RWE Renewables UK Dogger Bank South (West) Limited

RWE Renewables UK Dogger Bank South (East) Limited

Dogger Bank South Offshore Wind Farms

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Dogger Bank South: Underwater Noise Assessment

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Glossary

Term	Definition
Decibel (dB)	A customary scale commonly used (in various ways) for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be $10\log_{10}(actual/reference)$ where $(actual/reference)$ is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is $20\log_{10}(actual\ pressure/reference\ pressure)$. The standard reference for underwater sound is 1 micro pascal (μPa). The dB symbol is followed by a second symbol identifying the specific reference value (e.g., re 1 μPa).
Peak pressure	The highest pressure above or below ambient that is associated with a sound wave.
Peak-to-peak pressure	The sum of the highest positive and negative pressures that are associated with a sound wave.
Permanent Threshold Shift (PTS)	Onset of a permanent total or partial loss of hearing caused by acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the air, and thus a permanent reduction of hearing acuity.
Root Mean Square (RMS)	The square root of the arithmetic average of a set of squared instantaneous values. Used for presentation of an average sound pressure level.
Sound Exposure Level (SEL)	The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.
Sound Exposure Level, cumulative (SEL_{cum})	Single value for the collected, combined total of sound exposure over a specified time or multiple instances of a noise source.
Sound Exposure Level, single strike (SEL_{ss})	Calculation of the sound exposure level representative of a single noise impulse, typically a pile strike.
Sound Pressure Level (SPL)	The sound pressure level is an expression of sound pressure using the decibel (dB) scale; the standard frequency pressures of which are 1 μPa for water and 20 μPa for air.
Sound Pressure Level Peak (SPL_{peak})	The highest (zero-peak) positive or negative sound pressure, in decibels.
Temporary Threshold Shift (TTS)	Onset of a temporary reduction of hearing acuity because of exposure to sound over time. Exposure to high levels of sound over relatively short time periods could cause the same level of TTS as exposure to lower levels of sound over longer time periods. The 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.

Acronyms

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

Units

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

1 Introduction

The Dogger Bank South (DBS) offshore wind farm projects are located in the North Sea more than 100 km off the northeast coast of England and consist of two adjacent sites, DBS East and DBS West. As part of the Environmental Impact Assessment (EIA), Subacoustech Environmental Ltd. have undertaken detailed modelling and analysis in relation to the effect of underwater noise on marine mammals and fish at the sites.

The DBS sites cover a combined area of over 700 km^2, utilising up to 200 wind turbine generators (WTGs). The location of the two DBS sites is shown in Figure 1-1.

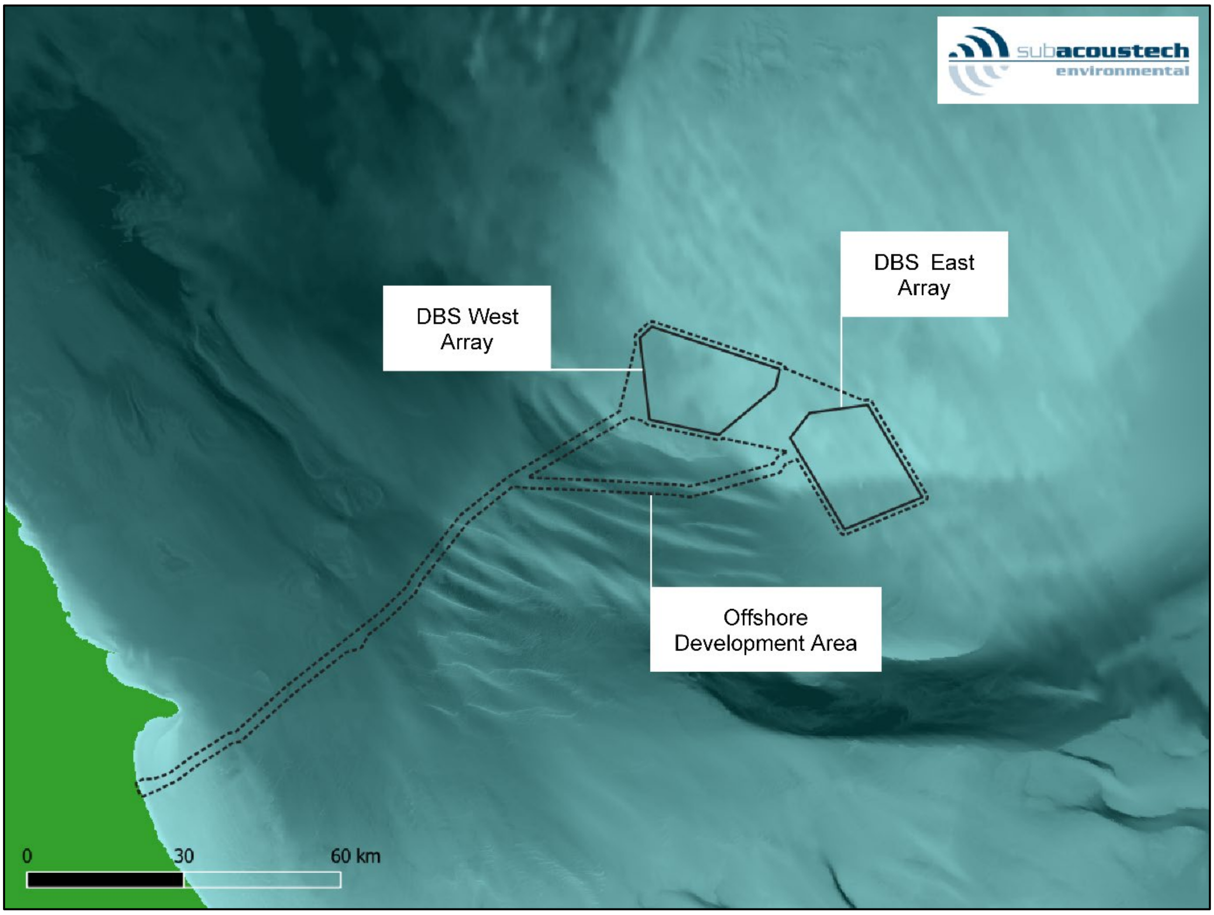

Figure 1-1 Overview map showing the DBS site boundaries and the surrounding bathymetry in the North Sea

This report presents a detailed assessment of the potential underwater noise during the construction and operation of DBS, and includes the following:

- Background information covering the units used for measuring and assessing underwater noise and a review of the underwater noise metrics and criteria used to assess the possible environmental effect in marine receptors (section 2);
- A brief discussion of baseline ambient noise (section 3);
- Discussion of the modelling approach, input parameters and assumptions made in the detailed noise modelling undertaken (section 4);
- Presentation and interpretation of the detailed subsea noise modelling for impact piling with regards to its effect on marine mammals and fish (section 5);

- Noise modelling of the other noise sources expected around the construction and operation of DBS including cable laying, dredging, drilling, rock placement, vessel movements, operational WTG noise and unexploded ordnance (UXO) clearance (section 6); and
- Summary and conclusions (section 7).

Additional modelling results for non-impulsive noise impact criteria are presented in Appendix A.

To note, revision 2 of this document also incorporates amendments in response to the Marine Management Organisation's relevant representation (see RR-030:5.7.2, RR-030: 5.7.4, and RR-030: 5.7.13 in **The Applicants' Responses to Relevant Representations** [PDA-013]). Namely, minor amendments have been made to Table 4-2 and Table 6-9:

- Table 4-2 – contained an incorrect value of 5 hours, 10 mins for the 6,000 kJ modelling, which has been amended to 4 hours, 10mins.
- Table 6-9 – contained incorrect values for low yield of 281.9 dB re 1 µPa @ 1 m for SPL_{peak} source level and 276.6 dB re 1 µPa2s @ 1 m for SE_{Lss} source level. These have been amended to 273.4 dB re 1 µPa @ 1 m for SPL_{peak} source level and 218.2 dB re 1 µPa^{2}s @ 1 m for SEL_{ss} source level.

Further text, as presented in RR-030: 5.7.12, has also been included within section 5.4 in response to RR-030: 5.7.13.

2 Background to underwater noise metrics

2.1 Underwater noise

Sound travels much faster in water (approximately 1500 ms^{-1}) than in air (340 ms^{-1}). Since water is a relatively incompressible, dense medium, the pressure associated with underwater sound tends to be much higher than in air.

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

2.1.1 Units of measurement

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

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

The fundamental definition of the dB scale is given by:

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

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

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

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

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

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

2.1.2 Sound Pressure Level (SPL)

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

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

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

2.1.3 Peak Sound Pressure Level (SPL_{peak})

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

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

2.1.4 Sound Exposure Level (SEL)

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

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

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

where p is the acoustic pressure in Pascals, T is the total duration of sound in seconds, and t is time in seconds. The SE is a measurement of acoustic energy and has units of Pascal squared seconds (Pa^2s).

To express the SE on a logarithmic scale by means of a dB, it must be compared with a reference acoustic energy (${p^2}_{ref}$) and a reference time (T_{ref}). The 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 using 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 (i.e., fractions of) one second, the SEL will be lower than the SPL. For periods greater than one second, the SEL will be numerically greater than the SPL (i.e., for a continuous sound of 10 seconds duration, the SEL will be 10 dB higher than the SPL; for a sound of 100 seconds duration the SEL will be 20 dB higher than the SPL, and so on).

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

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

Where SEL is the sound exposure level of one impulse and X is the total number of impulses or strikes. Unless otherwise defined, all SEL noise levels in this report are referenced to 1 μPa²s.

2.2 Analysis of environmental effects

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

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

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

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

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

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

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

2.2.1 <u>Marine mammals</u>

The Southall *et al*. (2019) paper provides identical thresholds to those from the National Marine Fisheries Service (NMFS) (2018) guidance for marine mammals (although describing marine mammal categories slightly differently).

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

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

Hearing group	Generalised hearing range	Example species
Low-frequency cetaceans (LF)	7 Hz to 35 kHz	Baleen whales
High-frequency cetaceans (HF)	150 Hz to 160 kHz	Dolphins, toothed whales, beaked whales, bottlenose whales (including bottlenose dolphin)
Very high-frequency cetaceans (VHF)	275 Hz to 160 kHz	True porpoises (including harbour porpoise)
Phocid carnivores in water (PCW)	50 Hz to 86 kHz	True seals (including harbour seals)

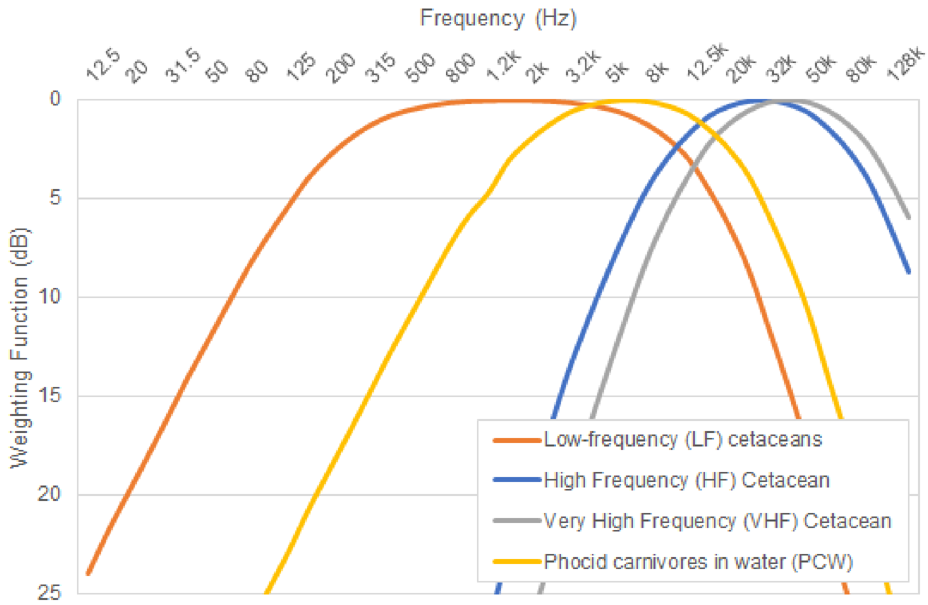

Figure 2-1 Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al., 2019)

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

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

As sound pulses propagate through the environment and dissipate, they also lose their most injurious characteristics (e.g., rapid pulse rise time and high peak sound pressure) and become more like a “non-pulse” at greater distances; Southall *et al*. (2019) briefly discusses this. Active research is currently underway into the identification of the distance at which the pulse can be considered effectively non-impulsive, and Hastie *et al*. (2019) have analysed a series of impulsive data to investigate it. Although the situation is complex, the paper reported that most of the signals crossed their threshold for rapid rise time and high peak sound pressure characteristics associated with impulsive noise at around 3.5 km from the source. Southall (2021) discusses this further and suggests that the impulsive characteristics can correspond with significant energy content of the pulse above 10 kHz. This will naturally change depending on the noise source and the environment over which it travels.

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

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

Table 2-2 and Table 2-3 present the unweighted SPL_{peak} and weighted SEL_{cum} criteria for marine mammals from Southall *et al*. (2019) covering both impulsive and non-impulsive noise.

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

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

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

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

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

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. 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; groups for sea turtles and fish eggs and larvae are also included. The guidance also gives specific criteria (as both unweighted SPL_{peak} and unweighted SEL_{cum} values) for a variety of noise sources. (It is recognised that these are related to sound pressure, whereas more recent documents (e.g., Popper and Hawkins, 2019) clearly state that many fish species are most sensitive to particle motion. This is discussed in section 2.2.2.1.)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2.2.2.1 Particle motion

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

Note that species in the “Fish: swim bladder involved in hearing” category, the species most sensitive to noise, are sensitive to sound pressure.

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

The primary reason for the continuing use of sound pressure as criteria metric, despite particle motion appearing to be the physical measure to which so many fish react or sense, is a lack of data (Popper and Hawkins, 2018) both in respect of predictions of the particle motion level as a consequence of a noise source such as piling, and a lack of knowledge of the sensitivity of a fish, or a wider category of fish, to a particle motion value. There continue to be calls for additional research on the levels of and effects with respect to levels of particle motion. Until sufficient data are available to enable revised thresholds based on the particle motion metric, Popper and Hawkins, 2019 states that “since there is an immediate need for updated criteria and guidelines on potential effects of anthropogenic sound on fishes, we recommend, as do our colleagues in Sweden (Andersson *et al*., 2017), that the criteria proposed by Popper *et al*. (2014) should be used.”

3 Baseline ambient noise

The baseline noise level in open water, in the absence of any specific anthropogenic noise source, is generally dependent on a mix of the movement of the water and sediment, weather conditions and shipping. There is a component of biological noise from marine mammal and fish vocalisation, as well as an element from invertebrates.

Outside of the naturally occurring ambient noise, man-made noise dominates the background. The North Sea is heavily shipped by fishing, cargo, and passenger vessels, which contribute to the ambient noise in the water. The larger vessels are not only louder but the noise tends to have a lower frequency, which travels more readily, especially in the deeper open water. Other vessels such as dredgers and small fishing boats have a lower overall contribution. There are no known dredging areas, active dredge zones, or dredging application options and prospecting areas within or in close proximity to DBS.

Typical underwater noise levels show a frequency dependency in relation to different noise sources; the classic curves are given in Wenz (1962) and are reproduced in Figure 3-1 below. Figure 3-1 shows that any unweighted overall (i.e., single-figure non-frequency-dependent) noise level is typically dependent on the very low frequency element of the noise. The introduction of a nearby anthropogenic noise source (such as piling or sources involving engines) will tend to increase the noise levels in the 100 Hz to 1 kHz region, but to a lesser extent will also extend into higher and lower frequencies.

There is minimal available background noise information taken directly at the Dogger Bank area of the North Sea. Some baseline noise data is available from monitoring undertaken at the Hornsea development areas, where spot measurements were taken which monitored the ambient noise levels between the 6th and 21st October 2020. The measurements taken during this survey identified the main contributing sources of noise that make up the ambient noise environment in the North Sea around the Hornsea wind farm developments. While it is recognised that this is in a more southern area of the North Sea, both locations are subject to similar ambient noise, such as shipping traffic. Although this survey was taken in 2020, it is expected that to represent a best estimate of the subsea noise levels in this region prior to installation of WTGs in the absence of anything more location specific.

The overview of the entire monitoring period showed that the range of underwater noise levels typically lie, with isolated exceptions, between 114 dB and 134 dB re 1 µPa SPL_{RMS}. Two primary sources influence the noise levels: flow-related noise associated with tides moving material on the seabed and vessel noise. The highest noise levels above are produced at times of greatest currents and the passing of vessels, whereas the quietest noise levels are at slack water with no significant anthropogenic influence.

The lowest noise levels were sampled in the absence of vessel movements and at slack water.

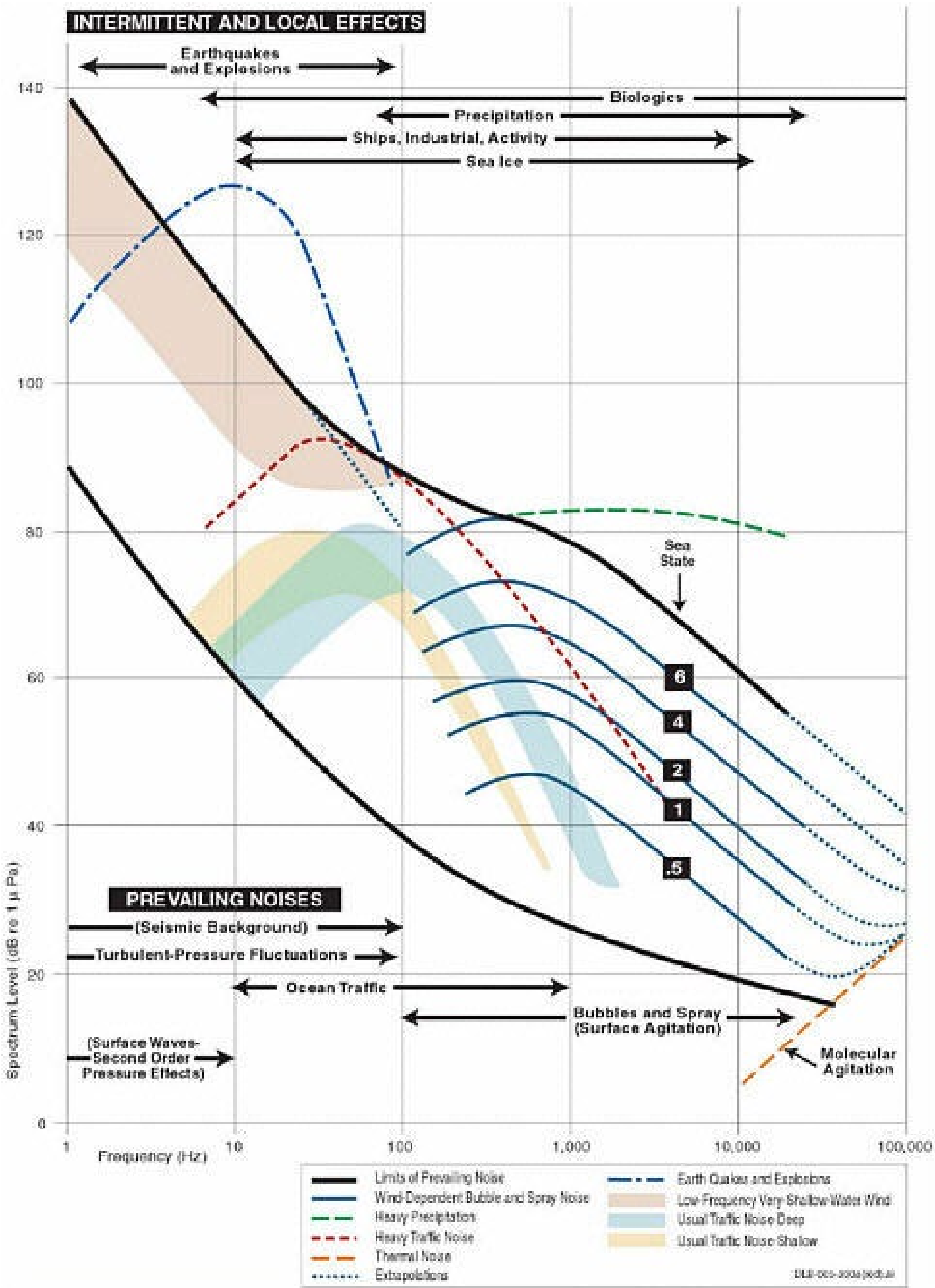

Figure 3-1 Ambient underwater noise following Wenz (1962) showing frequency dependency from different noise sources.

In principle, when noise introduced by anthropogenic sources propagates far enough it will reduce to the level of ambient noise, at which point it can be considered negligible. In practice, as the underwater noise thresholds defined in section 2.2 are all considerably above the level of background noise, any noise baseline would not influence an assessment to these criteria.

4 Modelling methodology

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

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

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

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

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

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

Simpler modelling approaches have been used for noise sources other than piling that may be present during the construction and operation of DBS. These are discussed in section 6.

4.1 Modelling confidence

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

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

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

Previous iterations of the INSPIRE model have endeavoured to give a worst-case estimate of underwater noise levels produced by various permutations of impact piling parameters. There is always some natural variability with underwater noise measurements, even when considering measurements of pile strikes under the same conditions (i.e., at the same blow energy, taken at the same range). For example, there can be variations in noise level of up to five or even 10 dB, as seen in Bailey *et al*. (2010) and the data shown in Figure 4-1. When modelling using the upper bounds of this range, in combination with other worst-case parameter selections, conservatism can be compounded to create excessively overcautious predictions, especially when calculating SEL_{cum}. With this in mind, the current version of INSPIRE attempts to calculate closer to the average fit of the measured noise levels at all ranges.

Figure 4-1 and Figure 4-2 present a small selection of the measured impact piling noise data, in terms of unweighted SPL_{peak} and SEL_{ss}, plotted against outputs from INSPIRE. The plots show data points from measured data (in blue) plotted alongside modelled data (in orange) using INSPIRE v5.2, matching the pile size, blow energy and position of the measured data. These show the fit to the data, with the INSPIRE data points sitting, more or less, in the middle of the measured noise levels at each range. When combined with the worst-case assumptions in parameter selection, modelled results will remain precautionary.

The greatest deviations from the model tend to be at the greatest distances, where the influence on the SEL_{cum} will be minimal.

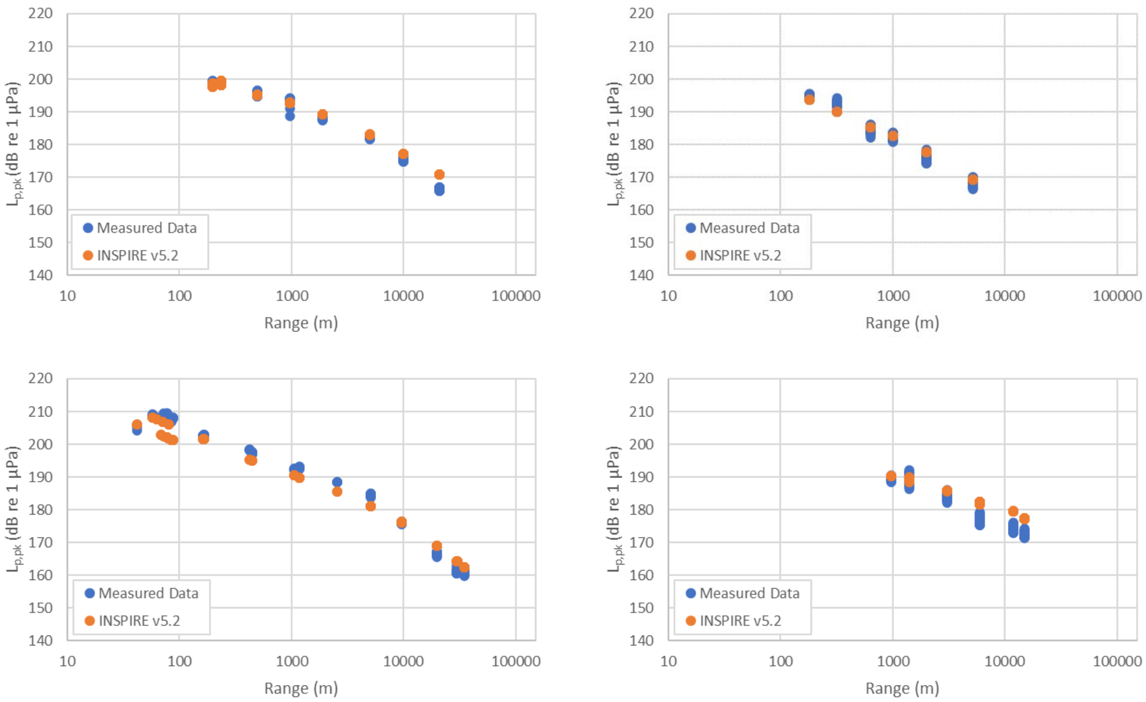

Figure 4-1 Comparison between example unweighted SPL_{peak} measured impact piling data (blue points) and modelled data using INSPIRE version 5.2 (orange points) [1]

[1] Top Left: 6.0 m pile, 1,010 kJ max hammer energy, off the Suffolk coast, North Sea, 2009; Top Right: 1.8 m pile, 260 kJ max hammer energy, West of Barrow-in-Furness, Irish Sea, 2010; Bottom Left: 5.3 m pile, 1,560 kJ max hammer energy, off the North Welsh coast, 2012; Bottom Right: 9.5 m pile, 1,600 kJ max hammer energy, North Sea, 2020.

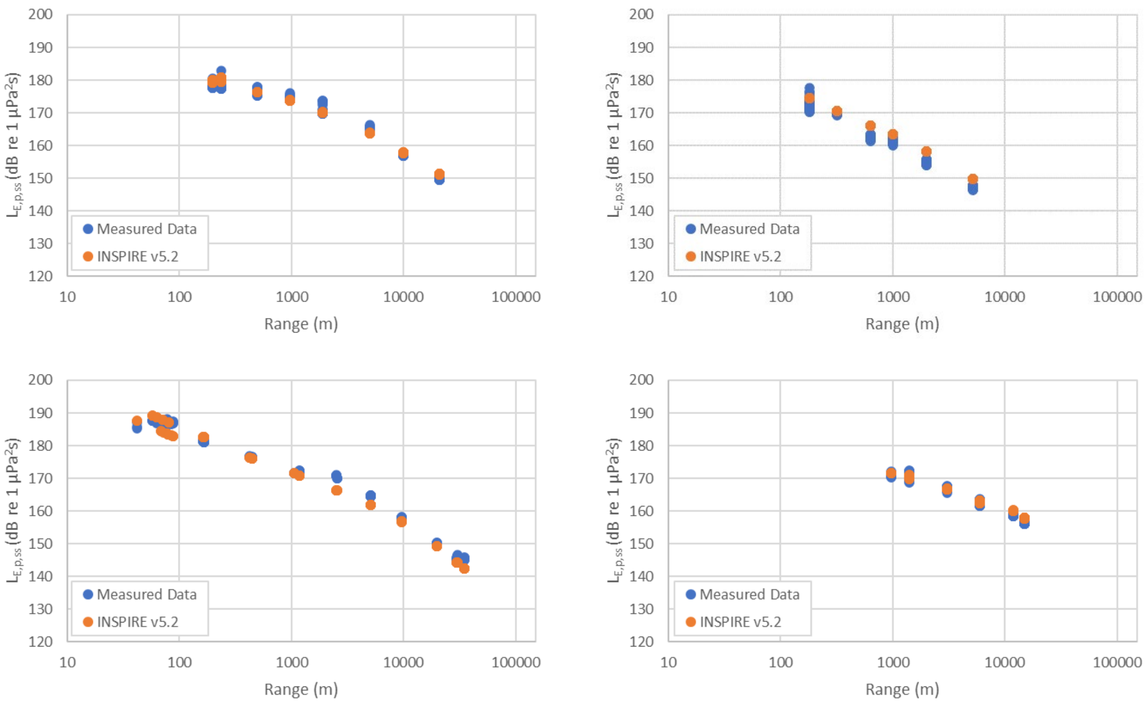

Figure 4-2 Comparison between example unweighted SEL_{ss} measured impact piling data (blue points) and modelled data using INSPIRE version 5.2 (orange points)[2]

4.2 Modelling parameters

4.2.1 Modelling locations

Modelling for impact piling has been undertaken at four representative locations covering the extents and various water depths of the two wind farm sites.

- DBS East: South (S) location – located at the southernmost extent of the DBS East site, the closest point to the deep-water Outer Silver Pit to the south;
- DBS East: North West (NW) location – located in the shallow water of Dogger Bank at the north western point of the DBS East site;
- DBS West: North East (NE) location – located in the shallow water of Dogger Bank at the north east corner of the DBS West site; and
- DBS West: West (W) location – located at the westernmost point of the DBS West site, closest to the deep water to the west of the DBS site.

These locations are illustrated in Figure 4-3 and summarised in Table 4-1.

[2] Top Left: 6.0 m pile, 1,010 kJ max hammer energy, off the Suffolk coast, North Sea, 2009; Top Right: 1.8 m pile, 260 kJ max hammer energy, West of Barrow-in-Furness, Irish Sea, 2010; Bottom Left: 5.3 m pile, 1,560 kJ max hammer energy, off the North Welsh coast, 2012; Bottom Right: 9.5 m pile, 1,600 kJ max hammer energy, North Sea, 2020.

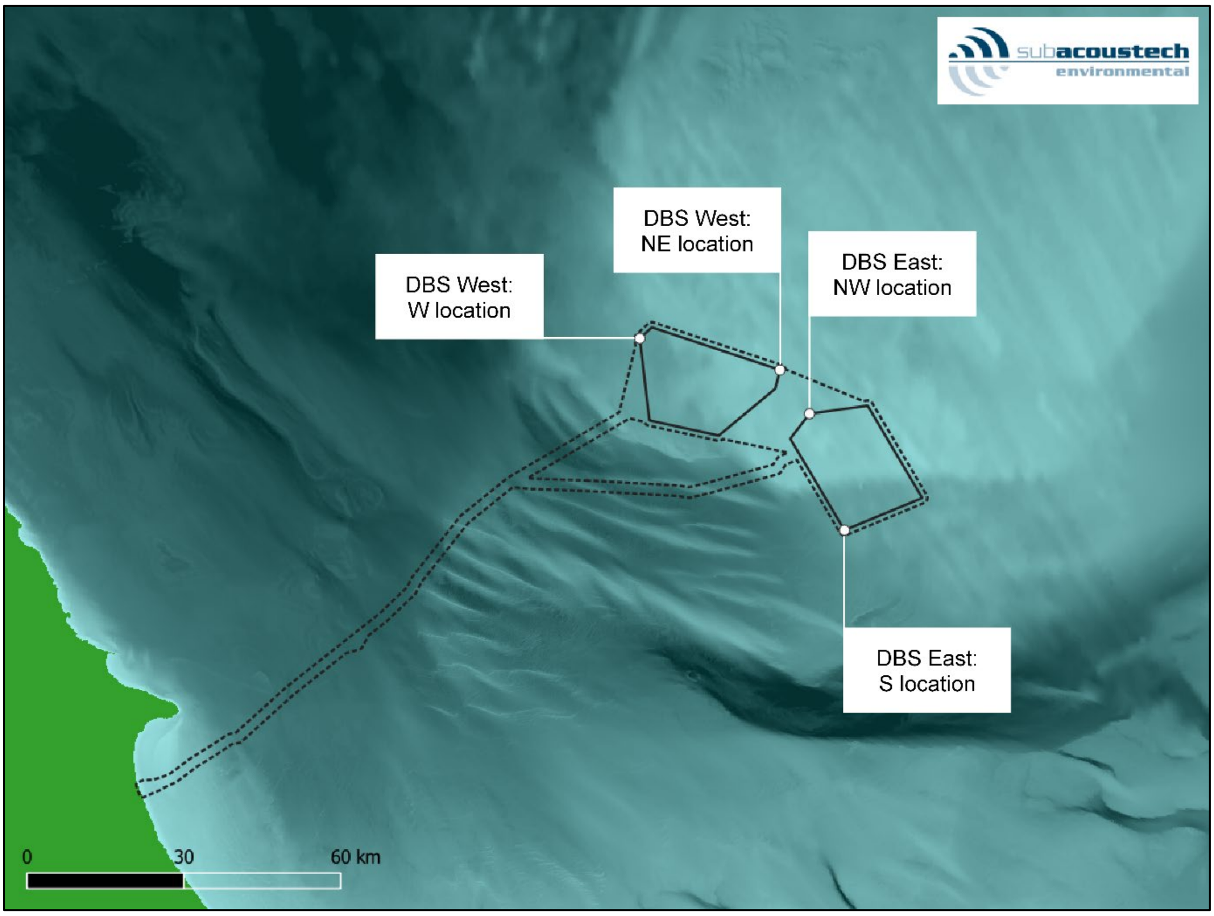

Figure 4-3 Approximate positions of the modelling locations at DBS

Table 4-1 Summary of the underwater noise modelling locations used for this study

Modelling locations	Latitude	Longitude	Water depth
DBS East: S location	54.35994°N	001.899883°E	36.52 m
DBS East: NW location	54.56375°N	001.821029°E	18.62 m
DBS West: NE location	54.64222°N	001.742604°E	21.15 m
DBS West: W location	54.71146°N	001.334179°E	33.65 m

4.2.2 WTG foundation and impact piling parameters

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

- A monopile foundation scenario, installing a 15 m diameter pile with a maximum blow energy of 6,000 kJ; and
- Multi-leg foundation scenarios, installing a 4 m diameter pile with a maximum blow energy of 3,000 kJ.

For SEL_{cum} criteria, the soft start and ramp up of blow energies along with the total duration of piling and strike rate must also be considered. These are summarised for the two foundation scenarios in Table 4-2 and Table 4-3.

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

Table 4-2 Summary of the soft start and ramp up scenario used for the monopile foundation modelling

Monopile foundation	900 kJ	1,500 kJ	3,000 kJ	4,500 kJ	6,000 kJ
No. of strikes	100	800	800	800	5,000
Duration	10 mins	20 mins	20 mins	20 mins	4 hours, 10 mins
Strike rate	10 bl/min	40 bl/min			20 bl/min
7,500 strikes over 5 hours 20 mins per pile 15,000 strikes over 10 hours 40 mins for 2 piles (max piles per day)					

Table 4-3 Summary of the soft start and ramp up scenario used for the multi-leg foundation modelling

Multi-leg foundation	450 kJ	750 kJ	1,500 kJ	2,250 kJ	3,000 kJ
No. of strikes	100	800	800	800	2,400
Duration	10 mins	20 mins	20 mins	20 mins	2 hours
Strike rate	10 bl/min	40 bl/min			20 bl/min
4,900 strikes over 3 hours 10 mins per pile 19,600 strikes over 12 hours 40 mins for 4 piles (max piles per day)					

There is also the potential for multiple piling rigs to be operating concurrently. Scenarios have been chosen that lead to the greatest (i.e. worst case) impact ranges, generally where the rigs are operating at the greatest separation between piling locations. This has been done for both monopile and multi-leg foundation types, where up to two rigs could be present.

Where the multiple location concurrent piling has been modelled, the following scenarios have been considered:

- Monopile foundation concurrent piling scenario (total 4 piles per day):
  - Two sequentially installed piles at DBS East: S location; and
  - Two sequentially installed piles at DBS West: W location.
- Multi-leg foundation concurrent piling scenario (total 8 piles per day):
  - Four sequentially installed piles at DBS East: S location; and
  - Four sequentially installed piles at DBS West: W location.

It is worth noting the precaution present in these multiple location scenarios. In an effort to minimise the risk under-prediction of the potential impact ranges that could occur in respect of sensitive marine mammal and fish receptors, conservative parameters are included for every element. The possibility that all of these could occur together is highly unlikely, but necessary for the purposes of the assessment.

4.2.3 Apparent source levels

Noise modelling requires knowledge of a source level, which is the theoretical noise level at one metre from the noise source. The INSPIRE model assumes that the noise source – that is, the hammer striking the pile – effectively acts as a single point, as it will appear at a distance. The source level is estimated based on the pile diameter and blow energy imparted on the pile by the hammer. This is adjusted depending on the water depth at the modelling location to allow for the length of the pile (and effective surface area) in contact with the water, which can affect the amount of noise that is transmitted from the pile into its surroundings.

It is worth noting that the 'source level' technically does not exist in the context of many shallow water (< 100 m) noise sources (Heaney *et al*., 2020). In practice, for underwater noise modelling such as this, it is effectively an 'apparent source level' that is used; essentially a value that can be used to produce correct noise levels at range (for a specific model), as required in impact assessments.

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

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

Apparent source levels	**Location**	**Monopile foundation** 15 m / 6,000 kJ	**Multi-leg foundation** 4 m / 3,000 kJ
Unwtd SPL_{peak}	DBS East: S location	243.0 dB re 1 μPa @ 1 m	241.7 dB re 1 μPa@ 1 m
	DBS East: NW location	243.0 dB re 1 μPa@ 1 m	241.5 dB re 1 μPa@ 1 m
	DBS West: NE location	243.0 dB re 1 μPa@ 1 m	241.6 dB re 1 μPa@ 1 m
	DBS West: W location	243.0 dB re 1 μPa@ 1 m	241.7 dB re 1 μPa@ 1 m
Unwtd SEL_{ss}	DBS East: S location	224.2 dB re 1 μPa²s@ 1 m	222.5 dB re 1 μPa²s@ 1 m
	DBS East: NW location	224.2 dB re 1 μPa²s@ 1 m	222.2 dB re 1 μPa²s@ 1 m
	DBS West: NE location	224.2 dB re 1 μPa²s@ 1 m	222.3 dB re 1 μPa²s@ 1 m
	DBS West: W location	224.2 dB re 1 μPa²s@ 1 m	222.5 dB re 1 μPa²s@ 1 m

4.2.4 Environmental conditions

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

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

4.3 Cumulative SELs and fleeing receptors

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

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

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

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

As an example, the graphs in Figure 4-4 and Figure 4-5 show the difference in the received SEL from a stationary receptor and a fleeing receptor travelling at a constant speed of 1.5 ms^{-1}, using the monopile foundation scenario at the Dogger Bank West: W location for a single pile installation.

The received SEL_{ss} from the stationary receptor, as illustrated in Figure 4-4, shows the noise level gradually increasing as the blow energy increases throughout the piling operation. These step changes are also visible for the fleeing receptor, but as the receptor is further from the noise source by the time the levels increase, the total received exposure reduces, resulting in progressively lower received noise levels. As an example, for the first 10 minutes of piling, where the blow energy is 900 kJ, fleeing at a rate of 1.5 ms^{-1}, a receptor has the potential to move 0.9 km from the noise source. After the full 5 hours and 20 minutes, the receptor has the potential to be almost 29 km from the noise source.

Figure 4-5 shows the effect these different received levels have when calculating the SEL_{cum}. It clearly shows the difference in cumulative effect between the receptor remaining still, as opposed to fleeing. To use an extreme example, starting at a range of 1 m, the first strike results in a received level of 218.7 dB re 1 μPa^2s. If the receptor were to remain stationary throughout the piling operation it would receive a cumulative level of 262.5 dB re 1 μPa^2s, whereas when fleeing at 1.5 ms^{-1} over the same scenario, a cumulative received level of just 222.6 dB re 1 μPa^2s is achieved.

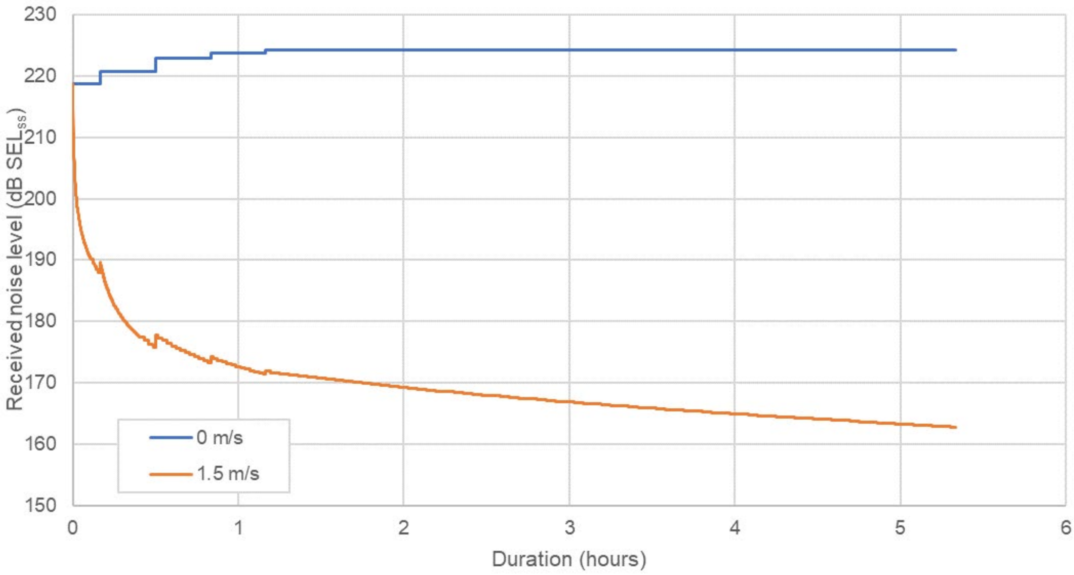

Figure 4-4 Received single-strike noise levels (SEL_{ss}) for receptors during the monopile foundation parameters at the Dogger Bank West: West location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source

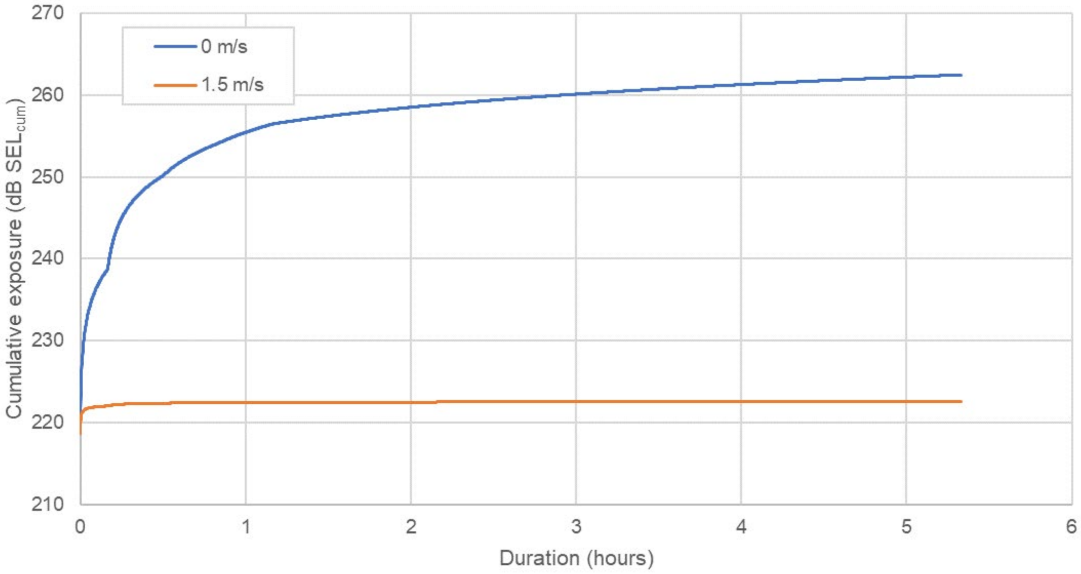

Figure 4-5 Cumulative received noise levels (SEL_{cum}) for receptors during monopile foundation parameters at the Dogger Bank West: West location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source

To summarise, if the receptor were to start fleeing in a straight line from the noise source starting at a range closer than the modelled value it would receive a noise exposure in excess of the criteria, and if the receptor were to start fleeing from a range further than the modelled value it would receive a noise exposure below the criteria. This is illustrated in Figure 4-6.

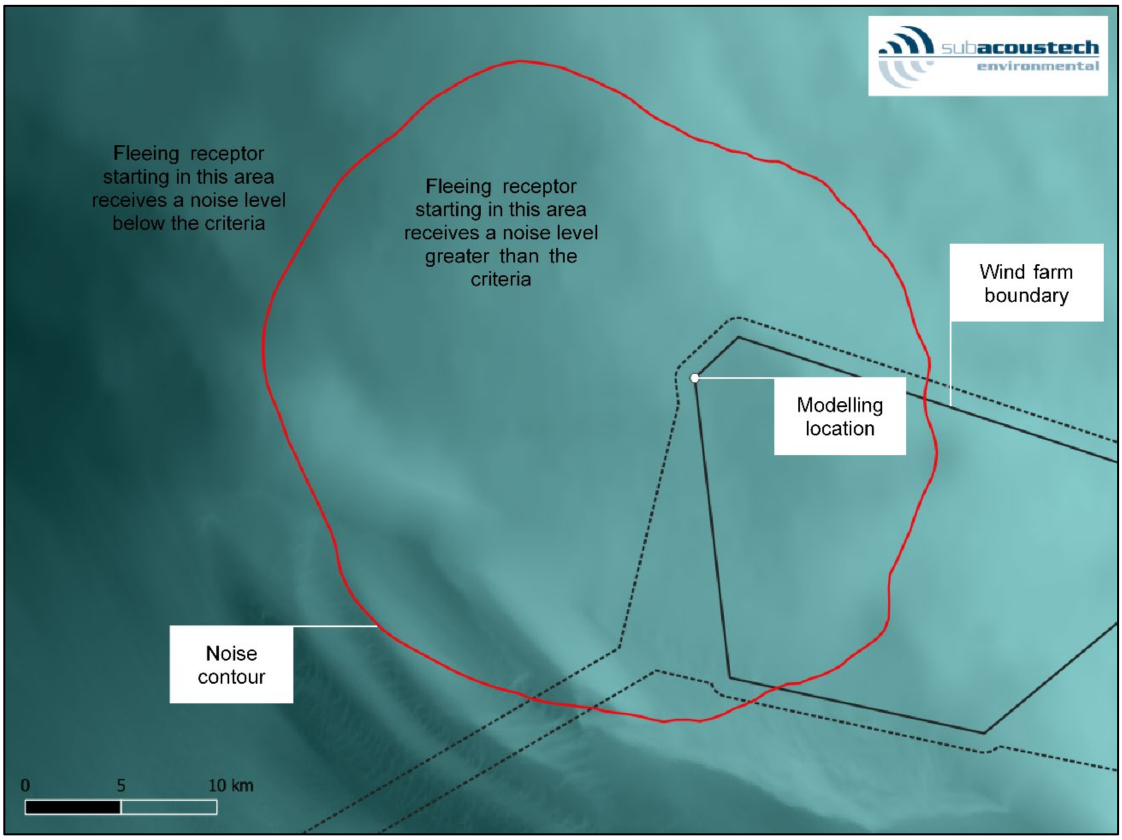

Figure 4-6 Plot showing a fleeing animal SEL_{cum} criteria contour and the areas where the cumulative noise exposure will exceed the impact criteria

Some modelling approaches include the effects of Acoustic Deterrent Devices (ADDs) that cause receptors to flee from the immediate area around the pile before activity commences. Subacoustech Environmental's modelling approach does not include this, however the effects of using an ADD can still be inferred from the results. For example, if a receptor were to flee for 20 minutes from an ADD at a rate of 1.5 ms^{-1}, it would travel 1.8 km before piling begins. If a cumulative SEL impact range from INSPIRE was calculated to be less than 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 any contribution to a receptor's SEL_{cum} exposure from the ADD would be minimal.

4.3.1 The effect of input parameters on SELs and fleeing receptors

As discussed in section 4.2.2, parameters such as bathymetry, hammer blow energies, piling ramp up, strike rate and duration all have an effect on predicted noise levels. When considered SEL_{cum} and a fleeing animal model, some of these parameters can have a greater influence than others.

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

Linked to the effect of the ramp up is the strike rate, as the more pile strikes that occur while the receptor is close to the noise source, the greater the exposure and the greater effect it will have on the SEL_{cum}. The faster the strike rate, the shorter the distance the receptor can flee between each pile strike, which leads to greater exposure.

In general, the greatest impacts are found when a receptor is close to the noise source. For example, if high blow energies or a fast strike rate are used at the start of the piling activities, bigger increases in impact ranges will be achieved.

The other main element that can cause big differences in calculated impact ranges is the bathymetry, as deep-water results in a slower attenuation of noise. However, it is not always feasible to limit piling activity in or near to deep water.

5 Modelling results

This section presents the modelled impact ranges for impact piling noise following the parameters detailed in section 4.2, covering the Southall *et al*. (2019) marine mammal criteria (section 2.2.1) and the Popper *et al*. (2014) fish criteria (section 2.2.2). To aid navigation, Table 5-1 contains a list of the impact range tables included in this section. The concurrent location modelling results are presented in section 5.4. The biggest modelled ranges are predicted for the monopile foundation scenarios at the DBS East: S location due to the nearby deep water.

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

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

Table 5-1 Summary of the impact piling modelling results tables presented in this section.

Table (page)	Parameters (section)		Criteria		
Table 5-3 (p25)	Monopile foundation (5.2)	DBS East: S (5.2.1)	Southall *et al.* (2019)	Unweighted SPL_{peak}	First strike
Table 5-4 (p26)					Maximum energy
Table 5-5 (p26)				Weighted SEL_{cum} (Impulsive)	Single pile
Table 5-6 (p26)					2 sequential piles
Table 5-7 (p26)			Popper *et al.* (2014)	Unweighted SPL_{peak}	First strike
Table 5-8 (p27)					Maximum energy
Table 5-9 (p27)				Unweighted SEL_{cum} (Pile driving)	Single pile
Table 5-10 (p27)					2 sequential piles
Table 5-11 (p28)		DBS East: NW (5.2.2)	Southall *et al.* (2019)	Unweighted SPL_{peak}	First strike
Table 5-12 (p28)					Maximum energy
Table 5-13 (p28)				Weighted SEL_{cum} (Impulsive)	Single pile
Table 5-14 (p29)					2 sequential piles
Table 5-15 (p29)			Popper *et al.* (2014)	Unweighted SPL_{peak}	First strike
Table 5-16 (p29)					Maximum energy
Table 5-17 (p29)				Unweighted SEL_{cum} (Pile driving)	Single pile
Table 5-18 (p30)					2 sequential piles
Table 5-19 (p30)		DBS West: NE (5.2.3)	Southall *et al.* (2019)	Unweighted SPL_{peak}	First strike
Table 5-20 (p30)					Maximum energy
Table 5-21 (p31)				Weighted SEL_{cum} (Impulsive)	Single pile
Table 5-22 (p31)					2 sequential piles
Table 5-23 (p31)			Popper *et al.* (2014)	Unweighted SPL_{peak}	First strike
Table 5-24 (p31)					Maximum energy
Table 5-25 (p32)				Unweighted SEL_{cum} (Pile driving)	Single pile
Table 5-26 (p32)					2 sequential piles
Table 5-27 (p32)		DBS West: W (5.2.4)	Southall *et al.* (2019)	Unweighted SPL_{peak}	First strike
Table 5-28 (p33)					Maximum energy
Table 5-29 (p33)				Weighted SEL_{cum} (Impulsive)	Single pile
Table 5-30 (p33)					2 sequential piles
Table 5-31 (p33)			Popper *et al.* (2014)	Unweighted SPL_{peak}	First strike
Table 5-32 (p34)					Maximum energy
Table 5-33 (p34)				Unweighted SEL_{cum} (Pile driving)	Single pile
Table 5-34 (p34)					2 sequential piles
Table 5-35 (p35)	Multi-leg foundation (5.3)	DBS East:	Southall *et al.* (2019)	Unweighted SPL_{peak}	First strike
Table 5-36 (p35)					Maximum energy
Table 5-37 (p36)					Single pile

Table (page)	Parameters (section)		Criteria		
Table 5-38 (p36)		S (5.3.1)		Weighted SEL_{cum} (Impulsive)	4 sequential piles
Table 5-39 (p36)			Popper *et al.* (2014)	Unweighted SPL_{peak}	First strike
Table 5-40 (p36)					Maximum energy
Table 5-41 (p37)				Unweighted SEL_{cum} (Pile driving)	Single pile
Table 5-42 (p37)					4 sequential piles
Table 5-43 (p37)		DBS West: W (5.3.2)	Southall *et al.* (2019)	Unweighted SPL_{peak}	First strike
Table 5-44 (p38)					Maximum energy
Table 5-45 (p38)				Weighted SEL_{cum} (Impulsive)	Single pile
Table 5-46 (p38)					4 sequential piles
Table 5-47 (p38)			Popper *et al.* (2014)	Unweighted SPL_{peak}	First strike
Table 5-48 (p39)					Maximum energy
Table 5-49 (p39)				Unweighted SEL_{cum} (Pile driving)	Single pile
Table 5-50 (p39)					4 sequential piles
Table 5-51 (p40)		DBS West: NE (5.3.3)	Southall *et al.* (2019)	Unweighted SPL_{peak}	First strike
Table 5-52 (p40)					Maximum energy
Table 5-53 (p40)				Weighted SEL_{cum} (Impulsive)	Single pile
Table 5-54 (p41)					4 sequential piles
Table 5-55 (p41)			Popper *et al.* (2014)	Unweighted SPL_{peak}	First strike
Table 5-56 (p41)					Maximum energy
Table 5-57 (p41)				Unweighted SEL_{cum} (Pile driving)	Single pile
Table 5-58 (p42)					4 sequential piles
Table 5-59 (p42)		DBS West: W (5.3.4)	Southall *et al.* (2019)	Unweighted SPL_{peak}	First strike
Table 5-60 (p42)					Maximum energy
Table 5-61 (p43)				Weighted SEL_{cum} (Impulsive)	Single pile
Table 5-62 (p43)					4 sequential piles
Table 5-63 (p43)			Popper *et al.* (2014)	Unweighted SPL_{peak}	First strike
Table 5-64 (p43)					Maximum energy
Table 5-65 (p44)				Unweighted SEL_{cum} (Pile driving)	Single pile
Table 5-66 (p44)					4 sequential piles

5.1 Predicted noise level at 750 m from the noise source

In addition to the source levels given in section 4.2.3, it is useful to look at the potential noise levels at a range of 750 m from the noise source, which is a common consideration for underwater noise studies at offshore wind farms, and has the added advantage of being comparable with other modelling or measurements. A summary of the modelled unweighted levels at a range of 750 m are given in Table 5-2 considering the transect with the greatest noise transmission at each location while piling at the maximum hammer blow energy.

Table 5-2 Summary of the maximum predicted unweighted SPL_{peak} and SEL_{ss} noise levels at a range of 750 m from the noise source when considering the maximum hammer blow energy

Predicted level at 750 m range	Location	**Monopile foundation** 15 m / 6,000 kJ	**Multi-leg foundation** 4 m / 3,000 kJ
Unweighted SPL_{peak}	DBS East: S location	203.3 dB re 1 μPa	202.0 dB re 1 μPa
	DBS East: NW location	201.1 dB re 1 μPa	199.6 dB re 1 μPa
	DBS West: NE location	200.3 dB re 1 μPa	198.9 dB re 1 μPa
	DBS West: W location	203.1 dB re 1 μPa	201.8 dB re 1 μPa
Unweighted SEL_{ss}	DBS East: S location	184.5 dB re 1 μPa²s	182.8 dB re 1 μPa²s
	DBS East: NW location	182.5 dB re 1 μPa²s	180.5 dB re 1 μPa²s
	DBS West: NE location	181.7 dB re 1 μPa²s	179.8 dB re 1 μPa²s
	DBS West: W location	184.4 dB re 1 μPa²s	182.6 dB re 1 μPa²s

5.2 Monopile foundations

Table 5-3 to Table 5-34 present the modelling results for the monopile foundation modelling scenarios at single locations, using the parameters presented in section 4.2, in terms of the Southall *et al*. (2019) marine mammal criteria (section 2.2.1) and the Popper *et al*. (2014) fish criteria (section 2.2.2). Separate sets of results have been presented for a single pile installation, and multiple piles installed sequentially at the same location: two in the case of monopile foundations.

The largest marine mammal impact ranges are predicted at the DBS East: S location due to the deep water to the south of this location. Maximum PTS injury ranges of up to 18 km are predicted for LF cetaceans using the SEL_{cum} criteria. For VHF cetaceans, PTS ranges are predicted up to 11 km for the same scenario. For fish, the largest recoverable injury ranges in the array are also predicted at the DBS East: S location, with ranges of up to 9.3 km assuming a stationary receptor; if a fleeing animal is assumed, these ranges reduce to 880 m. Comparable maximum PTS ranges were seen at DBS West: W location.

It is worth noting that there are only small increases in impact range between the single pile installation and multiple sequential pile installation SEL_{cum} scenarios for fleeing animals, as any additional piling occurs once a receptor has fled to a distance where noise levels are much lower than close to the source (as seen in section 4.3). This means that its additional accumulative noise to the total exposure is relatively low.

5.2.1 DBS East: S location

Table 5-3 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation modelling at the DBS East: S location for the first pile strike

Southall *et al.* (2019) Unweighted SPL_{peak}		**Monopile foundation, first strike**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.34 km²	330 m	330 m	330 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.01 km²	60 m	60 m	60 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	2.2 km²	850 m	840 m	850 m
	PCW (212 dB)	0.01 km²	70 m	70 m	70 m

Table 5-4 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation modelling at the DBS East: S location for the maximum hammer energy

Southall *et al.* (2019) Unweighted SPL_{peak}		Monopile foundation, maximum energy			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	0.01 km²	50 m	< 50 m	50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.7 km²	740 m	730 m	730 m
	PCW (218 dB)	0.01 km²	60 m	60 m	60 m
TTS (Impulsive)	LF (213 dB)	0.05 km²	130 m	130 m	130 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	11 km²	1.9 km	1.8 km	1.8 km
	PCW (212 dB)	0.07 km²	150 m	150 m	150 m

Table 5-5 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (single pile installation) modelling at the DBS East: S location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Monopile foundation, single pile			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	560 km²	18 km	8.4 km	13 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	240 km²	10 km	7.1 km	8.7 km
	PCW (185 dB)	6.2 km²	1.6 km	1.2 km	1.4 km
TTS (Impulsive)	LF (168 dB)	6,500 km²	67 km	22 km	43 km
	HF (170 dB)	3.2 km	1.1 km	900 m	1.0 km
	VHF (140 dB)	3,700 km²	47 km	19 km	33 km
	PCW (170 dB)	1,400 km²	28 km	13 km	20 km

Table 5-6 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (2 piles installed per 24 hours) modelling at the DBS East: S location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Monopile foundation, 2 sequential piles			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	570 km²	18 km	8.4 km	13 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	250 km²	11 km	7.2 km	8.9 km
	PCW (185 dB)	6.4 km²	1.6 km	1.3 km	1.4 km
TTS (Impulsive)	LF (168 dB)	6,500 km²	68 km	22 km	43 km
	HF (170 dB)	3.3 km²	1.2 km	900 m	1.0 km
	VHF (140 dB)	3,800 km²	49 km²	19 km	34 km
	PCW (170 dB)	1,500 km²	30 km	13 km	21 km

Table 5-7 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation modelling at the DBS East: S location for the first pile strike

Popper *et al.* (2014) Unweighted SPL_{peak}	Monopile foundation, first strike			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.01 km²	60 m	60 m	60 m
207 dB	0.07 km²	150 m	150 m	150 m

Table 5-8 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation modelling at the DBS East: S location for the maximum hammer energy

Popper *et al.* (2014) Unweighted SPL_{peak}	**Monopile foundation, maximum hammer energy**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.05 km²	130 m	130 m	130 m
207 dB	0.35 km²	330 m	330 m	330 m

Table 5-9 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (single pile installation) modelling at the DBS East: S location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Monopile foundation, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	1.6 km²	830 m	630 m	720 m
	186 dB	1,400 km²	28 km	13 km	20 km
Stationary	219 dB	1.2 km²	630 m	600 m	610 m
	216 dB	3.0 km²	1.0 km	950 m	980 m
	210 dB	17 km²	2.4 km	2.3 km	2.4 km
	207 dB	41 km²	3.7 km	3.5 km	3.6 km
	203 dB	120 km²	6.4 km	5.9 km	6.1 km
	186 dB	2,600 km²	38 km	19 km	28 km

Table 5-10 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (2 piles installed per 24 hours) modelling at the DBS East: S location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Monopile foundation, 2 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	1.7 km²	880 m	830 m	740 m
	186 dB	1,500 km²	30 km	13 km	21 km
Stationary (0 m/s)	219 dB	3.0 km²	1.0 km	950 m	980 m
	216 dB	7.3 km²	1.6 km	1.5 km	1.5 km
	210 dB	41 km²	3.7 km	3.6 km	3.6 km
	207 dB	90 km²	5.6 km	5.2 km	5.4 km
	203 dB	240 km²	9.3 km	8.4 km	8.8 km
	186 dB	4,000 km²	47 km	22 km	35 km

5.2.2 DBS East: NW location

Table 5-11 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation modelling at the DBS East: NW location for the first pile strike

Southall *et al.* (2019) Unweighted SPL_{peak}		Monopile foundation, first strike			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.18 km²	240 m	240 m	240 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	1.1 km²	590 m	560 m	580 m
	PCW (212 dB)	0.01 km²	50 m	50 m	50 m

Table 5-12 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation modelling at the DBS East: NW location for the maximum hammer energy

Southall *et al.* (2019) Unweighted SPL_{peak}		Monopile foundation, maximum energy			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.81 km²	520 m	490 m	510 m
	PCW (218 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.03 km²	100 m	100 m	100 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	4.5 km²	1.3 km	1.1 km	1.2 km
	PCW (212 dB)	0.04 km²	120 m	110 m	110 m

Table 5-13 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (single pile installation) modelling at the DBS East: NW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Monopile foundation, single pile			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	54 km²	5.5 km	2.5 km	4.0 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	43 km²	4.5 km	2.6 km	3.7 km
	PCW (185 dB)	< 0.1 km²	130 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	1,500 km²	26 km	16 km	22 km
	HF (170 dB)	< 0.1 km²	130 m	< 100 m	< 100 m
	VHF (140 dB)	880 km²	20 km	15 km	17 km
	PCW (170 dB)	200 km²	10 km	5.9 km	7.9 km

Table 5-14 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (2 piles installed per 24 hours) modelling at the DBS East: NW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Monopile foundation, 2 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	54 km²	5.5 km	2.5 km	4.1 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	43 km²	4.5 km	2.6 km	3.7 km
	PCW (185 dB)	< 0.1 km²	130 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	1,500 km²	26 km	16 km	22 km
	HF (170 dB)	< 0.1 km²	130 m	< 100 m	< 100 m
	VHF (140 dB)	900 km²	20 km	15 km	17 km
	PCW (170 dB)	200 km²	10 km	6.0 km	8.0 km

Table 5-15 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation modelling at the DBS East: NW location for the first pile strike

Popper *et al.* (2014) Unweighted SPL_{peak}	**Monopile foundation, first strike**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.01 km²	< 50 m	< 50 m	< 50 m
207 dB	0.04 km²	110 m	110 m	110 m

Table 5-16 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation modelling at the DBS East: NW location for the maximum hammer energy

Popper *et al.* (2014) Unweighted SPL_{peak}	**Monopile foundation, maximum hammer energy**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.03 km²	100 m	100 m	100 m
207 dB	0.18 km²	240 m	240 m	240 m

Table 5-17 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (single pile installation) modelling at the DBS East: NW location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Monopile foundation, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing ($1.5\ ms^{-1}$)	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	240 km²	11 km	6.7 km	8.6 km
Stationary	219 dB	0.6 km²	480 m	430 m	450 m
	216 dB	1.5 km²	730 m	650 m	690 m
	210 dB	7.6 km²	1.7 km	1.4 km	1.6 km
	207 dB	16 km²	2.4 km	2.0 km	2.3 km
	203 dB	41 km²	4.0 km	3.0 km	3.6 km
	186 dB	720 km²	18 km	13 km	15 km

Table 5-18 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (2 piles installed per 24 hours) modelling at the DBS East: NW location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Monopile foundation, 2 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	240 km^2	11 km	6.7 km	8.7 km
Stationary (0 m/s)	219 dB	1.4 km^2	700 m	650 m	680 m
	216 dB	3.3 km^2	1.1 km	980 m	1.0 km
	210 dB	16 km^2	2.4 km	2.0 km	2.2 km
	207 dB	32 km^2	3.5 km	2.7 km	3.2 km
	203 dB	75 km^2	5.5 km	3.9 km	4.9 km
	186 dB	1,000 km^2	22 km	15 km	18 km

5.2.3 <u>DBS West: NE location</u>

Table 5-19 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation modelling at the DBS West: NE location for the first pile strike

Southall *et al.* (2019) Unweighted SPL_{peak}		**Monopile foundation, first strike**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.15 km^2	220 m	220 m	220 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	0.86 km^2	530 m	520 m	520 m
	PCW (212 dB)	0.01 km^2	50 m	50 m	50 m

Table 5-20 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation modelling at the DBS West: NE location for the maximum hammer energy

Southall *et al.* (2019) Unweighted SPL_{peak}		**Monopile foundation, maximum energy**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.66 km^2	470 m	450 m	460 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.03 km^2	90 m	90 m	90 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	3.6 km^2	1.1 km	1.0 km	1.1 km
	PCW (212 dB)	0.04 km^2	110 m	110 m	110 m

Table 5-21 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (single pile installation) modelling at the DBS West: NE location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Monopile foundation, single pile			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	46 km²	4.6 km	2.9 km	3.8 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	38 km²	3.9 km	2.9 km	3.5 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	1,400 km²	27 km	15 km	21 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	890 km²	20 km	13 km	17 km
	PCW (170 dB)	180 km²	8.7 km	6.4 km	7.6 km

Table 5-22 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (2 piles installed per 24 hours) modelling at the DBS West: NE location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Monopile foundation, 2 sequential piles			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	47 km²	4.6 km	2.9 km	3.8 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	38 km²	3.9 km	2.9 km	3.5 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	1,400 km²	27 km	15 km	21 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	910 km²	20 km	13 km	17 km
	PCW (170 dB)	190 km²	8.8 km	6.4 km	7.7 km

Table 5-23 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation modelling at the DBS West: NE location for the first pile strike

Popper *et al.* (2014) Unweighted SPL_{peak}	Monopile foundation, first strike			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.01 km²	< 50 m	< 50 m	< 50 m
207 dB	0.03 km²	110 m	100 m	110 m

Table 5-24 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation modelling at the DBS West: NE location for the maximum hammer energy

Popper *et al.* (2014) Unweighted SPL_{peak}	Monopile foundation, maximum hammer energy			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.03 km²	90 m	90 m	90 m
207 dB	0.15 km²	220 m	220 m	220 m

Table 5-25 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (single pile installation) modelling at the DBS West: NE location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		Monopile foundation, single pile			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	230 km²	9.9 km	7.2 km	8.5 km
Stationary	219 dB	0.5 km²	430 m	400 m	410 m
	216 dB	1.2 km²	650 m	600 m	630 m
	210 dB	6.2 km²	1.5 km	1.3 km	1.4 km
	207 dB	13 km²	2.2 km	2.0 km	2.1 km
	203 dB	35 km²	3.6 km	3.1 km	3.3 km
	186 dB	730 km²	17 km	13 km	15 km

Table 5-26 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (2 piles installed per 24 hours) modelling at the DBS West: NE location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		Monopile foundation, 2 sequential piles			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	230 km²	9.9 km	7.2 km	8.6 km
Stationary (0 m/s)	219 dB	1.2 km²	650 m	600 m	630 m
	216 dB	2.8 km²	980 m	900 m	940 m
	210 dB	13 km²	2.2 km	2.0 km	2.1 km
	207 dB	28 km²	3.2 km	2.8 km	3.0 km
	203 dB	68 km²	5.0 km	4.2 km	4.7 km
	186 dB	1,100 km²	22 km	16 km	19 km

5.2.4 DBS West: W location

Table 5-27 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation modelling at the DBS West: W location for the first pile strike

Southall *et al.* (2019) Unweighted SPL_{peak}		Monopile foundation, first strike			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.32 km²	320 m	320 m	320 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.01 km²	60 m	60 m	60 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	2.1 km²	830 m	810 m	820 m
	PCW (212 dB)	0.01 km²	70 m	70 m	70 m

Table 5-28 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation modelling at the DBS West: W location for the maximum hammer energy

Southall *et al.* (2019) Unweighted SPL_{peak}		**Monopile foundation, maximum energy**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.6 km²	720 m	710 m	710 m
	PCW (218 dB)	0.01 km²	60 m	60 m	60 m
TTS (Impulsive)	LF (213 dB)	0.05 km²	130 m	130 m	130 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	9.8 km²	1.8 km	1.8 km	1.8 km
	PCW (212 dB)	0.07 km²	150 m	150 m	150 m

Table 5-29 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (single pile installation) modelling at the DBS West: W location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Monopile foundation, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	460 km²	16 km	8.5 km	12 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	200 km²	9.0 km	6.5 km	7.9 km
	PCW (185 dB)	4.3 km²	1.3 km	1.0 km	1.2 km
TTS (Impulsive)	LF (168 dB)	8,000 km²	74 km	25 km	48 km
	HF (170 dB)	2.3 km²	950 m	750 m	860 m
	VHF (140 dB)	3,800 km²	48 km	21 km	34 km
	PCW (170 dB)	1,200 km²	25 km	14 km	19 km

Table 5-30 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the monopile foundation (2 piles installed per 24 hours) modelling at the DBS West: W location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Monopile foundation, 2 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	470 km²	16 km	8.5 km	12 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	200 km²	9.3 km	6.5 km	8.0 km
	PCW (185 dB)	4.5 km²	1.3 km	1.0 km	1.2 km
TTS (Impulsive)	LF (168 dB)	8,100 km²	75 km	25 km	48 km
	HF (170 dB)	2.4 km²	950 m	750 m	870 m
	VHF (140 dB)	4,200 km²	52 km	21 km	35 km
	PCW (170 dB)	1,400 km²	28 km	14 km	20 km

Table 5-31 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation modelling at the DBS West: W location for the first pile strike

Popper *et al.* (2014) Unweighted SPL_{peak}	**Monopile foundation, first strike**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.01 km²	60 m	60 m	60 m
207 dB	0.07 km²	150 m	140 m	150 m

Table 5-32 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation modelling at the DBS West: W location for the maximum hammer energy

Popper *et al.* (2014) Unweighted SPL_{peak}	**Monopile foundation, maximum hammer energy**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.05 km²	130 m	130 m	130 m
207 dB	0.33 km²	330 m	320 m	320 m

Table 5-33 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (single pile installation) modelling at the DBS West: W location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Monopile foundation, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms⁻¹)	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	1.1 km²	650 m	480 m	580 m
	186 dB	1,300 km²	26 km	14 km	20 km
Stationary	219 dB	1.2 km²	630 m	600 m	610 m
	216 dB	2.8 km²	980 m	930 m	940 m
	210 dB	16 km²	2.3 km	2.2 km	2.3 km
	207 dB	37 km²	3.6 km	3.4 km	3.5 km
	203 dB	100 km²	6.0 km	5.5 km	5.8 km
	186 dB	2,500 km²	36 km	21 km	28 km

Table 5-34 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the monopile foundation (2 piles installed per 24 hours) modelling at the DBS West: W location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Monopile foundation, 2 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms⁻¹)	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	1.1 km²	680 m	480 m	590 m
	186 dB	1,400 km²	28 km	14 km	20 km
Stationary (0 m/s)	219 dB	2.8 km²	980 m	930 m	950 m
	216 dB	6.8 km²	1.5 km	1.5 km	1.5 km
	210 dB	38 km²	3.6 km	3.4 km	3.5 km
	207 dB	82 km²	5.3 km	5.0 km	5.1 km
	203 dB	210 km²	8.6 km	7.5 km	8.2 km
	186 dB	3,900 km²	46 km	24 km	35 km

5.3 Multi-leg foundations

Table 5-35 to Table 5-66 present the modelling results for the multi-leg foundation scenarios at single locations using the parameters presented in section 4.2, in terms of the Southall *et al.* (2019) marine mammal criteria (section 2.2.1) and the Popper *et al.* (2014) fish criteria (section 2.2.2). Separate results have been considered for a single pile installation and multiple piles installed sequentially at the same location, four in the case of multi-leg foundations.

The predicted ranges are generally smaller than those modelled for the monopile foundations at equivalent scenarios, due to the lower blow energies used.

For multi-leg foundations, the largest marine mammal impact ranges (Southall *et al*., 2019) are predicted at the DBS East: S location. Maximum PTS injury ranges are predicted for LF cetaceans using the SEL_{cum} criteria, with ranges of up to 13 km. For VHF cetaceans, PTS ranges are predicted out to 7.9 km for the same scenario. When considering the Popper *et al*. (2014) fish criteria, the largest recoverable injury ranges (203 dB SEL_{cum} threshold) for multi-leg foundations are predicted to be 8.5 km assuming a stationary receptor, reducing to less than 100 m when a fleeing receptor is assumed. As with the monopile foundations, only small increases in impact ranges are seen between the single pile and multiple sequential pile installation scenarios, when the fish is presumed to flee. The increases are greater for the stationary fish scenarios.

5.3.1 DBS East: S location

Table 5-35 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the multi-leg foundation modelling at the DBS East: S location for the first pile strike

Southall *et al*. (2019) Unweighted SPL_{peak}		Multi-leg foundation, first strike			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.09 km²	170 m	170 m	170 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	0.60 km²	440 m	440 m	440 m
	PCW (212 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m

Table 5-36 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the multi-leg foundation modelling at the DBS East: S location for the maximum hammer energy

Southall *et al*. (2019) Unweighted SPL_{peak}		Multi-leg foundation, maximum energy			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.1 km²	600 m	590 m	600 m
	PCW (218 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.03 km²	100 m	100 m	100 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	7.1 km²	1.5 km	1.5 km	1.5 km
	PCW (212 dB)	0.05 km²	120 m	120 m	120 m

Table 5-37 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the multi-leg foundation (single pile installation) modelling at the DBS East: S location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Multi-leg foundation, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	290 km²	13 km	6.3 km	9.4 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	130 km²	7.2 km	5.5 km	6.3 km
	PCW (185 dB)	1.3 km²	750 m	550 m	650 m
TTS (Impulsive)	LF (168 dB)	5,000 km²	58 km	19 km	38 km
	HF (170 dB)	0.2 km²	280 m	180 m	230 m
	VHF (140 dB)	2,700 km²	39 km	17 km	28 km
	PCW (170 dB)	1,000 km²	24 km	12 km	18 km

Table 5-38 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the multi-leg foundation (4 piles installed per 24 hours) modelling at the DBS East: S location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Multi-leg foundation, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	300 km²	13 km	6.3 km	9.6 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	140 km²	7.9 km	5.5 km	6.7 km
	PCW (185 dB)	1.7 km²	880 m	580 m	720 m
TTS (Impulsive)	LF (168 dB)	5,200 km²	60 km	19 km	38 km
	HF (170 dB)	0.2 km²	330 m	200 m	250 m
	VHF (140 dB)	3,100 km²	44 km	17 km	30 km
	PCW (170 dB)	1,300 km²	28 km	12 km	19 km

Table 5-39 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the multi-leg foundation modelling at the DBS East: S location for the first pile strike

Popper *et al.* (2014) Unweighted SPL_{peak}	**Multi-leg foundation, first strike**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
207 dB	0.02 km²	80 m	80 m	80 m

Table 5-40 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the multi-leg foundation modelling at the DBS East: S location for the maximum hammer energy

Popper *et al.* (2014) Unweighted SPL_{peak}	**Multi-leg foundation, maximum hammer energy**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.03 km²	100 m	100 m	100 m
207 dB	0.23 km²	270 m	270 m	270 m

Table 5-41 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the multi-leg foundation (single pile installation) modelling at the DBS East: S location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Multi-leg foundation, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	840 km^2	21 km	11 km	16 km
Stationary	219 dB	0.4 km^2	380 m	350 m	360 m
	216 dB	1.0 km^2	580 m	550 m	560 m
	210 dB	5.9 km^2	1.4 km	1.4 km	1.4 km
	207 dB	14 km^2	2.2 km	2.1 km	2.1 km
	203 dB	44 km^2	3.9 km	3.7 km	3.7 km
	186 dB	1,600 km^2	28 km	16 km	22 km

Table 5-42 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the multi-leg foundation (4 piles installed per 24 hours) modelling at the DBS East: S location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Multi-leg foundation, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	1,000 km^2	24 km	11 km	17 km
Stationary (0 m/s)	219 dB	2.5 km^2	900 m	880 m	890 m
	216 dB	5.9 km^2	1.4 km	1.4 km	1.4 km
	210 dB	34 km^2	3.4 km	3.2 km	3.3 km
	207 dB	75 km^2	5.1 km	4.8 km	4.9 km
	203 dB	200 km^2	8.5 km	7.7 km	8.1 km
	186 dB	3,600 km^2	45 km	21 km	33 km

5.3.2 DBS East: NW location

Table 5-43 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the multi-leg foundation modelling at the DBS East: NW location for the first pile strike

Southall *et al.* (2019) Unweighted SPL_{peak}		**Multi-leg foundation, first strike**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.05 km^2	130 m	130 m	130 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	0.30 km^2	310 m	300 m	310 m
	PCW (212 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table 5-44 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the multi-leg foundation modelling at the DBS East: NW location for the maximum hammer energy

Southall *et al.* (2019) Unweighted SPL_{peak}		Multi-leg foundation, maximum energy			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.52 km²	420 m	400 m	410 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km²	80 m	80 m	80 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	3.0 km²	1.0 km	920 m	980 m
	PCW (212 dB)	0.03 km²	90 m	90 m	90 m

Table 5-45 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the multi-leg foundation (single pile installation) modelling at the DBS East: NW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Multi-leg foundation, single pile			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	16 km²	3.1 km	1.0 km	2.2 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	19 km²	3.0 km	1.6 km	2.4 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	950 km²	21 km	13 km	17 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	620 km²	17 km	12 km	14 km
	PCW (170 dB)	140 km²	8.5 km	4.8 km	6.7 km

Table 5-46 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the multi-leg foundation (4 piles installed per 24 hours) modelling at the DBS East: NW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Multi-leg foundation, 4 sequential piles			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	16 km²	3.2 km²	1.0 km	2.2 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	20 km²	3.1 km	1.6 km	2.5 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	970 km²	21 km	13 km	17 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	660 km²	18 km	12 km	14 km
	PCW (170 dB)	150 km²	8.8 km	5.0 km	6.9 km

Table 5-47 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the multi-leg foundation modelling at the DBS East: NW location for the first pile strike

Popper *et al.* (2014) Unweighted SPL_{peak}	Multi-leg foundation, first strike			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
207 dB	0.01 km²	60 m	60 m	60 m

Table 5-48 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the multi-leg foundation modelling at the DBS East: NW location for the maximum hammer energy

Popper *et al.* (2014) Unweighted SPL_{peak}	**Multi-leg foundation, maximum hammer energy**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.02 km²	80 m	80 m	80 m
207 dB	0.12 km²	200 m	190 m	190 m

Table 5-49 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the multi-leg foundation (single pile installation) modelling at the DBS East: NW location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Multi-leg foundation, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	130 km²	8.0 km	4.6 km	6.3 km
Stationary	219 dB	0.2 km²	280 m	250 m	260 m
	216 dB	0.5 km²	430 m	380 m	390 m
	210 dB	2.6 km²	950 m	880 m	910 m
	207 dB	5.9 km²	1.5 km	1.3 km	1.4 km
	203 dB	16 km²	2.5 km	2.0 km	2.3 km
	186 dB	430 km²	14 km	9.7 km	12 km

Table 5-50 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the multi-leg foundation (4 piles installed per 24 hours) modelling at the DBS East: NW location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Multi-leg foundation, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	130 km²	8.2 km	4.8 km	6.5 km
Stationary (0 m/s)	219 dB	1.1 km²	630 m	580 m	600 m
	216 dB	2.6 km²	950 m	880 m	910 m
	210 dB	13 km²	2.2 km	1.8 km	2.0 km
	207 dB	26 km²	3.2 km	2.4 km	2.9 km
	203 dB	64 km²	5.0 km	3.6 km	4.5 km
	186 dB	930 km²	21 km	14 km	17 km

5.3.3 DBS West: NE location

Table 5-51 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the multi-leg foundation modelling at the DBS West: NE location for the first pile strike

Southall *et al.* (2019) Unweighted SPL_{peak}		Multi-leg foundation, first strike			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.04 km²	120 m	120 m	120 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	0.25 km²	290 m	280 m	280 m
	PCW (212 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m

Table 5-52 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the multi-leg foundation modelling at the DBS West: NE location for the maximum hammer energy

Southall *et al.* (2019) Unweighted SPL_{peak}		Multi-leg foundation, maximum energy			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.43 km²	380 m	370 m	370 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km²	80 m	70 m	70 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	2.4 km²	900 m	850 m	880 m
	PCW (212 dB)	0.02 km²	90 m	90 m	90 m

Table 5-53 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the multi-leg foundation (single pile installation) modelling at the DBS West: NE location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Multi-leg foundation, single pile			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	12 km²	2.4 km	1.3 km	1.9 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	16 km²	2.6 km	1.8 km	2.2 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	930 km²	21 km	12 km	17 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	630 km²	17 km	12 km	14 km
	PCW (170 dB)	130 km²	7.3 km	5.2 km	6.3 km

Table 5-54 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the multi-leg foundation (4 piles installed per 24 hours) modelling at the DBS West: NE location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Multi-leg foundation, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	12 km²	2.4 km	1.3 km	1.9 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	16 km²	2.6 km	1.8 km	2.3 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	950 km²	21 km	12 km	17 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	670 km²	17 km	12 km	15 km
	PCW (170 dB)	130 km²	7.5 km	5.4 km	6.5 km

Table 5-55 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the multi-leg foundation modelling at the DBS West: NE location for the first pile strike

Popper *et al.* (2014) Unweighted SPL_{peak}	**Multi-leg foundation, first strike**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
207 dB	0.01 km²	60 m	60 m	60 m

Table 5-56 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the multi-leg foundation modelling at the DBS West: NE location for the maximum hammer energy

Popper *et al.* (2014) Unweighted SPL_{peak}	**Multi-leg foundation, maximum hammer energy**			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.02 km²	80 m	70 m	70 m
207 dB	0.10 km²	180 m	180 m	180 m

Table 5-57 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the multi-leg foundation (single pile installation) modelling at the DBS West: NE location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Multi-leg foundation, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing ($1.5 ms^{-1}$)	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	120 km²	7.0 km	5.2 km	6.2 km
Stationary	219 dB	0.2 km²	250 m	230 m	240 m
	216 dB	0.4 km²	380 m	350 m	360 m
	210 dB	2.2 km²	880 m	800 m	830 m
	207 dB	4.9 km²	1.3 km	1.2 km	1.3 km
	203 dB	14 km²	2.2 km	2.0 km	2.1 km
	186 dB	420 km²	13 km	10 km	12 km

Table 5-58 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the multi-leg foundation (4 piles installed per 24 hours) modelling at the DBS West: NE location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Multi-leg foundation, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	130 km^2	7.3 km	5.3 km	6.3 km
Stationary (0 m/s)	219 dB	1.0 km^2	580 m	530 m	560 m
	216 dB	2.2 km^2	880 m	800 m	840 m
	210 dB	11 km^2	2.0 km	1.8 km	1.9 km
	207 dB	23 km^2	2.9 km	2.5 km	2.7 km
	203 dB	56 km^2	4.6 km	3.9 km	4.2 km
	186 dB	960 km^2	20 km	15 km	18 km

5.3.4 DBS West: W location

Table 5-59 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the multi-leg foundation modelling at the DBS West: W location for the first pile strike

Southall *et al.* (2019) Unweighted SPL_{peak}		**Multi-leg foundation, first strike**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.09 km^2	170 m	160 m	170 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	0.57 km^2	430 m	430 m	430 m
	PCW (212 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table 5-60 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the multi-leg foundation modelling at the DBS West: W location for the maximum hammer energy

Southall *et al.* (2019) Unweighted SPL_{peak}		**Multi-leg foundation, maximum energy**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.0 km^2	580 m	570 m	580 m
	PCW (218 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.03 km^2	100 m	100 m	100 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	6.5 km^2	1.5 km	1.4 km	1.4 km
	PCW (212 dB)	0.04 km^2	120 m	120 m	120 m

Table 5-61 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the multi-leg foundation (single pile installation) modelling at the DBS West: W location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Multi-leg foundation, single pile			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	220 km²	11 km	5.9 km	8.3 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	100 km²	6.3 km	4.8 km	5.7 km
	PCW (185 dB)	0.8 km²	580 m	400 m	490 m
TTS (Impulsive)	LF (168 dB)	5,800 km²	63 km	22 km	41 km
	HF (170 dB)	< 0.1 km²	200 m	130 m	160 m
	VHF (140 dB)	2,700 km²	39 km	19 km	28 km
	PCW (170 dB)	870 km²	21 km	13 km	16 km

Table 5-62 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the multi-leg foundation (4 piles installed per 24 hours) modelling at the DBS West: W location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Multi-leg foundation, 4 sequential piles			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	240 km²	11 km	5.9 km	8.5 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	110 km²	6.9 km	4.9 km	6.0 km
	PCW (185 dB)	1.0 km²	630 m	430 m	550 m
TTS (Impulsive)	LF (168 dB)	6,200 km²	67 km	22 km	42 km
	HF (170 dB)	0.1 km²	230 m	130 m	170 m
	VHF (140 dB)	3,300 km²	46 km	19 km	31 km
	PCW (170 dB)	1,200 km²	26 km	13 km	19 km

Table 5-63 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the multi-leg foundation modelling at the DBS West: W location for the first pile strike

Popper *et al.* (2014) Unweighted SPL_{peak}	Multi-leg foundation, first strike			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
207 dB	0.02 km²	80 m	70 m	80 m

Table 5-64 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the multi-leg foundation modelling at the DBS West: W location for the maximum hammer energy

Popper *et al.* (2014) Unweighted SPL_{peak}	Multi-leg foundation, maximum hammer energy			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.03 km²	100 m	100 m	100 m
207 dB	0.21 km²	260 m	260 m	260 m

Table 5-65 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the multi-leg foundation (single pile installation) modelling at the DBS West: W location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		Multi-leg foundation, single pile			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	700 km^2	18 km	11 km	15 km
Stationary	219 dB	0.4 km^2	350 m	330 m	340 m
	216 dB	0.9 km^2	550 m	530 m	540 m
	210 dB	5.5 km^2	1.4 km	1.3 km	1.3 km
	207 dB	13 km^2	2.1 km	2.0 km	2.1 km
	203 dB	40 km^2	3.7 km	3.5 km	3.6 km
	186 dB	1,400 km^2	25 km	17 km	21 km

Table 5-66 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the multi-leg foundation (4 piles installed per 24 hours) modelling at the DBS West: W location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		Multi-leg foundation, 4 sequential piles			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	890 km^2	23 km	12 km	16 km
Stationary (0 m/s)	219 dB	2.2 km^2	880 m	830 m	850 m
	216 dB	5.5 km^2	1.4 km	1.3 km	1.3 km
	210 dB	31 km^2	3.2 km	3.1 km	3.1 km
	207 dB	68 km^2	4.8 km	4.5 km	4.7 km
	203 dB	180 km^2	7.9 km	7.0 km	7.5 km
	186 dB	3,600 km^2	43 km	24 km	33 km

5.4 Concurrent location piling

Additional modelling has been carried out to investigate the potential impacts of multiple piling installations occurring simultaneously at separated foundation locations across DBS development area. These scenarios represent the worst case piling parameters in a 24-hour period. Using the monopile and multi-leg piling scenarios from the previous sections, modelling has been carried out for simultaneous piling at:

- DBS East: S location and DBS West: W location for monopile foundations (2 installed sequentially at each location – total of 4 per day); and
- DBS East: S location and DBS West: W location for multi-leg foundations (4 installed sequentially at each location – total of 8 per day).

These represent a worst case spread of locations (as summarised in section 4.2.2). All modelling in this section assumes that the piling operations at each location start at the same time.

When considering SEL_{cum} modelling, piling from multiple sources has the ability to increase impact ranges significantly as, in this case, it introduces noise from double the number of pile strikes to the water. Unlike the sequential piling investigated in sections 5.2 and 5.3, where fleeing receptors will be further from the piling by the time subsequent piles are driven, the receptor can be closer to a source for more pile strikes resulting in higher cumulative exposures. Figure 5-1 shows the TTS contour for fish from Popper *et al*. (2014) (186 dB SEL_{cum}) for a fleeing receptor as an example. The red contours show the impact from each location modelled individually (as presented in sections 5.2 and 5.3), and the blue contour shows the increase in impact range when multiple sources are active simultaneously, resulting in a contour encircling them all.

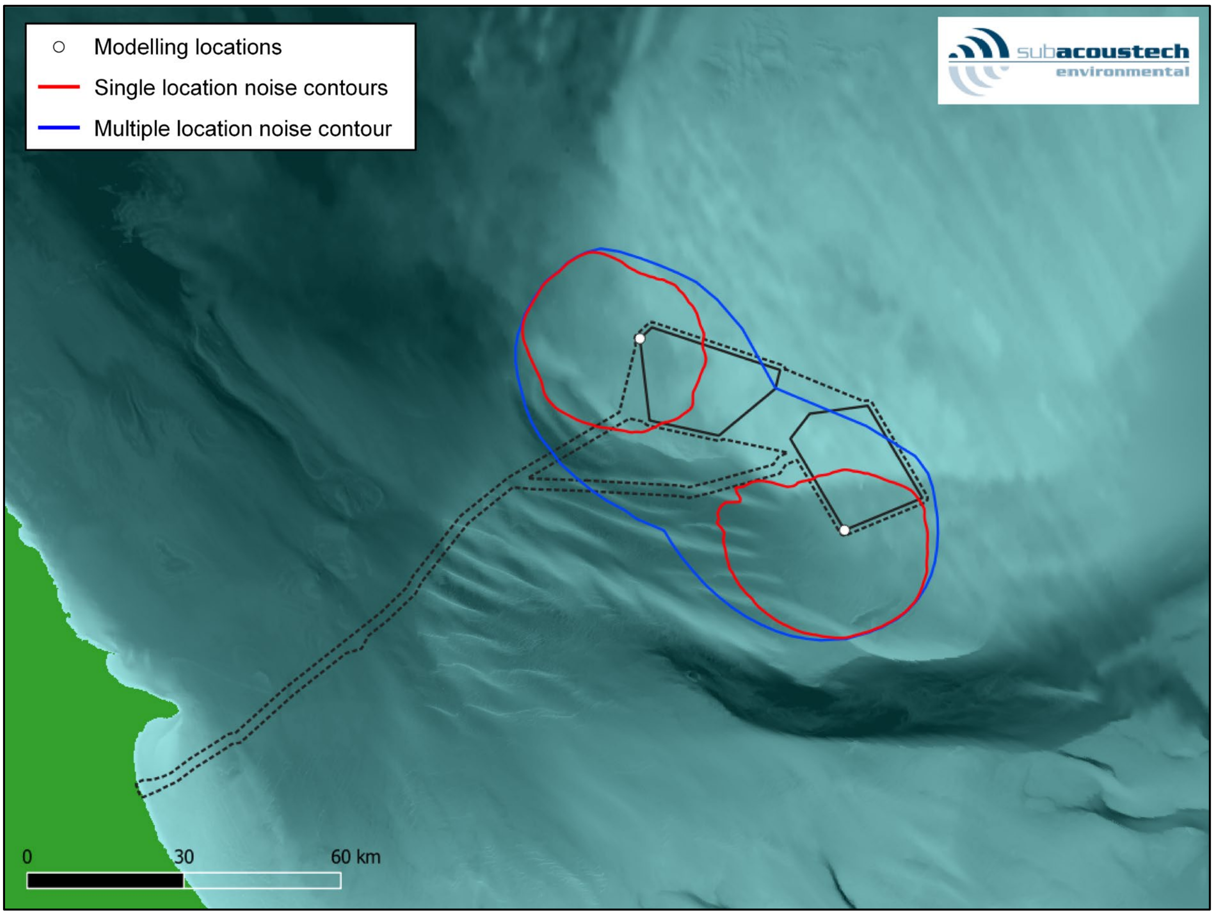

Figure 5-1 Example contour plot showing the interaction between three noise sources when occurring simultaneously (TTS in fish, 186 dB SEL_{cum}, fleeing animal, multi-leg foundation)

The modelling is undertaken by first generating a sound field surrounding the sources, combining noise radiating from each piling location. The animal noise exposure is calculated assuming the animal begins at each one of the piling locations in sequence. The radius of impact (whether for stationary or fleeing) is then calculated, in the same way as for single pile locations, but now with a greater overall spread of noise, both spatially and, potentially, temporally. This process is repeated at the starting position from each noise source, representing all of the potentially worst-case locations. This results in an output for each of the piling locations. For each assessment metric (e.g. LF cetacean SELcum PTS), these results are overlaid, and a combined contour drawn around the perimeter to calculate the total maximum cumulative impact area.

The scenarios modelled were chosen to provide the greatest geographical spread of impact range contours across the DBS development area. In a modelling scenario where piles are installed immediately adjacent to each other, there would be an expansion of the single location contour in all directions, but by less overall than the wide East-West spread seen in Figure 5-1.

Sections 5.4.1 and 5.4.2 present contour plots for the multiple location piling scenarios alongside tables showing the increases in combined area. Only areas are provided as results, impact ranges have not been presented in this section as there are multiple starting points for receptors (a linear impact range requires a single start point, typically the pile location, which is not possible with multiple pile locations). Fields with a dash "-" show where there is no in-combination effect when piling occurs at the two locations simultaneously, generally where the ranges are small enough that the distant sites do not produce an influencing additional exposure. Contours that are too small to be seen clearly at the scale of the figures are not included.

5.4.1 Monopile foundation scenario

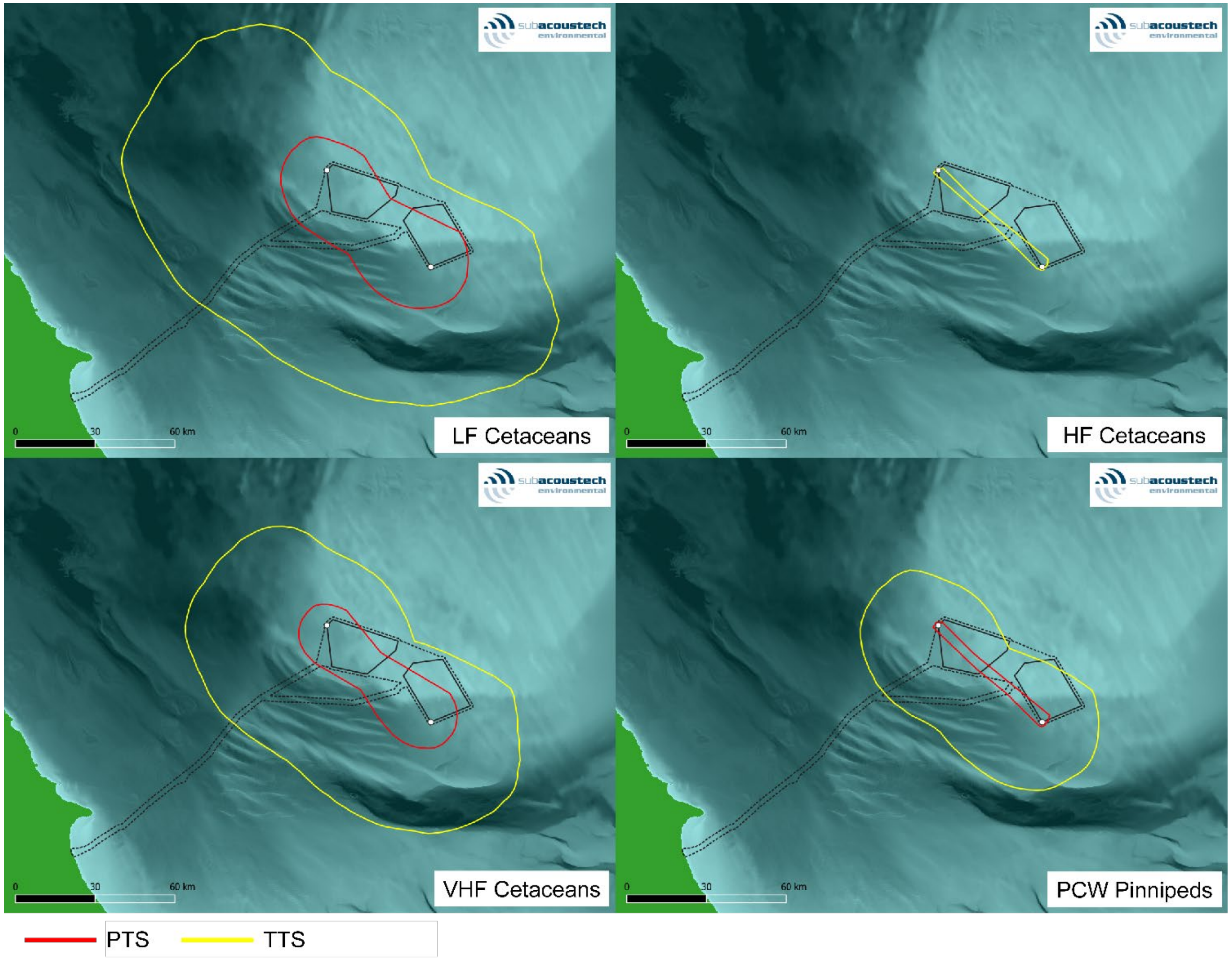

Figure 5-2 Contour plots showing the in-combination impacts of concurrent installation of monopile foundations at two locations across DBS for marine mammals using the impulsive Southall et al. (2019) criteria assuming a fleeing animal

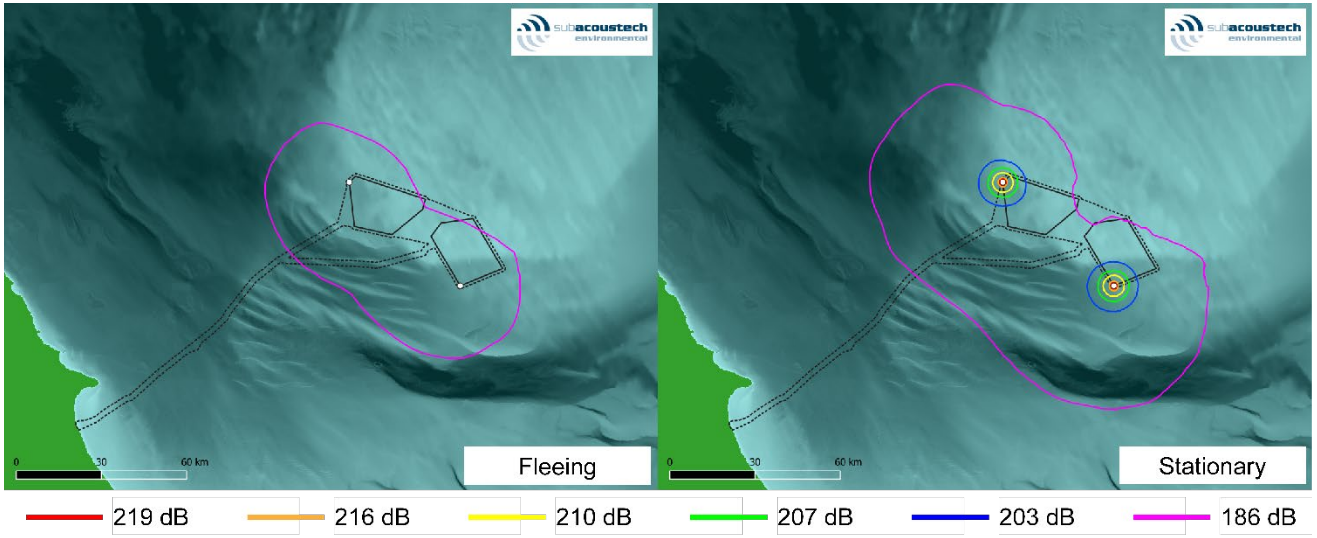

Figure 5-3 Contour plots showing the in-combination impacts of concurrent installation of monopile foundations at two locations across DBS for fish using the pile driving Popper et al. (2014) criteria assuming both a fleeing and stationary animal

Table 5-67 Summary of the impact areas for the installation of monopile foundations at two locations across DBS for marine mammals using the impulsive Southall et al. (2019) criteria assuming a fleeing animal

Monopile foundation Southall *et al.* (2019) Weighted SEL_{cum}		**DBS East: S location**	**DBS West: W location**	**In-combination area**
PTS (Impulsive)	LF (183 dB)	570 km²	470 km²	2,400 km²
	HF (185 dB)	< 0.1 km²	< 0.1 km²	-
	VHF (155 dB)	250 km²	200 km²	1,400 km²
	PCW (185 dB)	6.4 km²	4.5 km²	230 km²
TTS (Impulsive)	LF (168 dB)	6,500 km²	8,100 km²	15,000 km²
	HF (170 dB)	3.3 km²	2.4 km²	200 km²
	VHF (140 dB)	3,800 km²	4,200 km²	9,100 km²
	PCW (170 dB)	1,500 km²	1,400 km²	4,400 km²

Table 5-68 Summary of the impact areas for the installation of monopile foundations at two locations across DBS for fish using the pile driving Popper et al. (2014) criteria assuming both a fleeing and stationary animal

Monopile foundation Popper *et al.* (2014) Unweighted SEL_{cum}		**DBS East: S location**	**DBS West: W location**	**In-combination area**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km²	< 0.1 km²	-
	216 dB	< 0.1 km²	< 0.1 km²	-
	210 dB	< 0.1 km²	< 0.1 km²	-
	207 dB	< 0.1 km²	< 0.1 km²	-
	203 dB	1.7 km²	1.1 km²	-
	186 dB	1,500 km²	1,400 km²	4,400 km²
Stationary	219 dB	3.0 km²	2.8 km²	6.9 km²
	216 dB	7.3 km²	6.8 km²	16 km²
	210 dB	41 km²	38 km²	82 km²
	207 dB	90 km²	82 km²	180 km²
	203 dB	240 km²	210 km²	460 km²
	186 dB	4,000 km²	3,900 km²	8,000 km²

5.4.2 Multi-leg foundation scenario

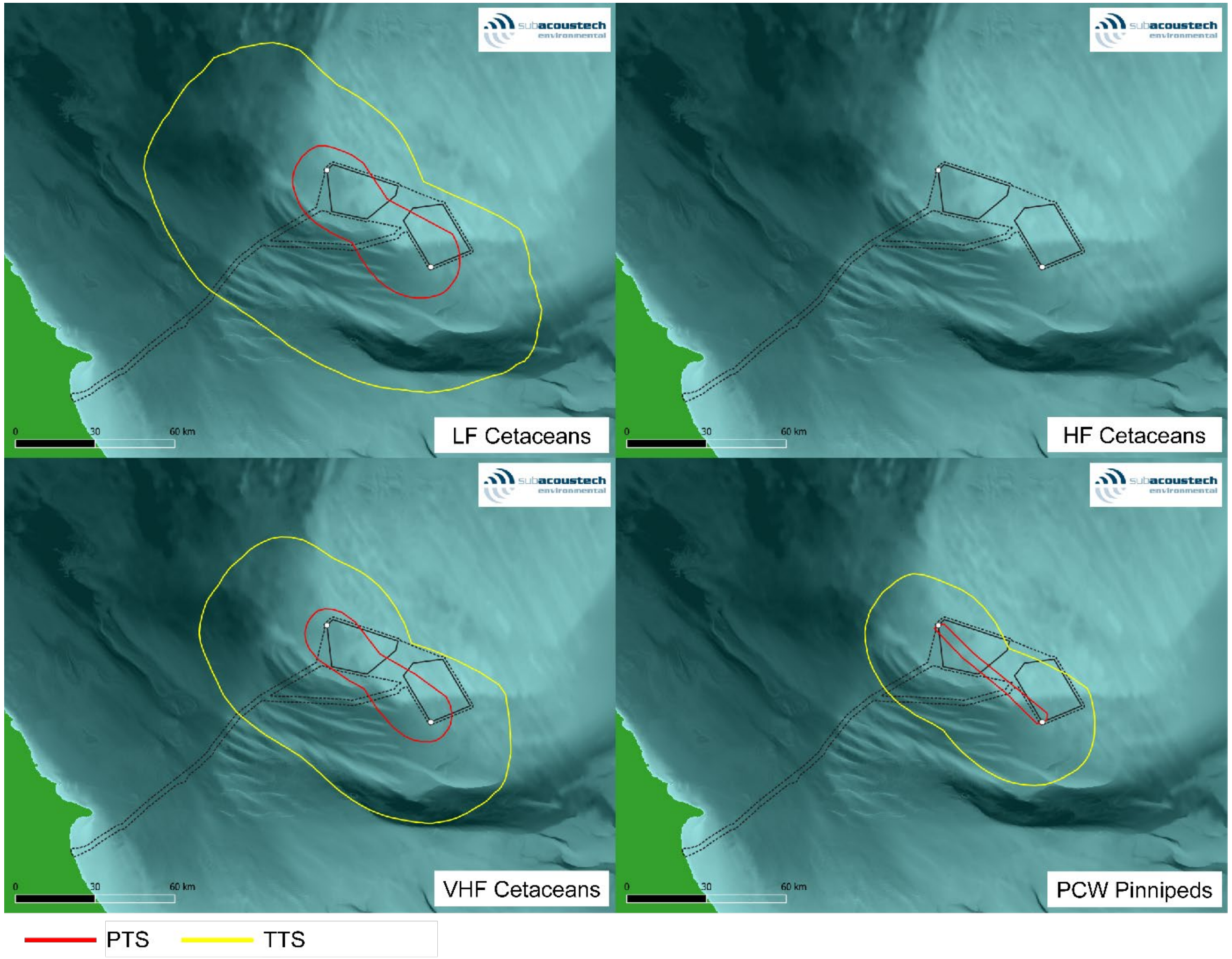

Figure 5-4 Contour plots showing the in-combination impacts of concurrent installation of multi-leg foundations at two locations across DBS for marine mammals using the impulsive Southall et al. (2019) criteria assuming a fleeing animal

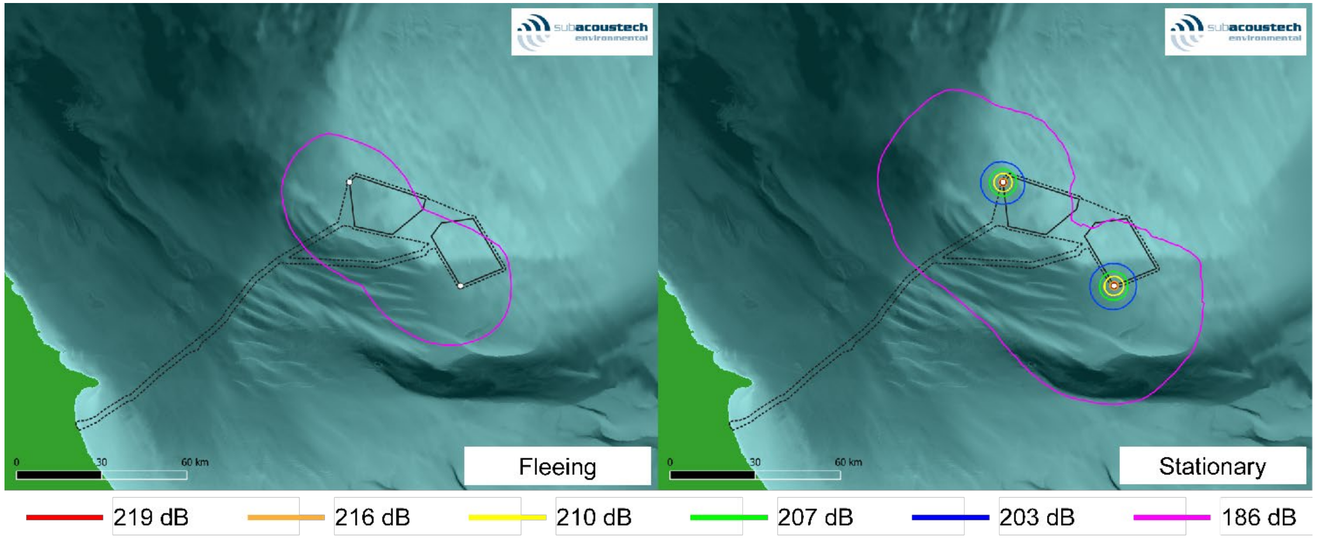

Figure 5-5 Contour plots showing the in-combination impacts of concurrent installation of multi-leg foundations at two locations across DBS for fish using the pile driving Popper et al. (2014) criteria assuming both a fleeing and stationary animal

Table 5-69 Summary of the impact areas for the installation of multi-leg foundations at two locations across DBS for marine mammals using the impulsive Southall et al. (2019) criteria assuming a fleeing animal

Multi-leg foundation Southall *et al.* (2019) Weighted SEL_{cum}		**DBS East: S location**	**DBS West: W location**	**In-combination area**
PTS (Impulsive)	LF (183 dB)	300 km^2	240 km^2	1,800 km^2
	HF (185 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (155 dB)	140 km^2	110 km^2	1,200 km^2
	PCW (185 dB)	1.7 km^2	1.0 km^2	230 km^2
TTS (Impulsive)	LF (168 dB)	5,200 km^2	6,200 km^2	12,000 km^2
	HF (170 dB)	0.2 km^2	0.1 km^2	-
	VHF (140 dB)	3,100 km^2	3,300 km^2	7,800 km^2
	PCW (170 dB)	1,300 km^2	1,200 km^2	4,100 km^2

Table 5-70 Summary of the impact areas for the installation of multi-leg foundations at two locations across DBS for fish using the pile driving Popper et al. (2014) criteria assuming both a fleeing and stationary animal

Multi-leg foundation Popper *et al.* (2014) Unweighted SEL_{cum}		**DBS East: S location**	**DBS West: W location**	**In-combination area**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 0.1 km^2	-
	216 dB	< 0.1 km^2	< 0.1 km^2	-
	210 dB	< 0.1 km^2	< 0.1 km^2	-
	207 dB	< 0.1 km^2	< 0.1 km^2	-
	203 dB	< 0.1 km^2	< 0.1 km^2	-
	186 dB	1,000 km^2	890 km^2	3,500 km^2
Stationary	219 dB	2.5 km^2	2.2 km^2	5.7 km^2
	216 dB	5.9 km^2	5.5 km^2	13 km^2
	210 dB	34 km^2	31 km^2	68 km^2
	207 dB	75 km^2	68 km^2	150 km^2
	203 dB	200 km^2	180 km^2	390 km^2
	186 dB	3,600 km^2	3,600 km^2	7,400 km^2

6 Other noise sources

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

Table 6-1 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 DBS East and DBS West sites.

Table 6-1 Summary of the possible noise making activities at DBS other than impact piling

Activity	Description
Cable laying	Noise from the cable laying vessel and any other associated noise during the offshore cable installation.
Dredging	Dredging may be required on site for seabed preparation work for certain foundation options, as well as for the export cable, array cables and interconnector cable installation. Suction dredging has been assumed as a worst-case.
Drilling	There is the potential for WTG foundations to be installed using drilling depending on seabed type or if a pile refuses during impact piling operations.
Rock placement	Potentially required on site for installation of offshore cables (cable crossings and cable protection) and scour protection around foundation structures.
Trenching	Plough trenching may be required during offshore cable installation.
Vessel noise	Jack-up barges for piling substructure and WTG installation. Other large and medium sized vessels to carry out other construction tasks and anchor handling. Other small vessels for crew transport and maintenance on site.
Operational WTG	Noise transmitted through the water from operational WTG. The project design envelope has made predictions for turbine parameters which could be available for DBS construction and has allowed for a maximum power output of around 27 MW.
UXO clearance	There is a possibility that Unexploded Ordnance (UXO) may exist within the DBS boundaries, which would need to be cleared before construction can begin.

Most of these activities are considered in section 6.1, with operational WTG noise and UXO clearance assessed in sections 6.2 and 6.3 respectively.

The NPL Good Practice Guide 133 for underwater noise measurements (Robinson *et al*., 2014) indicates that under certain circumstances, a simple modelling approach may be considered acceptable. Such an approach has been used for these noise sources, which are variously either quiet compared to impact piling (e.g., cable laying and dredging), or where detailed modelling would imply unjustified accuracy (e.g., where data is limited such as with 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.

6.1 Noise making activities

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

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

Predicted source levels and propagation calculations for the construction activities are presented in Table 6-2 along with a summary of the number of datasets used in each case. As previously, all SEL_{cum} criteria use the same assumptions as presented in section 2.2, and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. It should be reiterated that this modelling approach does not take bathymetry or any other environmental conditions into account, and as such can be applied to any location at, or surrounding, the DBS East and DBS West.

Table 6-2 Summary of the estimated unweighted source levels and transmission losses for the different considered noise sources related to construction

Source	Estimated unweighted source level	Transmission loss parameters	Comments
Cable laying	171 dB re 1 µPa @ 1 m (RMS)	N: 13, α: 0 (no absorption)	Based on 11 datasets from a pipe laying vessel measuring 300 m in length; this is considered a worst-case noise source for cable laying operations.
Dredging (Backhoe)	165 dB re 1 µPa @ 1 m (RMS)	N: 19, α: 0.0009	Based on three datasets from backhoe dredgers.
Dredging (Suction)	186 dB re 1 µPa @ 1 m (RMS)	N: 19, α: 0.0009	Based on five datasets from suction and cutter suction dredgers.
Drilling	169 dB re 1 µPa @ 1 m (RMS)	N: 16, α: 0.0006	Based on six datasets from various drilling operations covering ground investigations and pile installation. A 200kW drill has been assumed for modelling.
Rock placement	172 dB re 1 µPa @ 1 m (RMS)	N: 12, α: 0.0005	Based on four datasets from rock placement vessel '*Rollingstone*.'
Trenching	172 dB re 1 µPa @ 1 m (RMS)	N: 13, α: 0.0004	Based on three datasets of measurements from trenching vessels more than 100 m in length.
Vessel noise (large)	168 dB re 1 µPa @ 1 m (RMS)	N: 12, α: 0.0021	Based on five datasets of large vessels including container ships, FPSOs and other vessels more than 100 m in length. Vessel speed assumed as 10 knots.
Vessel noise (medium)	161 dB re 1 µPa @ 1 m (RMS)	N: 12, α: 0.0021	Based on three datasets of moderate sized vessels less than 100 m in length. Vessel speed assumed as 10 knots.

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

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

To account for the weightings required for modelling using the Southall *et al*. (2019) criteria (see section 2.2.1), reductions in source level have been applied to the various noise sources; Table 6-1 shows the representative noise measurements used for this, which have been adjusted for the source levels given in Table 6-2. Details of the reductions in sources levels for each of the weightings used for modelling are given in Table 6-3.

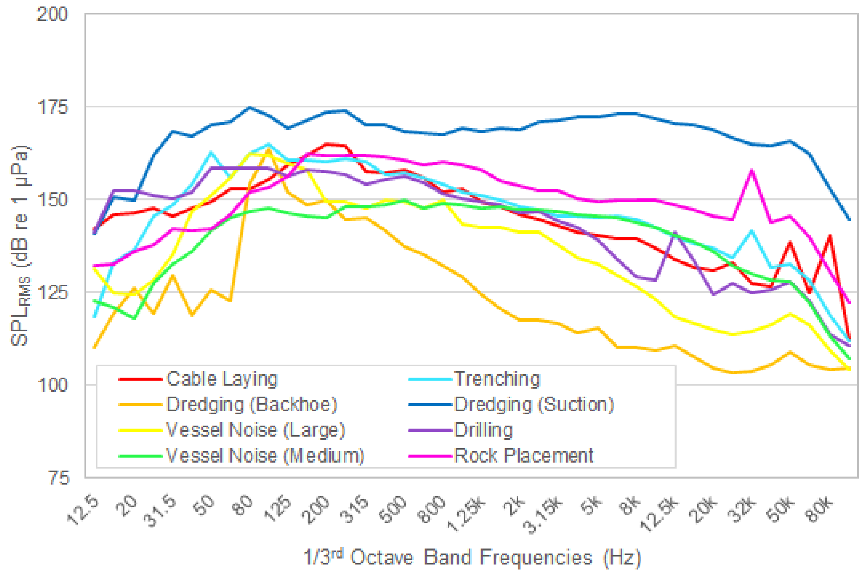

Figure 6-1 Summary of the 1/3rd octave frequency bands to which the Southall et al. (2019) weightings were applied in the simple modelling

Table 6-3 Reductions in source level for the different construction noise sources considered when the Southall et al. (2019) weightings are applied

Source	Reduction in source level from the unweighted level (Southall *et al*., 2019)			
	LF	HF	VHF	PCW
Cable laying	3.6 dB	22.9 dB	23.9 dB	13.2 dB
Dredging	2.5 dB	7.9 dB	9.6 dB	4.2 dB
Drilling	4.0 dB	25.8 dB	48.7 dB	13.2 dB
Rock placement	1.6 dB	11.9 dB	12.5 dB	8.2 dB
Trenching	4.1 dB	23.0 dB	25.0 dB	13.7 dB
Vessel noise	5.5 dB	34.4 dB	38.6 dB	17.4 dB

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

Given the modelled impact ranges, almost any marine mammal would have to be closer than 100 m from the continuous noise source at the start of the activity to acquire the necessary exposure to induce PTS as per Southall *et al*. (2019). The exposure calculation assumes the same receptor swim speeds as the impact piling modelling in section 5. As explained in section 4.3, this would only mean that the receptor reaches the ‘onset’ stage at these ranges, which is the minimum exposure that could potentially lead to the start of an effect and may only be marginal. In most hearing groups, the noise levels are low enough that there is a minimal risk.

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

All sources presented here result in much quieter levels than those presented for impact piling in section 5.

Table 6-4 Summary of the impact ranges for the different noise sources related to construction using the non-impulsive criteria from Southall et al. (2019) for marine mammals assuming a fleeing animal

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

Table 6-5 Summary of the impact ranges for the different noise sources related to construction using the non-impulsive criteria from Southall et al. (2019) for marine mammals assuming a stationary animal

Southall *et al.* (2019) Weighted SEL_{cum}	**PTS (non-impulsive)**				**TTS (non-impulsive)**			
	LF 199 dB	**HF** 198 dB	**VHF** 173 dB	**PCW** 201 dB	**LF** 179 dB	**HF** 178 dB	**VHF** 153 dB	**PCW** 181 dB
Cable laying	< 100 m	< 100 m	< 100 m	< 100 m	810 m	< 100 m	2.3 km	110 m
Dredging (Backhoe)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Dredging (Suction)	< 100 m	< 100 m	570 m	< 100 m	640 m	390 m	4.3 km	420 m
Drilling	< 100 m	< 100 m	< 100 m	< 100 m	160 m	< 100 m	200 m	< 100 m
Rock placement	< 100 m	< 100 m	900 m	< 100 m	2.1 km	410 m	13 km	460 m
Trenching	< 100 m	< 100 m	< 100 m	< 100 m	830 m	< 100 m	1.9 km	120 m
Vessel noise (large)	< 100 m	< 100 m	< 100 m	< 100 m	480 m	< 100 m	140 m	< 100 m
Vessel noise (medium)	< 100 m	< 100 m	< 100 m	< 100 m	130 m	< 100 m	< 100 m	< 100 m

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

Table 6-6 Summary of the impact ranges for the different noise sources related to construction using the continuous noise criteria from Popper et al. (2014) for fish (swim bladder involved in hearing)

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

6.2 Operational WTG noise

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

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

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

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

Indicative power outputs have been used to calculate impacts for this study. The smaller turbine has an indicative power output of 15 MW and the largest turbine has an indicative power output of 26.5 MW.

The maximum turbine sizes considered at DBS are much larger than those used for the estimation above, so caution must be used when considering the results presented in this section; no empirical data is available for large wind turbines close to the specification proposed here. Figure 6-2 presents a level against range plot for the two turbine sizes using the Tougaard *et al*. (2020) calculation, assuming an average 6 ms^{-1} wind speed.

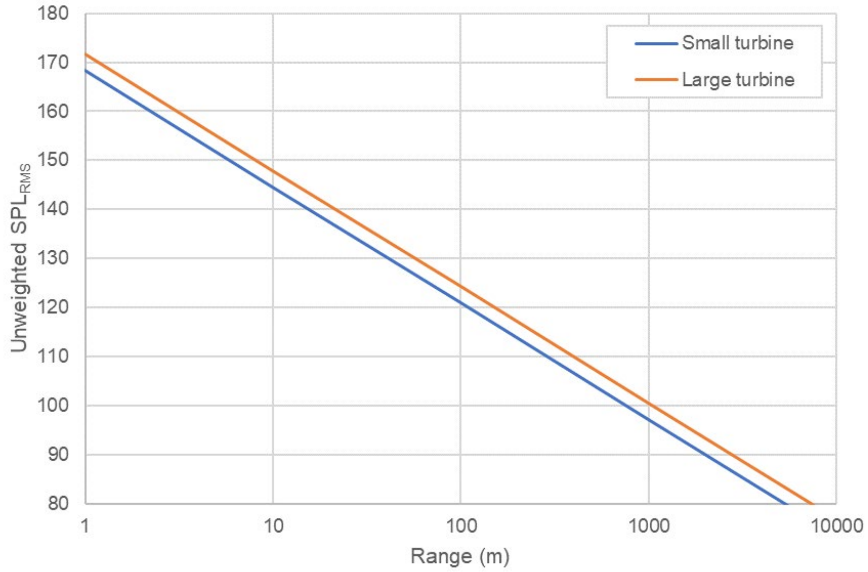

Figure 6-2 Predicted unweighted SPL_{RMS} from operational WTGs using the calculation from Tougaard et al. (2020)

Using this data, a summary of the predicted impact ranges has been produced, shown in Table 6-7 and Table 6-8. All SEL_{cum} criteria use the same assumptions as presented in section 2.2, and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. The operational WTG source is considered a non-impulsive or continuous source. For SEL_{cum} calculations, a stationary animal has been used and it is assumed that the operational WTG noise is present 24 hours a day.

Table 6-7 Summary of the operational WTG noise impact ranges using the non-impulsive noise criteria from Southall et al. (2019) for marine mammals

Southall *et al.* (2019) Weighted SEL_{cum}		**Operational WTG (small turbine)**	**Operational WTG (large turbine)**
PTS (non-impulsive)	199 dB (LF SEL_{cum})	< 100 m	< 100 m
	198 dB (HF SEL_{cum})	< 100 m	< 100 m
	173 dB (VHF SEL_{cum})	< 100 m	< 100 m
	201 dB (PCW SEL_{cum})	< 100 m	< 100 m
TTS (non-impulsive)	179 dB (LF SEL_{cum})	< 100 m	< 100 m
	178 dB (HF SEL_{cum})	< 100 m	< 100 m
	153 dB (VHF SEL_{cum})	< 100 m	< 100 m
	181 dB (PCW SEL_{cum})	< 100 m	< 100 m

Table 6-8 Summary of the operational WTG noise impact ranges using the continuous noise criteria from Popper et al. (2014) for fish (swim bladder involved in hearing)

Popper *et al.* (2014) Unweighted SPL_{RMS}	**Operational WTG (15 MW)**	**Operational WTG (26.5 MW)**
Recoverable injury 170 dB (48 hours) Unweighted SPL_{RMS}	< 50 m	< 50 m
TTS 158 dB (12 hours) Unweighted SPL_{RMS}	< 50 m	< 50 m

These results show that, for operational WTGs, injury risk is minimal. Taking the results from this and the previous section (6.1), and comparing them to the impact piling results in section 5, 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 DBS.

Stöber & Thomsen (2021) produced a similar study of an operational wind turbine dataset and raises the potential for behavioural disturbance caused by larger wind turbines. While prospective turbine sizes are increasing, Stöber & Thomsen conclude that these might only have limited impacts related to behavioural response on marine mammals and fish, although there is considerable uncertainty in criteria available to assess these. However, based on the highly precautionary NOAA Level B behavioural threshold (120 dB SPL_{RMS}, see NOAA, 2005) that the study utilises, it is estimated that the WTGs may only reach that threshold at ranges of approximately 150 m. As the distance between turbines at DBS is expected to be much greater than this, any array effect from the turbines is not expected.

6.3 UXO clearance

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

6.3.1 Estimation of underwater noise levels

6.3.1.1 High-order clearance

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

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

The maximum equivalent charge weight for the potential UXO devices that could be present within the DBS site boundary has been estimated as 698 kg. This has been modelled alongside a range of smaller devices, at charge weights of 25, 55, 120, 240, 525 and 698 kg. In each case, an additional donor weight of 0.5 kg has been included to initiate detonation. Natural England's Best Practice Advice (2022) is noted, suggesting up to 750 kg charge weight be modelled. Although this is not expected at this location, a quick check showed that the increase in noise from a 698 kg to 750 kg charge weight was <0.5 dB and would lead to negligible increases in impact range from those presented, especially bearing in mind the uncertainties inherent in the calculation of noise produced by UXO detonations.

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

6.3.1.2 Low-order clearance

Other techniques are being considered to reduce the impact of noise impacts from high order UXO clearance, caused by detonation of the main charge of the UXO. Deflagration is such an alternative technique, intended to result in a 'low order' burn of the explosive material in a UXO, which destroys, but does not detonate, the internal explosive.

Where the technique proceeds as intended, it is still not without noise impact. The process requires an initial shaped explosive donor charge, typically less than 250 g, to breach the casing and ignite the internal high explosive (HE) material without full detonation. The shaped charge and burn will both produce noise, although it will be significantly less than the high order detonation of the much larger UXO. It may not destroy all of the HE, necessitating further deflagration events or collection of the remnants. The deflagration may produce an unintentional high order event.

For calculation of the scenario of total destruction of the HE material using deflagration, it is anticipated that the initial shaped charge is the greatest source of noise (Cheong *et al.* 2020). The shaped charge is treated as a bulk charge with NEQ determined according to the size of UXO on which it is placed. A prediction of this impact is based on a charge weight of 250 g. The worst-case scenario would of course be a high order detonation with maximum pressures from complete detonation of the UXO, and this has also been used in the calculation of impact for comparison.

6.3.1.3 Low-yield clearance

The low-yield clearance is associated with the HYDRA UXO clearance system developed by EORCA UK. As with the low order deflagration technique, this involves the use of a small charge to initiate destruction of the UXO, avoiding a much louder detonation of the main explosive. Unlike deflagration, the HYDRA uses shaped charges to produce high pressure water jets that disintegrate the explosive material.

As with the low order clearance, the low yield clearance still generates sound from the donor charge. Based on recent tests from clearance using the HYDRA system at the Seagreen Alpha and Bravo offshore wind farm development sites (Cook and Banda, 2021), the donor charge is predicted to be 750 g, which will be used in the calculations of noise impact on the environment. This study also showed that for the low-yield technique, Soloway and Dahl (2014) underestimated the noise impacts at approximately 500 m and 1500 m. Although the conclusions from Cook and Banda (2021) state that the reasons for this underprediction cannot be determined on the basis of that study, a correction has been added to account for it to ensure a precautionary assessment.

6.3.2 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 of where it is used. An attenuation correction can be added to the

Soloway and Dahl (2014) equations for the absorption over long ranges (i.e., of the order of thousands of metres), based on measurements of high intensity noise propagation taken in the North Sea and Irish Sea. This uses standard frequency-based absorption coefficients for the seawater conditions expected in the region.

Despite this attenuation correction, the resulting noise levels still need to be considered carefully. For example, 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 are similar to the measurements presented by von Benda-Beckmann *et al*. (2015). At longer ranges, greater confidence is expected with the SEL calculations.

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

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

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

A summary of the unweighted UXO clearance source levels, calculated using the equations above, are given in Table 6-9.

Table 6-9 Summary of the unweighted SPL_{peak} and SEL_{ss} source levels used for UXO clearance modelling

Charge weight	SPL_{peak} source level	SEL_{ss} source level
Low yield	273.4 dB re 1 µPa @ 1 m	218.2 dB re 1 µPa²s @ 1 m
Low order (0.25 kg)	269.8 dB re 1 µPa @ 1 m	215.2 dB re 1 µPa²s @ 1 m
25 kg + donor	284.9 dB re 1 µPa @ 1 m	228.0 dB re 1 µPa²s @ 1 m
55 kg + donor	287.5 dB re 1 µPa @ 1 m	230.1 dB re 1 µPa²s @ 1 m
120 kg + donor	290.0 dB re 1 µPa @ 1 m	232.3 dB re 1 µPa²s @ 1 m
240 kg + donor	292.3 dB re 1 µPa @ 1 m	234.2 dB re 1 µPa²s @ 1 m
525 kg + donor	294.8 dB re 1 µPa @ 1 m	236.4 dB re 1 µPa²s @ 1 m
698 kg + donor	295.7 dB re 1 µPa @ 1 m	237.1 dB re 1 µPa²s @ 1 m

6.3.3 Impact ranges

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

Although the impact ranges in Table 6-10 to Table 6-13 are large, the duration the noise is present must also be considered. For the detonation of a UXO, each explosion is a single noise event, compared to the multiple pulse nature and longer durations of impact piling.

Table 6-10 Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, unweighted SPL_{peak} noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al.* (2019) Unweighted SPL_{peak}	**PTS (impulsive)**				**TTS (impulsive)**			
	LF 219 dB	**HF** 230 dB	**VHF** 202 dB	**PCW** 218 dB	**LF** 213 dB	**HF** 224 dB	**VHF** 196 dB	**PCW** 212 dB
Low yield	600 m	190 m	3.4 km	660 m	1.1 km	360 m	6.2 km	1.2 km
Low order (0.25 kg)	170 m	60m	990 m	190 m	320 m	100 m	1.8 km	360 m
25 kg + donor	820 m	260 m	4.6 km	910 m	1.5 km	490 m	8.5 km	1.6 km
55 kg + donor	1.0 km	340 m	6.0 km	1.1 km	1.9 km	640 m	11 km	2.1 km
120 kg + donor	1.3 km	450 m	7.8 km	1.5 km	2.5 km	830 m	14 km	2.8 km
240 kg + donor	1.7 km	560 m	9.8 km	1.9 km	3.2 km	1.0 km	18 km	3.5 km
525 kg + donor	2.2 km	730 m	12 km	2.5 km	4.1 km	1.3 km	23 km	4.6 km
698 kg + donor	2.4 km	810 m	13 km	2.7 km	4.5 km	1.4 km	25 km	5.0 km

Table 6-11 Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, weighted SEL_{ss} noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al.* (2019) Weighted SEL_{ss}	**PTS (impulsive)**				**TTS (impulsive)**			
	LF 183 dB	**HF** 185 dB	**VHF** 155 dB	**PCW** 185 dB	**LF** 168 dB	**HF** 170 dB	**VHF** 140 dB	**PCW** 170 dB
Low yield	1.6 km	< 50 m	450 m	290 m	22 km	110 m	2.1 km	3.9 km
Low order (0.25 kg)	230 m	< 50 m	80 m	40 m	3.2 km	< 50 m	750 m	570 m
25 kg + donor	2.2 km	< 50 m	570 m	390 m	29 km	150 m	2.4 km	5.2 km
55 kg + donor	3.2 km	< 50 m	740 m	570 m	41 km	210 m	2.8 km	7.5 km
120 kg + donor	4.7 km	< 50 m	950 m	830 m	57 km	300 m	3.2 km	10 km
240 kg + donor	6.5 km	< 50 m	1.1 km	1.1 km	76 km	390 m	3.5 km	14 km
525 kg + donor	9.5 km	50 m	1.4 km	1.6 km	100 km	530 m	4.0 km	19 km
698 kg + donor	10 km	60 m	1.5 km	1.9 km	110 km	590 m	4.1 km	22 km

Table 6-12 Summary of the PTS and TTS impact ranges for UXO detonation using the non-impulsive, weighted SEL_{ss} noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al.* (2019) Weighted SEL_{ss}	**PTS (non-impulsive)**				**TTS (non-impulsive)**			
	LF 199 dB	**HF** 198 dB	**VHF** 173 dB	**PCW** 201 dB	**LF** 179 dB	**HF** 178 dB	**VHF** 153 dB	**PCW** 181 dB
Low yield	100 m	< 50 m	< 50 m	< 50 m	3.3 km	< 50 m	590 m	590 m
Low order (0.25 kg)	< 50 m	< 50 m	< 50 m	< 50 m	460 m	< 50 m	110 m	80 m
25 kg + donor	130 m	< 50 m	< 50 m	< 50 m	4.4 km	< 50 m	730 m	790 m
55 kg + donor	190 m	< 50 m	< 50 m	< 50 m	6.4 km	60 m	940 m	1.1 km
120 kg + donor	280 m	< 50 m	70 m	< 50 m	9.4 km	80 m	1.1 km	1.6 km
240 kg + donor	390 m	< 50 m	100 m	70 m	13 km	110 m	1.4 km	2.3 km
525 kg + donor	570 m	< 50 m	130 m	100 m	18 km	160 m	1.7 km	3.3 km
698 kg + donor	660 m	< 50 m	150 m	110 m	21 km	180 m	1.8 km	3.8 km

Table 6-13 Summary of the impact ranges for UXO detonation using the unweighted SPL_{peak} explosion noise criteria from Popper et al. (2014) for species of fish

Popper *et al.* (2014) Unweighted SPL_{RMS}	**Mortality and potential mortal injury**	
	234 dB	229 dB
Low yield	130 m	210 m
Low order (0.25 kg)	40 m	65 m
25 kg + donor	170 m	290 m
55 kg + donor	230 m	380 m
120 kg + donor	300 m	490 m
240 kg + donor	370 m	620 m
525 kg + donor	490 m	810 m
698 kg + donor	530 m	890 m

6.3.4 Summary

The maximum PTS range calculated UXO is 13 km for the VHF cetacean category, when considering the unweighted SPL_{peak} criteria for the largest high-order clearance. For SEL_{ss} criteria, the largest PTS range is calculated for LF cetaceans with a predicted impact of 10 km using the impulsive noise criteria. As explained earlier, this assumes no degradation of the UXO and no smoothing of the pulse over that distance, which is very precautionary. Although an assumption of non-pulse could under-estimate the potential impact (Martin *et al*., 2020) (the equivalent range based on LF cetacean non-pulse criteria is 660 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.

7 Summary and conclusions

Subacoustech Environmental have undertaken a study on behalf of HaskoningDHV UK Ltd. to assess the potential underwater noise and its effects during the construction and operation of the proposed DBS wind farm sites, located off the northeast coast of England in the North Sea.

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

Four representative modelling locations were chosen to give spatial variations across the two DBS sites, as well as accounting for changes in water depth. At each location two modelling scenarios were considered:

- A monopile foundation considering a 15 m diameter pile installed using a maximum hammer energy of 6,000 kJ and up to four piles installed per day (two piles per vessel per day); and
- A multi-leg foundation considering a 4 m diameter pile installed using a maximum blow energy of 3,000 kJ and up to eight piles installed per day (four piles per vessel per day).

The loudest levels of noise and the greatest impact ranges were generally predicted for the monopile foundation scenarios at the DBS East: S modelling location.

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

For marine mammals, maximum PTS ranges were predicted for LF cetaceans, with ranges of up to 18 km based on the monopile foundation scenario. For fish, the largest recoverable injury ranges (203 dB SEL_{cum}) were predicted to be 9.3 km for a stationary receptor, reducing to 880 m for a fleeing receptor.

Noise sources other than piling were considered using a high-level, simple modelling approach, including cable laying, dredging, drilling, rock placement, vessel movements, 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 minimal as the noise emissions from these are close to, or below, the appropriate injury criteria even when very close to the source of the noise.

UXO clearance has also been considered at the DBS site, and for the expected UXO clearance noise, there is a risk of PTS up to 13 km from the largest, 698 kg, UXO device considered, using the unweighted SPL_{peak} criteria for VHF cetaceans. However, this is likely to be highly precautionary as the impact range is based on a worst-case criterion and calculation methodology that does not account for any smoothing of the pulse over long ranges, which would reduce the pulse peak and other characteristics of the sound that cause injury.

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

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Appendix A Additional modelling results

Following from the Southall *et al*. (2019) modelled impact ranges presented in section 5 of the main report, the modelling results for the non-impulsive criteria from impact piling noise at DBS, as discussed in section 2.2.1, are presented below. The predicted ranges here fall well below the impulsive criteria previously presented.

A.1 Single location modelling

Table A 1 to Table A 16 present the modelling results considering single locations for the non-impulsive Southall *et al*. (2019) criteria.

A.1.1 Monopile foundations

Table A 1 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the monopile foundation (single pile installation) modelling at the DBS East: S location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		Monopile foundation, single pile			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	1,300 km²	29 km	12 km	20 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	400 km²	14 km	8.6 km	11 km
	PCW (181 dB)	63 km²	5.1 km	3.9 km	4.5 km

Table A 2 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the monopile foundation (2 piles installed per 24 hours) modelling at the DBS East: S location assuming a fleeing animal

Southall *et al*. (2019) Weighted SEL_{cum}		Monopile foundation, 2 sequential piles			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	1,300 km²	29 km	12 km	20 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	410 km²	14 km	8.6 km	11 km
	PCW (181 dB)	67 km²	5.3 km	3.9 km	4.6 km

Table A 3 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the monopile foundation (single pile installation) modelling at the DBS East: NW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Monopile foundation, single pile			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	170 km²	9.5 km	5.3 km	7.2 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	76 km²	6.0 km	3.6 km	4.9 km
	PCW (181 dB)	3.5 km²	1.4 km	500 m	1.0 km

Table A 4 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the monopile foundation (2 piles installed per 24 hours) modelling at the DBS East: NW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Monopile foundation, 2 sequential piles			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	170 km²	9.5 km	5.3 km	7.2 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	77 km²	6.0 km	3.6 km	4.9 km
	PCW (181 dB)	3.5 km²	1.4 km	500 m	1.0 km

Table A 5 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the monopile foundation (single pile installation) modelling at the DBS West: NE location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Monopile foundation, single pile			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	160 km²	8.7 km	5.8 km	7.2 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	70 km²	5.3 km	3.9 km	4.7 km
	PCW (181 dB)	1.7 km²	930 m	500 m	720 m

Table A 6 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the monopile foundation (2 piles installed per 24 hours) modelling at the DBS West: NE location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Monopile foundation, 2 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	160 km²	8.7 km	5.8 km	7.2 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	70 km²	5.3 km	4.0 km	4.7 km
	PCW (181 dB)	1.7 km²	930 m	500 m	730 m

Table A 7 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the monopile foundation (single pile installation) modelling at the DBS West: W location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Monopile foundation, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	1,200 km²	27 km	13 km	19 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	330 km²	12 km	8.2 km	10 km
	PCW (181 dB)	48 km²	4.3 km	3.3 km	3.9 km

Table A 8 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the monopile foundation (2 piles installed per 24 hours) modelling at the DBS West: W location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Monopile foundation, 2 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	1,300 km²	28 km	13 km	19 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	340 km²	13 km	8.2 km	10 km
	PCW (181 dB)	51 km²	4.5 km	3.4 km	4.0 km

A.1.2 Multi-leg foundations

Table A 9 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the multi-leg foundation (single pile installation) modelling at the DBS East: S location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Multi-leg foundation, single pile			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	820 km²	22 km	9.4 km	16 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	230 km²	9.9 km	7.0 km	8.5 km
	PCW (181 dB)	32 km²	3.6 km	2.8 km	3.2 km

Table A 10 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the multi-leg foundation (4 piles installed per 24 hours) modelling at the DBS East: S location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Multi-leg foundation, 4 sequential piles			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	850 km²	23 km	9.4 km	16 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	260 km²	11 km	7.0 km	9.0 km
	PCW (181 dB)	38 km²	4.1 km	2.9 km	3.5 km

Table A 11 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the multi-leg foundation (single pile installation) modelling at the DBS East: NW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Multi-leg foundation, single pile			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	79 km²	6.7 km	3.2 km	4.9 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	39 km²	4.3 km	2.4 km	3.5 km
	PCW (181 dB)	0.8 km²	700 m	180 m	470 m

Table A 12 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the multi-leg foundation (4 piles installed per 24 hours) modelling at the DBS East: NW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Multi-leg foundation, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	80 km²	6.7 km	3.2 km	4.9 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	40 km²	4.4 km	2.5 km	3.5 km
	PCW (181 dB)	0.8 km²	730 m	180 m	480 m

Table A 13 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the multi-leg foundation (single pile installation) modelling at the DBS West: NE location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Multi-leg foundation, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	73 km²	5.8 km	3.7 km	4.8 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	34 km²	3.7 km	2.7 km	3.3 km
	PCW (181 dB)	0.2 km²	380 m	130 m	250 m

Table A 14 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the multi-leg foundation (4 piles installed per 24 hours) modelling at the DBS West: NE location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Multi-leg foundation, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	73 km²	5.8 km	3.7 km	4.8 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	35 km²	3.8 km	2.7 km	3.3 km
	PCW (181 dB)	0.2 km²	380 m	130 m	260 m

Table A 15 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the multi-leg foundation (single pile installation) modelling at the DBS West: W location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Multi-leg foundation, single pile**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	710 km^2	20 km	10 km	15 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	180 km^2	8.6 km	6.3 km	7.6 km
	PCW (181 dB)	24 km^2	3.0 km	2.4 km	2.8 km

Table A 16 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the multi-leg foundation (4 piles installed per 24 hours) modelling at the DBS West: W location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Multi-leg foundation, 4 sequential piles**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	760 km^2	21 km	10 km	15 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	210 km^2	9.7 km	6.4 km	8.1 km
	PCW (181 dB)	28 km^2	3.4 km	2.5 km	3.0 km

A.2 Concurrent location modelling

Figure A 1, Figure A 2, Table A 17 and Table A 18 expand on the results presented in section 5.4 for concurrent multiple location piling, covering the non-impulsive criteria from Southall *et al*. (2019) for marine mammals. As before, contours too small to be seen at scale have not been included, impact ranges have not been presented as there are multiple starting points for receptors, and fields denoted with a dash "-" show where there is no in-combination effect when the piles are installed simultaneously.

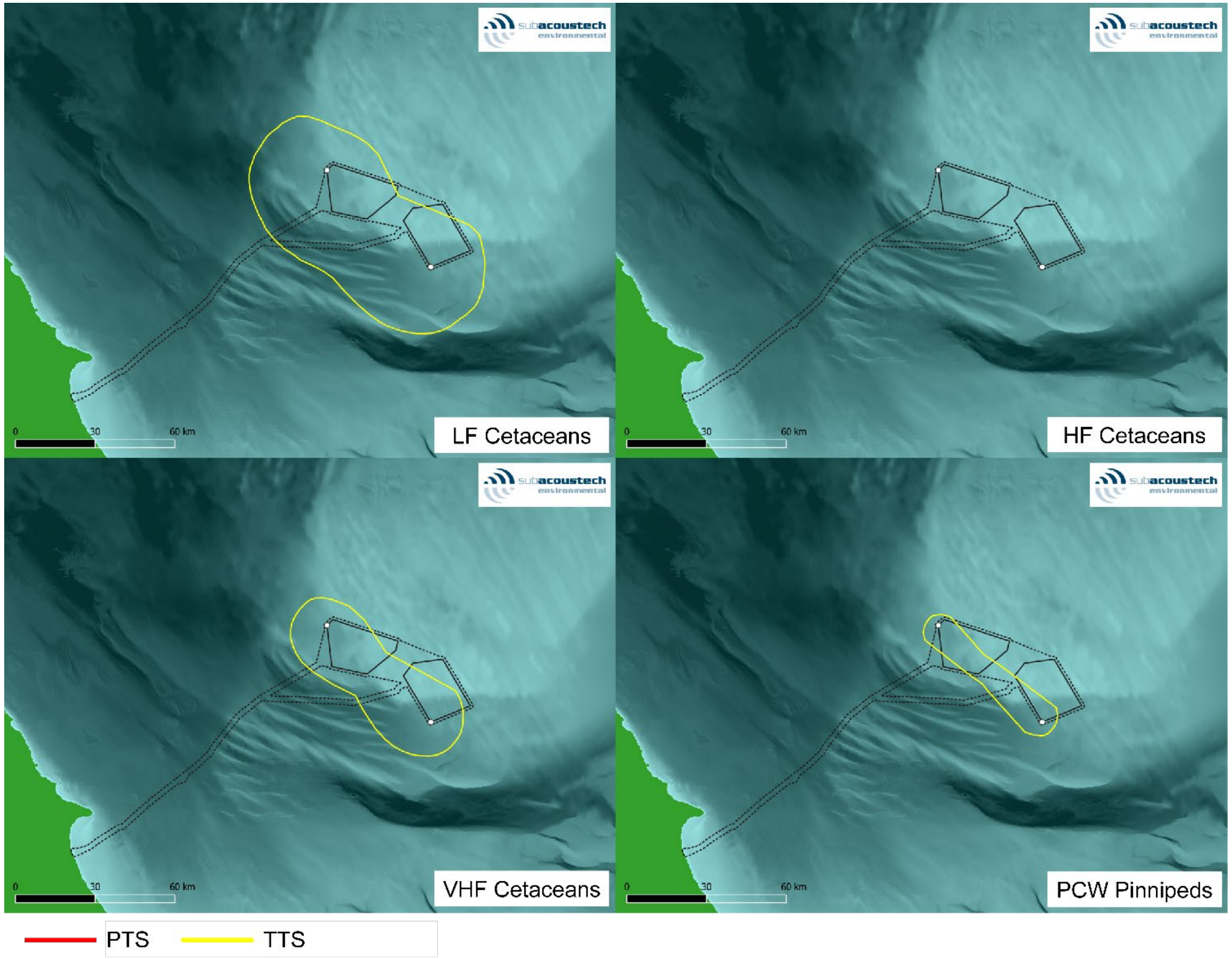

Figure A 1 Contour plots showing the in-combination impacts of concurrent installation of monopile foundations at two locations across DBS for marine mammals using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal

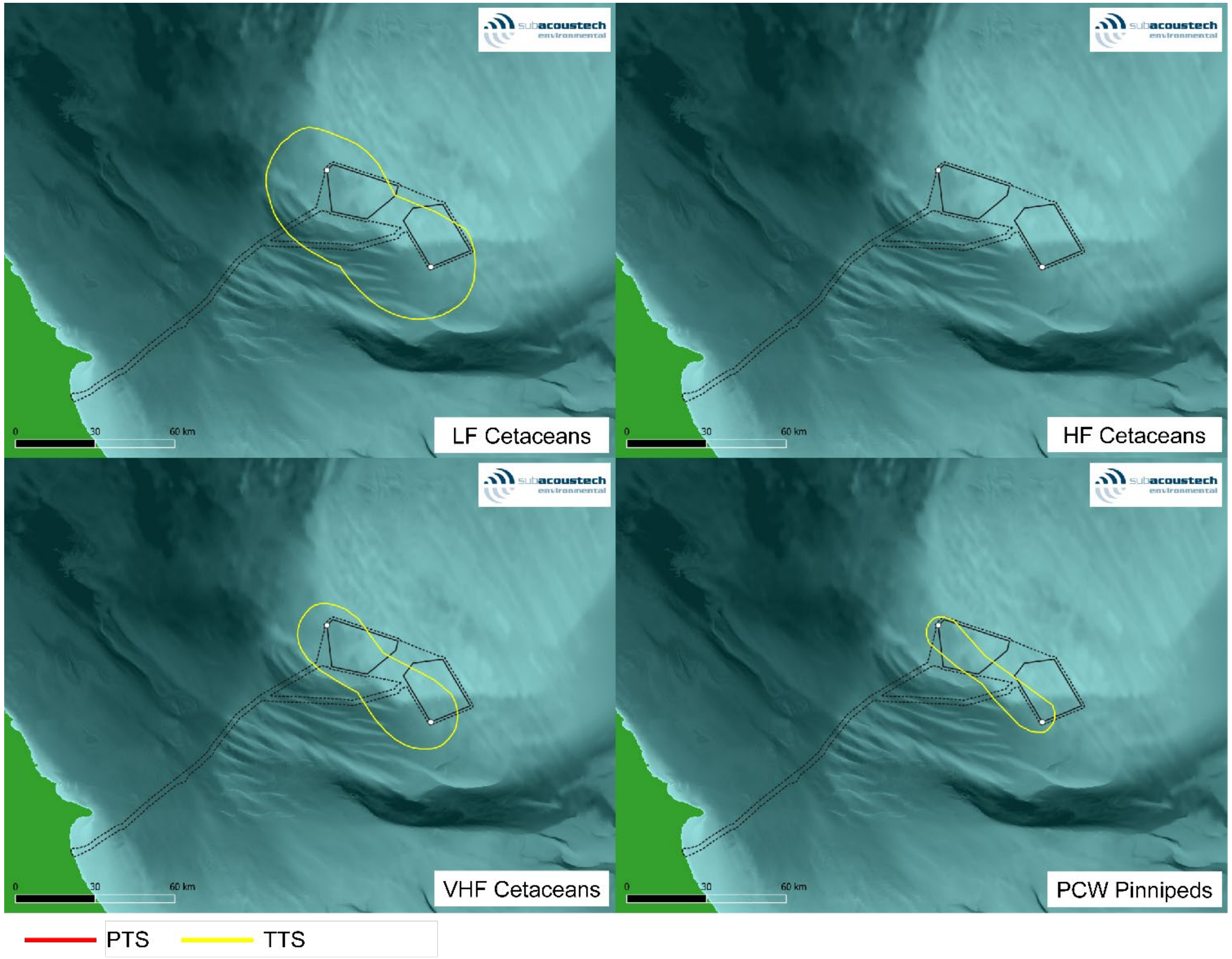

Figure A 2 Contour plots showing the in-combination impacts of concurrent installation of multi-leg foundations at three locations across DBS for marine mammals using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal

Table A 17 Summary of the impact areas for the installation of monopile foundations at two locations across DBS for marine mammals using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal

Monopile foundation Southall *et al*. (2019) Weighted SEL_{cum}		**DBS East: S location**	**DBS West: W location**	**In-combination area**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 0.1 km²	-
	HF (198 dB)	< 0.1 km²	< 0.1 km²	-
	VHF (173 dB)	< 0.1 km²	< 0.1 km²	-
	PCW (201 dB)	< 0.1 km²	< 0.1 km²	-
TTS (Non-impulsive)	LF (179 dB)	1,300 km²	1,300 km²	4,300 km²
	HF (178 dB)	< 0.1 km²	< 0.1 km²	-
	VHF (153 dB)	410 km²	340 km²	1,900 km²
	PCW (181 dB)	67 km²	51 km²	700 km²

Table A 18 Summary of the impact areas for the installation of multi-leg foundations at three locations across DBS for marine mammals using the non-impulsive Southall et al. (2019) criteria assuming a fleeing animal

Monopile foundation Southall *et al*. (2019) Weighted SEL_{cum}		**DBS East: S location**	**DBS West: W location**	**In-combination area**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 0.1 km²	-
	HF (198 dB)	< 0.1 km²	< 0.1 km²	-
	VHF (173 dB)	< 0.1 km²	< 0.1 km²	-
	PCW (201 dB)	< 0.1 km²	< 0.1 km²	-
TTS (Non-impulsive)	LF (179 dB)	850 km²	760 km²	3,300 km²
	HF (178 dB)	< 0.1 km²	< 0.1 km²	-
	VHF (153 dB)	260 km²	210 km²	1,500 km²
	PCW (181 dB)	38 km²	28 km²	660 km²

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P331R0100	01	13/12/2022	Initial writing and internal review
P331R0101	01	18/01/2023	Issue to client
P331R0102	-	19/01/2023	Minor updated to operational WTG noise section
P331R0103	-	23/03/2023	Fixed hammer blow energy typo
P331R0104	-	25/10/2023	Updates following changes to modelling parameters
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P331R0106	-	05/10/2024	Additional concurrent location modelling and removal of ECR modelling.
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