	240 m	240 m	240 m	0.19 km^2	250 m	250 m	250 m
	181 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A 25 Summary of the full energy single strike impact ranges from worst case monopile modelling at the DEP site using the non-impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al.* (2019) Weighted SEL_{ss}		Worst case pin piles (full energy)							
		SEP E				**SEP N**			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	0.24 km^2	280 m	270 m	280 m	0.19 km^2	250 m	250 m	250 m
	185 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	155 dB (VHF)	0.08 km^2	160 m	160 m	160 m	0.07 km^2	150 m	150 m	150 m
	185 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	168 dB (LF)	16 km^2	2.3 km	2.2 km	2.2 km	12 km^2	2.0 km	1.9 km	1.9 km
	170 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	140 dB (VHF)	3.6 km^2	1.1 km	1.1 km	1.1 km	3.1 km^2	1.0 km	990 m	1.0 km
	170 dB (PCW)	0.09 km^2	170 m	170 m	170 m	0.08 km^2	160 m	160 m	160 m

Table A 26 Summary of the full energy single strike impact ranges from worst case pin pile modelling at the SEP site using impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al*. (2019) Weighted SEL_{ss}		Worst case pin piles (full energy)							
		DEP NE				DEP SE			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	0.27 km^2	290 m	290 m	290 m	0.3 km^2	310 m	310 m	310 m
	185 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	155 dB (VHF)	0.08 km^2	160 m	160 m	160 m	0.08 km^2	160 m	160 m	160 m
	185 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	168 dB (LF)	18 km^2	2.5 km	2.3 km	2.4 km	21 km^2	2.6 km	2.6 km	2.6 km
	170 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	140 dB (VHF)	3.8 km^2	1.1 km	1.1 km	1.1 km	4.1 km^2	1.2 km	1.1 km	1.1 km
	170 dB (PCW)	0.1 km^2	180 m	180 m	180 m	0.11 km^2	190 m	190 m	190 m

Table A 27 Summary of the full energy single strike impact ranges from worst case pin pile modelling at the DEP site using impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al*. (2019) Weighted SEL_{ss}		Worst case pin piles (full energy)							
		SEP E				SEP N			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	198 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	201 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	179 dB (LF)	0.79 km^2	500 m	500 m	500 m	0.63 km^2	450 m	450 m	450 m
	178 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	153 dB (VHF)	0.13 km^2	200 m	200 m	200 m	0.12 km^2	200 m	190 m	200 m
	181 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A 28 Summary of the full energy single strike impact ranges from worst case pin pile modelling at the SEP site using non-impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al*. (2019) Weighted SEL_{ss}		Worst case pin piles (full energy)							
		DEP NE				DEP SE			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	198 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	201 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	179 dB (LF)	0.9 km^2	540 m	530 m	540 m	1.0 km^2	580 m	570 m	570 m
	178 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	153 dB (VHF)	0.14 km^2	210 m	210 m	210 m	0.14 km^2	210 m	210 m	210 m
	181 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A 29 Summary of the full energy single strike impact ranges from worst case pin pile modelling at the DEP site using non-impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

A.1.2 Fish

First strike

Popper *et al*. (2014) Unweighted SPL_{peak}	Worst case monopiles (first strike)							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
213 dB	< 0.01 km^2	50 m	50 m	50 m	< 0.01 km^2	50 m	50 m	50 m
207 dB	0.05 km^2	130 m	130 m	130 m	0.04 km^2	120 m	120 m	120 m

Table A 30 Summary of the first strike impact ranges from worst case monopile modelling at the SEP site using the Popper et al. (2014) unweighted SPL_{peak} criteria for fish

Popper *et al*. (2014) Unweighted SPL_{peak}	Worst case monopiles (first strike)							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
213 dB	< 0.01 km^2	50 m	50 m	50 m	< 0.01 km^2	60 m	50 m	60 m
207 dB	0.05 km^2	130 m	130 m	130 m	0.06 km^2	140 m	140 m	140 m

Table A 31 Summary of the first strike impact ranges from worst case monopile modelling at the DEP site using the Popper et al. (2014) unweighted SPL_{peak} criteria for fish

Popper *et al*. (2014) Unweighted SEL_{ss}	Worst case monopiles (first strike)							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
186 dB	0.1 km^2	180 m	180 m	180 m	0.08 km^2	160 m	160 m	160 m

Table A 32 Summary of the first strike impact ranges from worst case monopile modelling at the SEP site using the Popper et al. (2014) unweighted SEL_{ss} criteria for fish

Popper *et al*. (2014) Unweighted SEL_{ss}	Worst case monopiles (first strike)							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
186 dB	0.11 km^2	190 m	180 m	190 m	0.12 km^2	190 m	190 m	190 m

Table A 33 Summary of the first strike impact ranges from worst case monopile modelling at the DEP site using the Popper et al. (2014) unweighted SEL_{ss} criteria for fish

Popper *et al*. (2014) Unweighted SPL_{peak}	Worst case pin piles (first strike)							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	< 0.01 km^2	60 m	50 m	60 m	< 0.01 km^2	50 m	50 m	50 m

Table A 34 Summary of the first strike impact ranges from worst case pin pile modelling at the SEP site using the Popper et al. (2014) unweighted SPL_{peak} criteria for fish

Popper *et al*. (2014) Unweighted SPL_{peak}	Worst case pin piles (first strike)							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	< 0.01 km^2	60 m	60 m	60 m	< 0.01 km^2	60 m	60 m	60 m

Table A 35 Summary of the first strike impact ranges from worst case pin pile modelling at the DEP site using the Popper et al. (2014) unweighted SPL_{peak} criteria for fish

Popper *et al*. (2014) Unweighted SEL_{ss}	Worst case pin piles (first strike)							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
186 dB	0.02 km^2	80 m	80 m	80 m	0.02 km^2	70 m	70 m	70 m

Table A 36 Summary of the first strike impact ranges from worst case pin pile modelling at the SEP site using the Popper et al. (2014) unweighted SEL_{ss} criteria for fish

Popper *et al*. (2014) Unweighted SEL_{ss}	Worst case pin piles (first strike)							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
186 dB	0.02 km^2	80 m	80 m	80 m	0.02 km^2	80 m	80 m	80 m

Table A 37 Summary of the first strike impact ranges from worst case pin pile modelling at the DEP site using the Popper et al. (2014) unweighted SEL_{ss} criteria for fish

Full energy

Popper *et al*. (2014) Unweighted SEL_{ss}	Worst case monopiles (full energy)							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
203 dB	1.1 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
186 dB	210 km^2	370 m	370 m	370 m	0.35 km^2	340 m	330 m	340 m

Table A 38 Summary of the full energy single strike impact ranges from worst case monopile modelling at the SEP site using the Popper et al. (2014) unweighted SEL_{ss} criteria for fish

Popper *et al*. (2014) Unweighted SEL_{ss}	Worst case monopiles (full energy)							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
186 dB	0.47 km^2	390 m	380 m	390 m	0.52 km^2	410 m	410 m	410 m

Table A 39 Summary of the full energy single strike impact ranges from worst case monopile modelling at the DEP site using the Popper et al. (2014) unweighted SEL_{ss} criteria for fish

Popper *et al*. (2014) Unweighted SEL_{ss}	Worst case pin piles (full energy)							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
186 dB	0.23 km^2	280 m	270 m	270 m	0.19 km^2	250 m	250 m	250 m

Table A 40 Summary of the full energy single strike impact ranges from worst case pin pile modelling at the SEP site using the Popper et al. (2014) unweighted SEL_{ss} criteria for fish

Popper *et al*. (2014) Unweighted SEL_{ss}	Worst case pin piles (full energy)							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
186 dB	0.26 km^2	290 m	290 m	290 m	0.29 km^2	310 m	310 m	310 m

Table A 41 Summary of the full energy single strike impact ranges from worst case pin pile modelling at the DEP site using the Popper et al. (2014) unweighted SEL_{ss} criteria for fish

A.2 Most likely parameters

Table (page)	Parameters			Criteria	
Table A 43 (p56)	SEP	Most likely	Monopiles	Southall *et al*. (2019)	Unweighted SPL_{peak} (First strike)
Table A 44 (p57)	DEP				
Table A 45 (p57)	SEP				Weighted SEL_{ss} (impulsive) (First strike)
Table A 46 (p57)	DEP				
Table A 47 (p57)	SEP				Weighted SEL_{ss} (non-impulsive) (First strike)
Table A 48 (p58)	DEP				
Table A 49 (p58)	SEP			Lucke *et al*. (2009)	Unweighted $SPL_{peak\text{-}to\text{-}peak}$
Table A 50 (p58)	DEP				
Table A 51 (p58)	SEP				Unweighted SEL_{ss}
Table A 52 (p58)	DEP				
Table A 53 (p59)	SEP			Southall *et al*. (2019)	Weighted SEL_{ss} (impulsive) (Full energy)
Table A 54 (p59)	DEP				
Table A 55 (p59)	SEP				Weighted SEL_{ss} (non-impulsive) (Full energy)
Table A 56 (p60)	DEP				
Table A 57 (p60)	SEP			Popper *et al*. (2014)	Unweighted SPL_{peak} (First strike)
Table A 58 (p60)	DEP				
Table A 59 (p60)	SEP				Unweighted SEL_{ss} (First strike)
Table A 60 (p60)	DEP				
Table A 61 (p61)	SEP				Unweighted SEL_{ss} (Full energy)
Table A 62 (p61)	DEP				

Table A 42 Summary of the most likely, single strike modelling results tables presented in this section

A.2.1 Marine mammals

Southall *et al*. (2019) Unweighted SPL_{peak}		Most likely monopiles (first strike)							
		SEP E				SEP N			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS	219 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	230 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	202 dB (VHF)	0.1 km^2	180 m	180 m	180 m	0.09 km^2	170 m	170 m	170 m
	218 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	213 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	224 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	196 dB (VHF)	0.59 km^2	440 m	440 m	440 m	0.5 km^2	400 m	400 m	400 m
	212 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A 43 Summary of the first strike impact ranges from most likely monopile modelling at the SEP site using the Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al*. (2019) Unweighted SPL_{peak}		Most likely monopiles (first strike)							
		DEP NE				DEP SE			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS	219 dB (LF)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	230 dB (HF)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	202 dB (VHF)	0.11 km²	190 m	190 m	190 m	0.12 km²	200 m	200 m	200 m
	218 dB (PCW)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS	213 dB (LF)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	224 dB (HF)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	196 dB (VHF)	0.66 km²	460 m	460 m	460 m	0.73 km²	490 m	480 m	480 m
	212 dB (PCW)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m

Table A 44 Summary of the first strike impact ranges from most likely monopile modelling at the DEP site using the Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al*. (2019) Weighted SEL_{ss}		Most likely monopiles (first strike)							
		SEP E				SEP N			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	0.04 km²	110 m	110 m	110 m	0.03 km²	100 m	100 m	100 m
	185 dB (HF)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	155 dB (VHF)	< 0.01 km²	70 m	70 m	70 m	< 0.01 km²	70 m	70 m	70 m
	185 dB (PCW)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	168 dB (LF)	3.5 km²	1.1 km	1.1 km	1.1 km	2.8 km²	960 m	930 m	960 m
	170 dB (HF)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	140 dB (VHF)	0.76 km²	490 m	490 m	490 m	0.68 km²	470 m	460 m	470 m
	170 dB (PCW)	0.03 km²	100 m	100 m	100 m	0.03 km²	100 m	90 m	100 m

Table A 45 Summary of the first strike impact ranges from most likely monopile modelling at the SEP site using the impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al*. (2019) Weighted SEL_{ss}		Most likely monopiles (first strike)							
		DEP NE				DEP SE			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	0.04 km²	120 m	120 m	120 m	0.05 km²	120 m	120 m	120 m
	185 dB (HF)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	155 dB (VHF)	0.02 km²	70 m	70 m	70 m	0.02 km²	70 m	70 m	70 m
	185 dB (PCW)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	168 dB (LF)	4.1 km²	1.2 km	1.1 km	1.1 km	4.7 km²	1.2 km	1.2 km	1.2 km
	170 dB (HF)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	140 dB (VHF)	0.8 km²	510 m	510 m	510 m	0.85 km²	520 m	520 m	520 m
	170 dB (PCW)	0.03 km²	110 m	100 m	100 m	0.04 km²	110 m	110 m	110 m

Table A 46 Summary of the first strike impact ranges from most likely monopile modelling at the DEP site using the impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al*. (2019) Weighted SEL_{ss}		Most likely monopiles (first strike)							
		SEP E				SEP N			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	198 dB (HF)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	201 dB (PCW)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	179 dB (LF)	0.14 km²	210 m	210 m	210 m	0.11 km²	190 m	190 m	190 m
	178 dB (HF)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m
	153 dB (VHF)	0.02 km²	90 m	90 m	90 m	0.02 km²	90 m	90 m	90 m
	181 dB (PCW)	< 0.01 km²	< 50 m	< 50 m	< 50 m	< 0.01 km²	< 50 m	< 50 m	< 50 m

Table A 47 Summary of the first strike impact ranges from most likely monopile modelling at the SEP site using the non-impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al*. (2019) Weighted SEL_{ss}		Most likely monopiles (first strike)							
		DEP NE				DEP SE			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	198 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	201 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	179 dB (LF)	0.15 km^2	220 m	220 m	220 m	0.17 km^2	230 m	230 m	230 m
	178 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	153 dB (VHF)	0.03 km^2	90 m	90 m	90 m	0.03 km^2	90 m	90 m	90 m
	181 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A 48 Summary of the first strike impact ranges from most likely monopile modelling at the DEP site using the non-impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Lucke *et al*. (2009) Unweighted $SPL_{peak\text{-}to\text{-}peak}$	Most likely monopiles (first strike)							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (199.7 dB)	0.03 km^2	110 m	100 m	110 m	0.04 km^2	120 m	110 m	120 m
Behavioural (174 dB)	30 km^2	3.3 km	3.0 km	3.1 km	40 km^2	3.7 km	3.4 km	3.6 km

Table A 49 Summary of the first strike impact ranges from most likely monopile modelling at the SEP site using the Lucke et al. (2009) unweighted $SPL_{peak\text{-}to\text{-}peak}$ criteria for harbour porpoise

Lucke *et al*. (2009) Unweighted $SPL_{peak\text{-}to\text{-}peak}$	Most likely monopiles (first strike)							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (199.7 dB)	0.04 km^2	120 m	110 m	120 m	0.05 km^2	130 m	120 m	130 m
Behavioural (174 dB)	45 km^2	4.0 km	3.6 km	3.8 km	52 km^2	4.2 km	4.0 km	4.1 km

Table A 50 Summary of the first strike impact ranges from most likely monopile modelling at the DEP site using the Lucke et al. (2009) unweighted $SPL_{peak\text{-}to\text{-}peak}$ criteria for harbour porpoise

Lucke *et al*. (2009) Unweighted SEL_{ss}	Most likely monopiles (first strike)							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (164.3 dB)	16 km^2	2.3 km	2.2 km	2.2 km	20 km^2	2.6 km	2.5 km	2.5 km
Behavioural (145 dB)	350 km^2	12 km	8.5 k	11 km	480 km^2	14 km	11 km	12 km

Table A 51 Summary of the first strike impact ranges from most likely monopile modelling at the SEP site using the Lucke et al. (2009) unweighted $SPL_{peak\text{-}to\text{-}peak}$ criteria for harbour porpoise

Lucke *et al*. (2009) Unweighted SEL_{ss}	Most likely monopiles (first strike)							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
TTS (164.3 dB)	23 km^2	2.9 km	2.6 km	2.7 km	27 km^2	3.0 km	2.9 km	2.9 km
Behavioural (145 dB)	500 km^2	15 km	11 km	13 km	660 km^2	17 km	12 km	14 km

Table A 52 Summary of the first strike impact ranges from most likely monopile modelling at the DEP site using the Lucke et al. (2009) unweighted $SPL_{peak\text{-}to\text{-}peak}$ criteria for harbour porpoise

Full energy

Southall *et al.* (2019) Weighted SEL_{ss}		Most likely monopiles (full energy)							
		SEP E				SEP N			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	0.35 km^2	330 m	330 m	330 m	0.28 km^2	300 m	300 m	300 m
	185 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	155 dB (VHF)	0.1 km^2	180 m	170 m	180 m	0.09 km^2	170 m	170 m	170 m
	185 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	168 dB (LF)	21 km^2	2.6 km	2.5 km	2.6 km	16 km^2	2.3 km	2.2 km	2.2 km
	170 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	140 dB (VHF)	4.4 km^2	1.2 km	1.2 km	1.2 km	3.8 km^2	1.1 km	1.1 km	1.1 km
	170 dB (PCW)	< 0.01 km^2	190 m	190 m	190 m	0.09 km^2	170 m	170 m	170 m

Table A 53 Summary of the full energy single strike impact ranges from most likely monopile modelling at the SEP site using the impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al.* (2019) Weighted SEL_{ss}		Most likely monopiles (full energy)							
		DEP NE				DEP SE			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Impulsive)	183 dB (LF)	0.39 km^2	360 m	350 m	350 m	0.43 km^2	370 m	370 m	370 m
	185 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	155 dB (VHF)	0.1 km^2	180 m	180 m	180 m	0.1 km^2	180 m	180 m	180 m
	185 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	168 dB (LF)	24 km^2	2.9 km	2.7 km	2.8 km	28 km^2	3.0 km	2.9 km	3.0 km
	170 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	140 dB (VHF)	4.7 km^2	1.2 km	1.2 km	1.2 km	5.1 km^2	1.3 km	1.3 km	1.3 km
	170 dB (PCW)	0.12 km^2	200 m	190 m	190 m	0.13 km^2	200 m	200 m	200 m

Table A 54 Summary of the full energy single strike impact ranges from most likely monopile modelling at the DEP site using the impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al.* (2019) Weighted SEL_{ss}		Most likely monopiles (full energy)							
		SEP E				SEP N			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	198 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	201 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	179 dB (LF)	1.1 km^2	610 m	600 m	610 m	0.92 km^2	550 m	540 m	540 m
	178 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	153 dB (VHF)	0.16 km^2	230 m	230 m	230 m	0.15 km^2	220 m	220 m	220 m
	181 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A 55 Summary of the full energy single strike impact ranges from most likely monopile modelling at the SEP site using the non-impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

Southall *et al*. (2019) Weighted SEL_{ss}		Most likely monopiles (full energy)							
		DEP NE				DEP SE			
		Area	Max	Min	Mean	Area	Max	Min	Mean
PTS (Non-impulsive)	199 dB (LF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	198 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	201 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Non-impulsive)	179 dB (LF)	1.3 km^2	650 m	640 m	650 m	1.5 km^2	690 m	680 m	690 m
	178 dB (HF)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	153 dB (VHF)	0.17 km^2	230 m	230 m	230 m	0.18 km^2	240 m	240 m	240 m
	181 dB (PCW)	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table A 56 Summary of the full energy single strike impact ranges from most likely monopile modelling at the DEP site using the non-impulsive Southall et al. (2019) weighted SEL_{ss} criteria for marine mammals

A.2.2 Fish

First strike

Popper *et al*. (2014) Unweighted SPL_{peak}	Most likely monopiles (first strike)							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	0.02 km^2	90 m	90 m	90 m	0.02 km^2	80 m	80 m	80 m

Table A 57 Summary of the first strike impact ranges from most likely monopile modelling at the SEP site using the Popper et al. (2014) unweighted SPL_{peak} criteria for fish

Popper *et al*. (2014) Unweighted SPL_{peak}	Most likely monopiles (first strike)							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	0.02 km^2	90 m	90 m	90 m	0.03 km^2	90 m	90 m	90 m

Table A 58 Summary of the first strike impact ranges from most likely monopile modelling at the DEP site using the Popper et al. (2014) unweighted SPL_{peak} criteria for fish

Popper *et al*. (2014) Unweighted SEL_{ss}	Most likely monopiles (first strike)							
	SEP E				SEP N			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
186 dB	0.05 km^2	120 m	120 m	120 m	0.04 km^2	110 m	110 m	110 m

Table A 59 Summary of the first strike impact ranges from most likely monopile modelling at the SEP site using the Popper et al. (2014) unweighted SEL_{ss} criteria for fish

Popper *et al*. (2014) Unweighted SEL_{ss}	Most likely monopiles (first strike)							
	DEP NE				DEP SE			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
186 dB	0.05 km^2	130 m	130 m	130 m	0.05 km^2	130 m	130 m	130 m

Table A 60 Summary of the first strike impact ranges from most likely monopile modelling at the DEP site using the Popper et al. (2014) unweighted SEL_{ss} criteria for fish

Full energy

Popper *et al*. (2014) Unweighted SEL_{ss}	**Most likely monopiles (full energy)**							
	SEP E				**SEP N**			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
186 dB	0.38 km^2	350 m	350 m	350 m	0.32 km^2	320 m	320 m	320 m

Table A 61 Summary of the full energy single strike impact ranges from most likely monopile modelling at the SEP site using the Popper et al. (2014) unweighted SEL_{ss} criteria for fish

Popper *et al*. (2014) Unweighted SEL_{ss}	**Most likely monopiles (full energy)**							
	DEP NE				**DEP SE**			
	Area	Max	Min	Mean	Area	Max	Min	Mean
219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
216 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
210 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
203 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m	< 0.01 km^2	< 50 m	< 50 m	< 50 m
186 dB	0.42 km^2	370 m	360 m	370 m	0.46 km^2	390 m	390 m	390 m

Table A 62 Summary of the full energy single strike impact ranges from most likely monopile modelling at the DEP site using the Popper et al. (2014) unweighted SEL_{ss} criteria for fish

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