Bowdun Offshore Wind Farm, Offshore EIA Report

Volume 3, Technical Appendix 10.4: Subsea Noise Technical Report

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Glossary

Defined Term	Definition
Aerodynamic Noise	Noise generated by air passing over an object, for example Wind Turbine blades.
Array Area	The Array Area is the area in which the Offshore Generation Assets will be located.
Bowdun Offshore Wind Farm Limited (BOWFL)	A Special-Purpose Vehicle (SPV) (legal entity) for the purpose of developing the Project. BOWFL are the Applicant for the Offshore Application.
Cetacean	Marine mammals that are entirely aquatic. These include whales, dolphins, and porpoises.
Embedded Mitigation	Measures that are adopted as part of the Proposed Development and therefore assessed within the Environmental Impact Assessment (EIA). The proposed approach for the EIA for the Proposed Development is that Embedded Mitigation includes both primary mitigation and tertiary mitigation. These are defined by the ISEP as follows: Primary: Modifications to the location or design of the development made during the pre-application phase that are an inherent part of the project, and do not require additional action to be taken. Tertiary: Actions that would occur with or without input from the EIA feeding into the design process. These include actions that will be undertaken to meet other existing legislative requirements, or actions that are considered to be standard practices used to manage commonly occurring environmental effects.
Environmental Impact Assessment (EIA)	Process for the assessment of likely significant environmental effects of a project on the physical, biological, and human environment during construction, Operation and Maintenance (O&M) and decommissioning.
Impulsive Sound	Sound which is broadband, very brief with a high rise time and high peak level compared to the energy averaged sound level.
Marine Directorate (MD)	The Marine Directorate of the Scottish Government, formerly known as Marine Scotland. The planning and licensing authority for Scotland's seas and custodian of Scotland's National Marine Plan (NMP). The Marine Directorate - Licensing Operations Team (MD-LOT) are specifically responsible for managing Section 36 Consent and Marine Licence Applications seaward of MHWS.
Maximum Design Scenario (MDS)	The scenario within the design envelope likely to result in the greatest impact on a particular topic receptor, and therefore the one that should be assessed for that topic receptor.
Mitigation	Measures to avoid, prevent, reduce or control effects on the environment. See also the definitions for Embedded Mitigation.
Non-impulsive (or continuous) sound	Sound which is either continuous or intermittent but without the characteristics described above for impulsive sound.
Offshore Environmental Impact Assessment (EIA) Report (hereafter, 'Offshore EIA Report')	Document prepared to report the findings of the EIA for the Proposed Development and produced in accordance with the EIA Regulations. The Offshore EIA Report is submitted to support the Offshore Application for the Proposed Development, and to comply with EIA Regulations.

Defined Term	Definition
Offshore Substation Platform(s) (OSPs)	OSPs comprise the support structure, topside and electrical components used for collecting and/or converting electricity generated by the Wind Turbines for transmission by the Offshore Export Cables.
Operation and Maintenance (O&M)	The phase of the Proposed Development following completion of construction. This phase of development includes routine inspections, repairs and replacement of infrastructure and equipment (including Interconnector Cables and IACs), Scour Protection replenishment or replacement, major component replacement, painting and/or other coating works, removal of marine growth, and replacement of access ladders.
Particle Motion	Component of the pressure wave comprising the movement of particles within the water or sediment relative to an equilibrium point.
Piling	The action of installing piles: installation can use various methodologies, the most common of which are impact piling (in which the piles are struck by a “hammer”) and drilling (during which a hole is drilled into the seafloor, the drilling tool is removed, and the pile is slotted into that hole).
Project (the)	An overarching term for the Bowdun Offshore Wind Farm (Bowdun OWF) comprising the offshore and onshore infrastructure required to generate and transmit electricity from the Array Area to the onshore Grid Connection Point. The Project includes the Offshore Generation Assets, the Offshore Transmission Assets and the Onshore Transmission Assets.
Study Area	For each environmental topic, the baseline environment will be characterised, and the potential environmental impacts will be described within a topic-specific study area. Specific study areas are defined for each topic and are based on the maximum spatial extent across which potential impacts of the Project may be experienced by the relevant receptors (i.e. Zone of Influence).
Thistle Wind Partners (TWP)	Company established for the development of the Project.
Wind Turbines	Structures comprising of a tubular tower, rotor blades, and a nacelle which houses the Wind Turbine generator.

Acronyms

Acronym	Definition
ADD	Acoustic Deterrent Device
AUD INJ	Auditory Injury
BGS	British Geological Survey
BOWFL	Bowdun Offshore Wind Farm Limited
CTV	Crew Transfer Vessel
DP	Dynamic Positioning
EIA	Environmental Impact Assessment
EMODNet	European Marine Observation and Data Network
GEBCO	General Bathymetric Chart of the Oceans

Acronym	Definition
HF	High Frequency
HVAC	High Voltage Alternating Current
IAC	Inter-Array Cable
JNCC	Joint Nature Conservation Committee
LF	Low Frequency
MBES	Multibeam Echosounder
MD	Marine Directorate
MDS	Maximum Design Scenario
MD-LOT	Marine Directorate - Licensing Operations Team
MD-SEDD	Marine Directorate - Science, Evidence, Data and Digital
MF	Mid-frequency
NEQ	Net Explosive Quantity
NMFS	National Marine Fisheries Service
OCA	Other Marine Carnivore in Air
OCW	Other Marine Carnivore in Water
OSP	Offshore Substation Platform
OWF	Offshore Wind Farm
O&M	Operation and Maintenance
PCA	Phocid Carnivore in Air
PCW	Phocid Carnivore in Water
POA	Plan Option Area
PTS	Permanent Threshold Shift
RL	Received Level
rms	Root Mean Square
SBES	Single Beam Echosounder
SBP	Sub-bottom Profiler
SEL	Sound Exposure Level
SMP	Sectoral Marine Plan
SL	Source Level
SPL	Sound Pressure Level
SSS	Side Scan Sonar
TL	Transmission Loss
TNO	Netherlands Organisation for Applied Scientific Research
TOB	Third Octave Bands
TTS	Temporary Threshold Shift
TWP	Thistle Wind Partners Limited
UHRS	Ultra-High Resolution Seismic
UK	United Kingdom

Acronym	Definition
UXO	Unexploded Ordnance
WTD 71	Jasco Applied Sciences, Curtin University and Bundeswehr Technical Centre for Ships and Naval Weapons, Maritime Technology and Research
VHF	Very High Frequency
WW2	World War Two

Table of Units

Units	Definition
%	Percent
°	Degree
dB	Decibel
dB re 1 μPa	Decibel referenced to one micropascal
Hz	Hertz
J	Joule
kg	Kilogram
kHz	Kilohertz
kJ	Kilojoule
km	Kilometre
km^2	Square kilometre
kn	Knotts
m	Metre
m/s	Metre per second
ms	Millisecond
MW	MegaWatt
μPa	Micropascal
μPa^{2}s	Micropascal squared seconds
nm	Nautical mile
nm/s	Nanometres per second
Pa	Pascal
s^{-1}	per second

1 Introduction

1.1.1 This Subsea Noise Technical Report presents the results of a desktop study considering the potential effects of underwater sound on the marine environment from the construction and operation of the offshore elements of the Bowdun Offshore Wind Farm (OWF) Project (hereafter referred to as the Proposed Development). The Proposed Development covers the Option Lease Area (OLA) comprises of the Array Area, which is located in the E3 Plan Option Area (POA) detailed in the Scottish Sectoral Marine Plan (SMP) (Scottish Government, 2020), and the Export Cable Corridor. The Array Area is located 38 km from the Aberdeenshire coast at its closest point, covering an area of 187 km^2. The Proposed Development will comprise of Wind Turbines (fixed foundations), Inter-Array Cables (IACs), Offshore Substation Platforms (OSPs), Interconnector Cables, Offshore Export Cables and any necessary scour/cable protection. The Export Cable Corridor will include a maximum of three High Voltage Alternating Current (HVAC) Offshore Export Cables, each with a length of up to 70 km and will make Landfall at Benholm, Aberdeenshire.

1.1.2 Sound is readily transmitted into the underwater environment and there is potential for sound emissions from all phases of the Proposed Development to adversely affect marine mammals and fish. At a close range from a source that generates high sound levels, permanent or temporary hearing effects may occur to marine species, while at a very close range and very high sound levels, for example explosions, gross physical trauma is possible. At far ranges the introduction of any additional sound could potentially cause short-term behavioural changes, for example displacement from the area, or changes to the time spent foraging. Masking of key sound signals may affect the ability of species to communicate and to determine the presence of predators, food, underwater features, and obstructions (it should be noted that it is currently unclear whether, or how, close range or short-term impacts may translate to long-term population level impacts, this is an area of active research). This report provides an overview of the potential effects due to subsea noise from the Proposed Development on the surrounding marine environment.

1.1.3 The aim of this Subsea Noise Technical Report is to predict likely distances at which the onset of potential auditory injury or impairment and behavioural effects on different marine fauna may occur when exposed to the different anthropogenic sounds that occur during different phases of the Proposed Development. The results from this Subsea Noise Technical Report have been used to inform the following chapters of the Offshore Environmental Impact Assessment (EIA) Report in order to determine the potential impact of underwater sound on marine life:

- Volume 2, Chapter 9: Fish and Shellfish Ecology;
- Volume 2, Chapter 10: Marine Mammals; and
- Volume 2, Chapter 13: Commercial Fisheries.

1.1.4 Consequently, the sensitivity of species, magnitude of potential impact and significance of effect from underwater sound associated with the Proposed Development are addressed within the relevant Offshore EIA Report chapters.

1.1.5 This Subsea Noise Technical Report uses peer reviewed models to calculate the impact ranges to marine mammals and fish for each phase of the Proposed Development: pre-construction, construction, operation and maintenance (O&M) and decommissioning. Key modelled sources include:

- clearance of Unexploded Ordnance (UXO);
- geophysical and geotechnical surveys;
- impact piling;
- vessels; and
- operational Wind Turbines.

2 Subsea Noise Study Area

2.1.1 No separate study area has been outlined for underwater sound as this is defined by the receptors and discussed within the relevant topics listed in Paragraph 1.1.3 above.

2.1.2 The modelled area covers the Array Area and an area extending to up to 75 km from the boundaries north, south, east and west (except where restricted by land). This area is designed to cover the areas where piling will occur but is considered representative of the activities along the cable route as a worst case scenario.

2.1.3 Bathymetry data used within the modelling was obtained from the General Bathymetric Chart of the Oceans (GEBCO). The GEBCO 2024 Grid, is a global terrain model for ocean and land, providing elevation data, in metres, on a 15 arc-second interval grid.

3 Acoustic Concepts and Terminology

3.1.1 Sound travels through water as vibrations of the fluid particles in a series of pressure waves. These waves comprise a series of alternating compressions (positive pressure) and rarefactions (negative pressure). As sound consists of variations in pressure, the unit for measuring sound is usually referenced to a unit of pressure, the Pascal (Pa). The decibel (dB) is a logarithmic ratio scale used to communicate the large range of acoustic pressures that can be perceived or detected, with a known pressure amplitude chosen as a reference value (i.e. 0 dB). In the case of underwater sound, the reference value (P_{ref}) is taken as 1 µPa, whereas the airborne sound is usually referenced to a pressure of 20 µPa.

3.1.2 There are several descriptors used to characterise a sound wave. The difference between the lowest pressure variation (rarefaction) and the highest-pressure variation (compression) is called the peak to peak (pk-pk) sound pressure level. The difference between the highest variation (either positive or negative) and the mean pressure is called the peak pressure level. Lastly, the Root Mean Square (rms) sound pressure level is used as a description of the average amplitude of the variations in pressure over a specific time window. Decibel values reported should always be quoted along with the Pref value employed during calculations. For example, the measured Sound Pressure Level (SPL_{rms}) value of a pulse may be reported as 100 dB re 1 µPa. These descriptions are shown graphically in Figure 3.1.

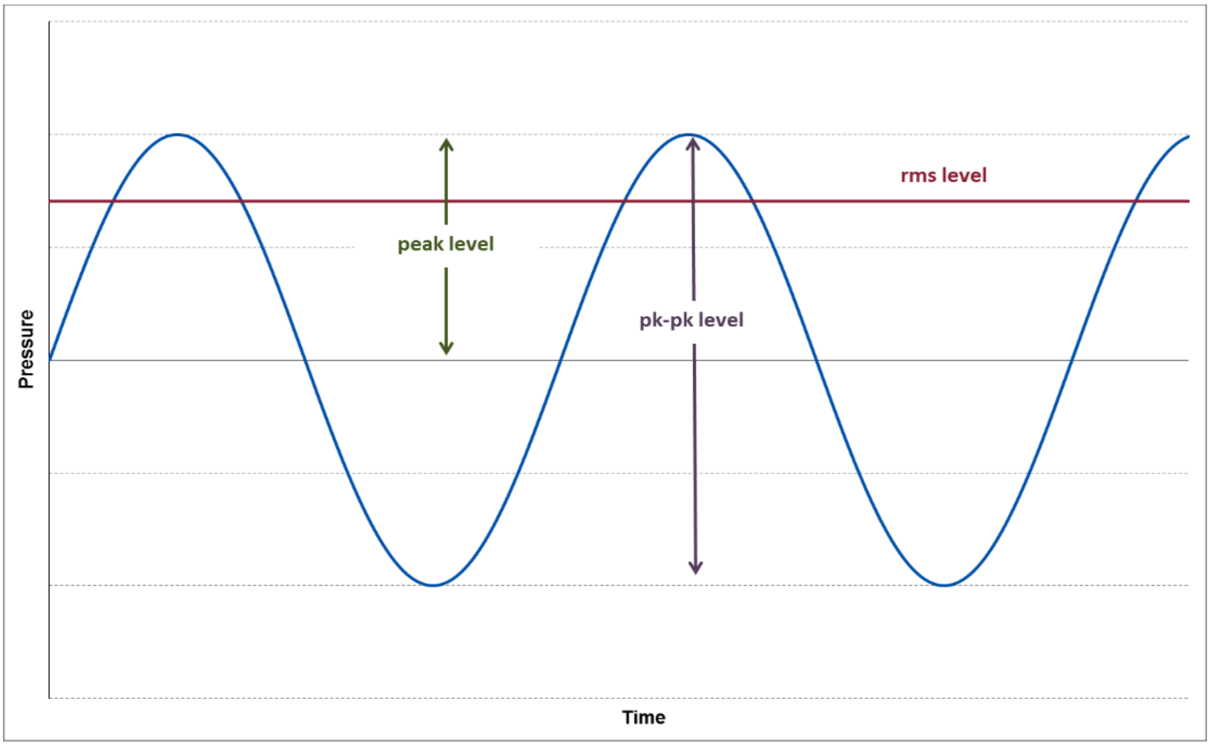

Figure 3.1: Graphical Representation of Acoustic Wave Descriptors

3.1.3 The SPL_{rms} is defined as:

$$SPL_{rms} = 10log_{10}\left(\frac{1}{T}\int_{0}^{T}\left(\frac{p^2}{p_{ref}^2}\right)dt\right)$$

3.1.4 The magnitude of the rms sound pressure level for an impulsive sound (such as that from a seismic source array) will depend upon the integration time, T, used for the calculation (Madsen, 2005). It has become customary to utilise the T90 time period for calculating and reporting rms sound pressure levels[1]. This is the interval over which the cumulative energy curve rises from 5% to 95% of the total energy and therefore contains 90% of the sound energy.

3.1.5 Another useful measure of sound used in underwater acoustics is the Sound Exposure Level (SEL). This descriptor is used as a measure of the total sound energy of an event or a sequence of events (e.g. over the course of a day) and is normalised to one second. This allows the total acoustic energy contained in events lasting a different amount of time to be compared on a like for like basis[2]. The SEL is defined as:

$$SEL = 10log_{10}\left(\int_{0}^{T}\left(\frac{p^2(t)}{p_{ref}^2 t_{ref}}\right)dt\right)$$

3.1.6 The frequency, or pitch, of the sound is the rate at which the acoustic oscillations occur in the medium (air/water) and is measured in cycles per second, or Hertz (Hz). When sound is measured in a way which approximates to how a human would perceive it using an A-weighting filter on a sound level metre, the resulting level is described in values of dBA. However, the hearing capability of marine species is not the same as humans, with marine mammals hearing over a wider range of frequencies and with different sensitivities. It is therefore important to understand how an animal's hearing varies over its entire frequency range to assess the effects of anthropogenic sound on marine mammals. Consequently, use can be made of marine mammal frequency weighting scales to determine the level of the sound in comparison with the auditory response of the animal concerned. A comparison between the typical hearing response curves for fish, humans and marine mammals is shown in Figure 3.2[3].

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[1] The integration time and T90 window are often not reported, particularly in some older studies, meaning that it is often difficult to compare reported rms sound pressure levels between studies.

[2] Historically, rms and peak SPL metrics were used for assessing potential effects of sound on marine life. However, SEL is increasingly being used as it allows exposure duration and the effect of exposure to multiple events to be considered.

[3] It is worth noting that hearing thresholds are sometimes shown as audiograms with sound level on the y axis rather than sensitivity, resulting in the graph shape being the inverse of the graph shown.

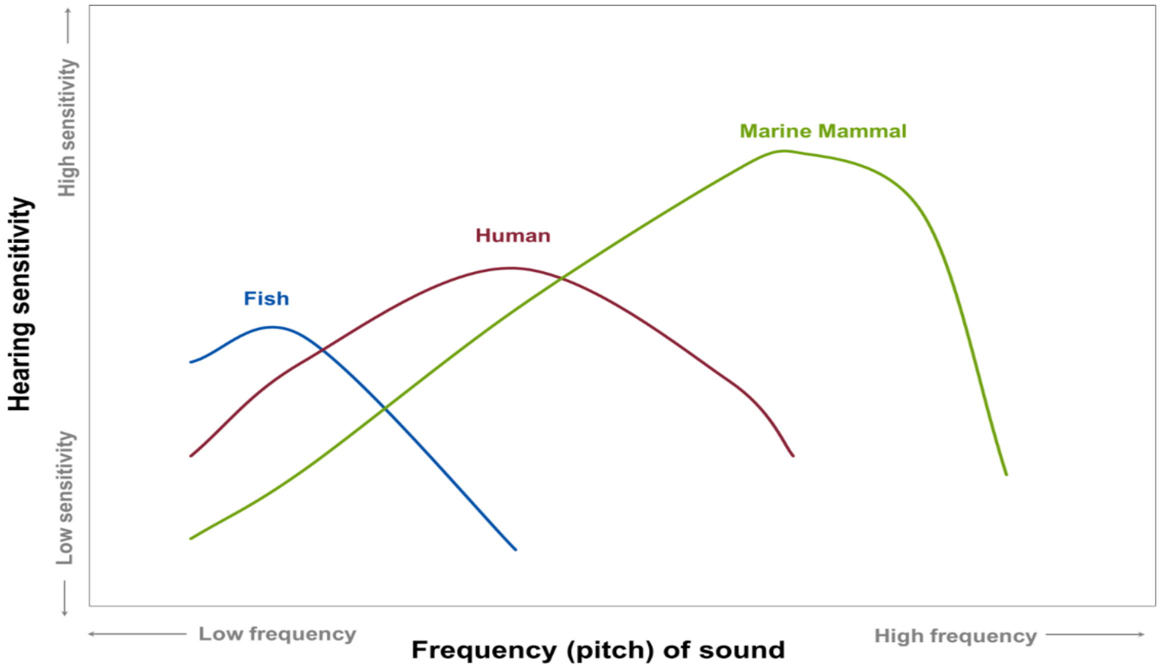

Figure 3.2: Generic Comparison Between Hearing Thresholds of Different Animals

3.1.7 Third Octave Bands (TOB) - The broadband acoustic power (i.e. containing all the possible frequencies) emitted by a sound source, measured/modelled at a location within the Array Area is generally split into and reported in a series of frequency bands. In marine acoustics, the spectrum is generally reported in standard one-third octave band frequencies, where an octave represents a doubling in sound frequency[4].

3.1.8 Source Level (SL) - The source level is the sound pressure level of an equivalent and infinitesimally small version of the source (known as point source) at a hypothetical distance of 1 m from it. The source level is commonly used in combination with the Transmission Loss (TL) associated with the environment to obtain the Received Level (RL) at distances from (in the far field of) the source. The far field distance is chosen so that the behaviour of a distributed source[5] can be approximated to that of a point source. Source levels do not indicate the real sound pressure level at 1 m, for example, for distributed sound sources actual sound levels close to the source would often be lower than a representative source level.

3.1.9 The TL at a frequency of interest is defined as the loss of acoustic energy as the signal propagates from a hypothetical (point) source location to the chosen receiver location. The TL is dependent on water depth, source depth, receiver

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[4] There are two definitions for third octave bands, one using a base 2 and the other using base 10, also known as a decidecade. The frequency ratio corresponding to a decidecade is smaller than a one-third octave (base 2) by approximately 0.08% (ISO, 2017).

[5] A distributed source in this context refers to either a combination of two or more smaller sources, or a large source which cannot be treated as a point or monopole source.

depth, frequency, geology, and environmental conditions. The TL values are generally evaluated using an acoustic propagation model (various numerical methods exist) accounting for the above dependencies.

3.1.10 The RL is the sound level of the acoustic signal recorded (or modelled) at a given location, that corresponds to the acoustic pressure/energy generated by a known active sound source. This considers the acoustic output of a source and is modified by propagation effects. This RL value is strongly dependant on the source, environmental properties, geological properties and measurement location/depth. The RL is reported in dB either in rms or peak SPL, and SEL metrics, within the relevant one-third octave band frequencies. The RL is related to the SL as:

$$RL = SL - TL$$

where TL is the transmission loss of the acoustic energy within the region.

3.1.11 The directional dependence of the source signature and the variation of TL with azimuthal direction α (which is strongly dependent on bathymetry) are generally combined and interpolated to report a 2-D plot of the RL around the chosen source point up to a chosen distance.

4 Acoustic Assessment Criteria

4.1 Introduction

4.1.1 Subsea noise has the potential to affect marine life in different ways depending on its sound level and characteristics. Richardson *et al.* (1995) defined four zones of sound influence which vary with distance from the source and level. These are:

- The zone of audibility: this is the area within which the animal can detect the sound. Audibility itself does not implicitly mean that the sound will affect the marine mammal.
- The zone of masking: this is defined as the area within which sound can interfere with the detection of other sounds such as communication or echolocation clicks. This zone is very hard to estimate due to a paucity of data relating to how marine mammals detect sound in relation to masking levels[6] (for example, humans can hear tones well below the numeric value of the overall sound level).
- The zone of responsiveness: this is defined as the area within which the animal responds either behaviourally or physiologically. The zone of responsiveness is usually smaller than the zone of audibility because, as stated previously, audibility does not necessarily evoke a reaction.
- The zone of injury/hearing loss: this is the area where the sound level is high enough to cause tissue damage in the ear. This can be classified as either temporary or permanent reduction in hearing ability. At even closer ranges, and for very high-intensity sound sources (e.g. underwater explosions), physical trauma or even death are possible.

4.1.2 For this study, it is the zones of injury and disturbance (i.e. responsiveness) that are of interest (there is insufficient scientific evidence to properly evaluate masking). To determine the potential spatial range of injury and disturbance, a review has been undertaken of available evidence, including international guidance and scientific literature. The following sections summarise the relevant thresholds for onset of effects and describe the evidence base used to derive them.

4.2 Injury (Physiological Damage) to Mammals

4.2.1 Sound propagation models can be constructed to allow the received sound level at different distances from the source to be calculated. To determine the potential consequence of these received levels on any marine mammal which might experience such sound emissions, it is necessary to relate the levels to known or estimated potential impact thresholds. The auditory injury threshold criteria proposed by Southall *et al.* (2019) are based on a combination of unweighted SPL_{peak} levels and mammal hearing weighted SEL. The hearing

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[6] The understanding of how masking occurs and what the implications may be for individual species and populations is an area of active research efforts.

weighting function is designed to represent the frequency characteristics (bandwidth and sound level) for each group within which acoustic signals can be perceived and therefore assumed have auditory effects. The categories as detailed in Southall *et al.* (2019) include:

- **Low Frequency (LF) cetaceans**: marine mammal species such as baleen whales (e.g. minke whale *Balaenoptera acutorostrata*);
- **High Frequency (HF) cetaceans**: marine mammal species such as dolphins, toothed whales, beaked whales and bottlenose whales (e.g. bottlenose dolphin *Tursiops truncates* and white-beaked dolphin *Lagenorhynchus albirostris*);
- **Very High Frequency (VHF) cetaceans**: marine mammal species such as true porpoises, river dolphins and pygmy/dwarf sperm whales and some oceanic dolphins, generally with auditory centre frequencies above 100 kHz) (e.g. harbour porpoise *Phocoena phocoena*);
- **Phocid Carnivores in Water (PCW)**: true seals (e.g. harbour seal *Phoca vitulina* and grey seal *Halichoreus grypus*); hearing in air is considered separately in the group Phocid Carnivores in Air (PCA); and
- **Other Marine Carnivores in Water (OCW)**: including otariid pinnipeds (e.g. sea lions and fur seals), sea otters and polar bears; air hearing considered separately in the group Other Marine Carnivores in Air (OCA).

4.2.2 These weighting functions from both Southall *et al.* (2019) and National Marine Fisheries Service (NMFS) (2024) have therefore been used in this study and are shown in Figure 4.1.

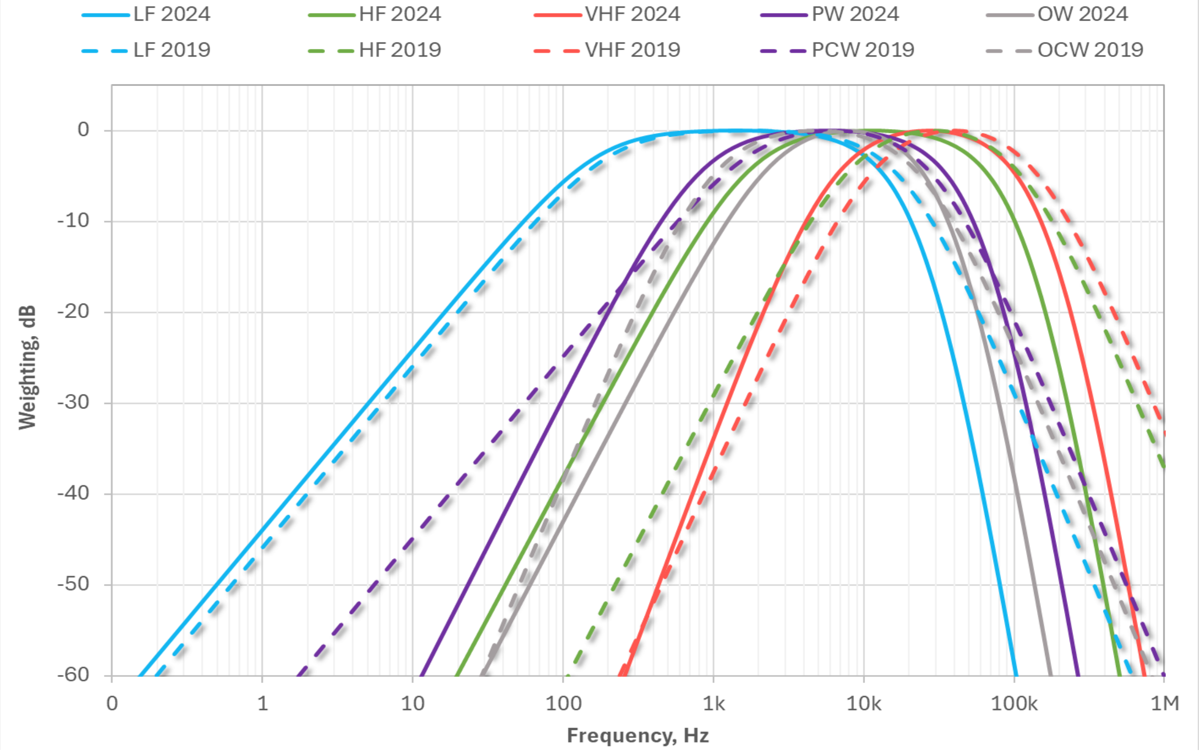

Figure 4.1: Hearing Weighting Functions for Pinnipeds and Cetaceans (Southall *et al.*, 2019, and NMFS, 2024)

4.2.3 Auditory injury criteria proposed in Southall *et al.* (2019) and NMFS (2024) are for two different types of sound as follows:

- **Impulsive sounds** which are typically transient, brief (less than one second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay (ANSI, 1986 and 2005; NIOSH, 1998). This category includes sound sources such as seismic surveys, impact piling and underwater explosions; and
- **Non-impulsive sounds** which can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent and typically do not have a high peak sound pressure with rapid rise/decay time that impulsive sounds do (ANSI, 1995; NIOSH, 1998). This category includes sound sources such as continuous running machinery, sonar-like sources for imaging, and vessels.

4.2.4 The criteria for impulsive and non-impulsive sound have been adopted for this study given the nature of the variety of sound source used during the various activities. The relevant criteria proposed by Southall *et al.* (2019) are as summarised in Table 4.1, and for NMFS (2024) in Table 4.2. While the previous iteration of the NMFS criteria (NMFS, 2018) were aligned with those presented in Southall *et al.* (2019), the NMFS (2024) criteria differ both in the weighting functions as shown in Figure 4.1, and in the thresholds themselves, therefore it is important to consider both aspects of the criteria when determining which results in a worst case impact, rather than simply using the worst case threshold shown in the tables.

4.2.5 Impacts are determined in terms of auditory injury (Permanent Threshold Shift (PTS) in Southall *et al.* (2019) and Auditory Injury (AUD INJ) in NMFS (2024)) and Temporary Threshold Shift (TTS); PTS is defined as permanent, irreversible increase in the threshold of audibility at a specified frequency or portion of an individual's hearing range above a previously established reference level, whereas TTS is defined as a temporary, reversible change.

4.2.6 Both documents recommend the use of the dual metric approach to impact assessment. This involves calculating both the SEL_{cum} and SPL_{peak} injury ranges and taking the larger range forward to determine the impact. This is considered in Volume 2, Chapter 10: Marine Mammals.

Table 4.1: Summary of TTS and PTS Onset Acoustic Thresholds (Southall *et al.*, 2019)

Hearing Group	Parameter	Impulsive		Non-Impulsive	
		TTS	PTS	TTS	PTS
LF cetaceans	Peak SPL, unweighted	213	219	-	-
	SEL, LF weighted	168	183	179	199
HF cetaceans	Peak SPL, unweighted	224	230	-	-
	SEL, HF weighted	170	185	178	198
VHF cetaceans	Peak SPL, unweighted	196	202	-	-
	SEL, VHF weighted	140	155	153	173
PCW	Peak SPL, unweighted	212	218	-	-

Hearing Group	Parameter	Impulsive		Non-Impulsive	
		TTS	PTS	TTS	PTS
	SEL, PCW weighted	170	185	181	201
OCW	Peak SPL, unweighted	226	232	-	-
	SEL, OCW weighted	188	203	199	219

Table 4.2: Summary of TTS and Injury Onset Acoustic Thresholds (NMFS, 2024)

Hearing Group	Parameter	Impulsive		Non-Impulsive	
		TTS	AUD INJ	TTS	AUD INJ
LF cetaceans	Peak SPL, unweighted	216	222	-	-
	SEL, LF weighted	168	183	177	197
HF cetaceans	Peak SPL, unweighted	224	230	-	-
	SEL, HF weighted	178	193	181	201
VHF cetaceans	Peak SPL, unweighted	196	202	-	-
	SEL, VHF weighted	144	159	160	181
PCW	Peak SPL, unweighted	217	223	-	-
	SEL, PCW weighted	168	183	175	195
OCW	Peak SPL, unweighted	224	230	-	-
	SEL, OCW weighted	170	185	179	199

4.3 Disturbance to Marine Mammals

4.3.1 Beyond the area in which auditory injury may occur, the effect on marine mammal behaviour is an important measure of potential impact. Non-trivial disturbance may occur when there is a risk of animals incurring sustained or chronic disruption of behaviour or when animals are displaced from an area, with subsequent redistribution being significantly different from that occurring due to natural variation.

4.3.2 To consider the possibility of disturbance resulting from the Proposed Development, it is necessary to consider:

- whether or not a sound can be detected/heard by a receptor above background sound levels or level of acclimatisation above background levels;
- the likelihood that the sound could cause non-trivial disturbance;
- the likelihood that the sensitive receptors will be exposed to that sound; and
- whether the number of animals exposed are likely to be significant at the population level.

4.3.3 Assessing this is however a very difficult task due to the complex and variable nature of sound propagation, the variability of documented animal responses to similar levels of sound, and the availability of population estimates and regional density estimates for all marine mammal species. Behavioural responses are widely recognised as being highly variable and context specific (Southall *et al.*, 2007; 2019; 2021). Assessing the severity of such potential impacts and development of probability-based response functions continues to be an area of ongoing scientific research interest (Graham *et al.*, 2019; Harris *et al.*, 2018; Southall *et al.*, 2021).

4.3.4 Southall *et al.* (2007) recommended that at the time the only feasible way to assess whether a specific sound could cause disturbance is to compare the circumstances of the situation with empirical studies. Joint Nature Conservation Committee (JNCC) guidance in the UK (JNCC, 2010) indicates that a score of five or more on the Southall *et al.* (2007) behavioural response severity scale could be significant. The more severe the response on the scale, the lower the amount of time that the animals will tolerate it before there could be adverse consequences to life functions, which would constitute a disturbance. The severity scale was revised in Southall *et al.* (2021), which included splitting severity assessment methods on captive studies from assessments on field studies. Behavioural responses related to field studies included impacts to survival, reproduction and foraging.

4.3.5 Southall *et al.* (2007) and (2021) both present a summary of observed behavioural responses for various mammal groups exposed to different types of sound: continuous (non-impulsive) or impulsive (single or multiple pulsed).

4.3.6 Disturbance to marine mammals is discussed in more detail in Volume 2, Chapter 10: Marine Mammals.

Continuous (Non-Impulsive) Sound

4.3.7 For non-pulsed sound (e.g. installation of pile foundations using drilling, vessels etc.), the lowest SPL at which a score of five or more on the Southall *et al.* (2007) behavioural response severity scale occurs for LF cetaceans is 90 dB to 100 dB re 1 µPa (rms). However, this relates to a study involving only migrating grey whale *Eschrichtius robustus*. A study for minke whale showed a response score of three at a RL of 100 dB to 110 dB re 1 µPa (rms), with no higher severity score encountered for this species. For mid-frequency cetaceans (MF, analogous to high-frequency cetaceans in the latest guidance (Southall *et al.,* 2019 and NMFS, 2024)), a response score of eight was encountered at a RL of 90 dB to 100 dB re 1 µPa (rms), but this was for one mammal (a sperm whale *Physeter macrocephalus*) and might not be applicable for the species likely to be encountered in the vicinity of the Proposed Development. For white-beaked dolphin, a response score of three was encountered for received levels of 110 to 120 dB re 1 µPa (rms), with no higher severity score encountered. For HF cetaceans such as bottlenose dolphins, a number of individual responses with a response score of six are noted ranging from 80 dB re 1 µPa (rms) and upwards. There is a significant increase in the number of mammals responding at a response score of six once the received sound pressure level is greater than 140 dB re 1 µPa (rms).

4.3.8 It is worth noting that the above sound pressure levels are based on the rms sound pressure level metric, which was historically often reported in such studies. More recent studies often use other metrics such as the SEL and care must be taken not to directly compare sound levels quoted using different parameters. See Section 3 for a discussion of these different metrics.

4.3.9 The NMFS (2005) guidance sets the marine mammal Level B harassment threshold (analogous to disturbance) for continuous sound at 120 dB re 1 µPa (rms). This threshold is based on studies by Malme *et al.* (1984) which investigate the effects of sound from the offshore petroleum industry on migrating grey whale behaviour offshore Alaska. This value sits approximately mid-way between the range of values identified in Southall *et al.* (2007) for continuous sound but is lower than the value at which the majority of marine mammals responded at a response score of six (i.e. once the received rms sound pressure level is greater than 140 dB re 1 µPa). Considering the paucity and high-level variation of data relating to onset of behavioural effects due to continuous sound, any ranges predicted using this number are likely to be probabilistic and potentially over precautionary.

Impulsive Sound

4.3.10 Southall *et al.* (2007) presents a summary of observed behavioural responses due to multiple pulsed sound, although the data is primarily based on responses to seismic exploration activities (rather than for piling). Although these datasets contain much relevant data for LF cetaceans, there is less data for MF or HF cetaceans within the document[7]. LF cetaceans, other than bow-head whale *Balaena mysticetus*, were typically observed to respond significantly at a RL between 140 dB to 160 dB re 1 µPa (rms). Behavioural changes at these levels during multiple pulses may have included visible startle response, extended cessation or modification of vocal behaviour, brief cessation of reproductive behaviour or brief/minor separation of females and dependent offspring. The data available for MF cetaceans indicate that some significant response was observed at a SPL of 120 dB to 130 dB re 1 µPa (rms), although the majority of cetaceans in this category did not display behaviours of this severity until exposed to a level of 170 dB to 180 dB re 1 µPa (rms). Furthermore, other MF cetaceans within the same study were observed to have no behavioural response even when exposed to a level of 170 dB to 180 dB re 1 µPa (rms).

4.3.11 A more recent study is described in Graham *et al.* (2019). Empirical evidence from piling at the Beatrice OWF (Moray Firth, Scotland) was used to derive a dose-response curve for harbour porpoise. The unweighted single pulse SEL contours were plotted in 5 dB increments and applied the dose-response curve to estimate the number of animals that would be disturbed by piling within each stepped contour. The study shows a 100% probability of disturbance at an (unweighted) SEL of 180 dB re 1 µPa^{2}s, 50% at 155 dB re 1 µPa^{2}s and dropping to

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[7] Southall *et al.* (2007) used a slightly different definition of the cetacean groups, however MF and HF cetaceans are analogous to HF and VHF cetaceans in Southall *et al.* (2019) and NMFS (2024).

approximately 0% at an SEL of 120 dB re 1 µPa^{2}s. This approach to understanding the behavioural effects from piling has been applied at other UK OWFs (for example Seagreen Alpha/Bravo Environmental Statement Chapter 10 Marine Mammals (Seagreen Wind Energy, 2018); Hornsea Three Environmental Statement Volume 2 Chapter 4: Marine mammals (Orsted, 2020); and Awel y Môr Environmental Statement Volume 2, Chapter 7: Marine mammals (RWE, 2022)). Similar stepped/probability-based threshold criteria have been used on other studies such as for assessing the response of marine mammals to geophysical activities (e.g. Forney *et al.*, 2017). The assessment of behavioural response and disturbance is presented in Volume 2, Chapter 10: Marine Mammals.

4.3.12 NMFS (2024) suggests that TTS should be used as a proxy for disturbance due to UXO clearance activities. The TTS threshold is used in this Subsea Noise Technical Report to assess behavioural response where one detonation occurs per day, and the behavioural threshold (-5 dB from TTS onset) is taken for multiple detonations within a 24-hour period.

4.3.13 For impulsive sound sources other than piling and UXO clearance (e.g. some geotechnical and geophysical surveys), this assessment adopts the NMFS (2005) Level B harassment threshold of 160 dB re 1 µPa (rms) for impulsive sound. Level B harassment is defined by NMFS (2005) as having the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioural patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering but which does not have the potential to injure a marine mammal or marine mammal stock in the wild. This is similar to the JNCC (2010) description of non-trivial disturbance and has therefore been used as the basis for onset of behavioural change in the assessment.

4.3.14 For assessing the severity of behavioural response, the distinction between impulsive and non-impulsive sound was removed from Southall *et al.* (2021) as "*some source types, such as airguns, may produce impulsive sounds near the source and non-impulsive sounds at greater ranges*" (see Southall, 2021). Southall *et al.* (2021) instead assigns categories to various sources based on the operational characteristics and applies revised severity assessments to selected studies in each category. For example, Table 7 within that paper details a number of observational studies of marine mammals and their responses to piling, with an indication of severity of response and in some cases a RL. However, Southall *et al.* (2021) does not present thresholds for assessing disturbance; therefore, the thresholds discussed above have been adopted for this study.

4.3.15 It is important to understand that exposure to sound levels in excess of the behavioural change thresholds stated above does not necessarily imply that the sound will result in significant disturbance. As noted previously, it is also necessary to assess the likelihood that the sensitive receptors will be exposed to that sound and whether the numbers exposed are likely to be significant at the population level.

4.3.16 It should be borne in mind that there is a considerable degree of uncertainty and variability in the onset of disturbance and therefore any disturbance ranges should be treated as potentially over precautionary. Another important consideration is that the majority of sound produced by project activities, with the exception of operational Wind Turbine sound, will be either temporary or transitory, as opposed to permanent and fixed. These important considerations are not taken into account in the sound modelling but will be assessed in the relevant marine ecology topic chapters. A summary of disturbance criteria used in the assessment is described in Table 4.3.

Table 4.3: Summary of Disturbance Criteria Used in the Assessment

Effect	Non-impulsive threshold	Impulsive threshold (other than piling and UXO)	UXO Clearance	Impulsive threshold (piling)
Mild disturbance (all marine mammals)	-	140 dB re 1µPa (rms)	-	Addressed in Volume 2, Chapter 10: Marine Mammals
Strong disturbance (all marine mammals)	120 dB re 1µPa (rms)	160 dB re 1µPa (rms)	TTS onset	

4.4 Injury and Disturbance to Fish

4.4.1 For fish, the most relevant criteria for injury effects are considered to be those contained in the Sound Exposure Guidelines for Fishes and Sea Turtles (Popper *et al.*, 2014), with the numerical grouping defined in Popper and Hawkins (2019). These guidelines broadly group fish into the following categories based on their anatomy and the available information on hearing of other fish species with comparable anatomies:

- Group 1: fish with no swim bladder or other gas chamber (e.g. elasmobranchs, flatfishes and lampreys). These species are less susceptible to barotrauma and are only sensitive to particle motion, not sound pressure. Basking shark *Cetorhinus maximus*, which do not have a swim bladder, also fall into this hearing group.

- Group 2: fish with swim bladders but the swim bladder does not play a role in hearing (e.g. salmonids). These species are susceptible to barotrauma, although hearing only involves particle motion, not sound pressure.

- Group 3: fish with swim bladders that are close, but not connected, to the ear (e.g. gadoids and eels). These fishes are sensitive to both particle motion and sound pressure and show a more extended frequency range than Groups 1 and 2, extending to about 500 Hz.

- Group 4: fish that have special structures mechanically linking the swim bladder to the ear (e.g. clupeids such as herring *Clupea* spp., sprat *Sprattus sprattus* and shad *Alosa* genus). These fishes are sensitive primarily to sound pressure, although they also detect particle motion. These species have a wider frequency range, extending to several kHz and generally show higher sensitivity to sound pressure than fishes in Groups 1, 2 and 3.

- Sea turtles: there is limited information on auditory criteria for sea turtles and the effect of impulsive sound is therefore inferred from documented effects to other vertebrates. Bone conducted hearing is the most likely mechanism for auditory reception in sea turtles and, since high frequencies are attenuated by bone, the range of hearing are limited to low frequencies only. For leatherback turtle *Dermochelys coriacea* the hearing range has been recorded as between 50 Hz and 1,200 Hz with maximum sensitivity between 100 and 400 Hz.
- Fish eggs and larvae: separated due to greater vulnerability and reduced mobility. Very few peer reviewed studies report on the response of eggs and larvae to anthropogenic sound.

4.4.2 The guidelines set out criteria for injury effects due to different sources of sound. Those relevant to the Proposed Development are considered to be those for impulsive piling sources only, as non-impulsive sources were not considered to be a key potential impact and therefore were screened out of the guidance. The criteria include a range of indices including SEL, rms and peak SPLs. Where insufficient data exist to determine a quantitative guideline value, the risk is categorised in relative terms as ‘high’, ‘moderate’ or ‘low’ at three distances from the source: ‘near’ (i.e. in the tens of metres), ‘intermediate’ (i.e. in the hundreds of metres) or ‘far’ (i.e. in the thousands of metres). It should be noted that these qualitative criteria cannot differentiate between exposures to different sound levels and therefore all sources of sound, no matter how loud, would theoretically elicit the same assessment result. However, because the qualitative risks are generally qualified as ‘low’, with the exception of a moderate risk at ‘near’ range (i.e. within tens of metres) for some types of hearing groups and impairment effects, this is not considered to be a significant issue with respect to determining the potential effect of sound on fish.

4.4.3 The injury threshold criteria used in this underwater sound assessment for impulsive piling are given in Table 4.4 (both SPL_{peak} and SEL criteria are unweighted). Physiological effects relating to injury criteria are described below (Popper *et al.*, 2014; Popper and Hawkins, 2016):

- **Mortality and potential mortal injury**: either immediate mortality or tissue and/or physiological damage that is sufficiently severe (e.g. a barotrauma) that death occurs sometime later due to decreased fitness. Mortality has a direct effect upon animal populations, especially if it affects individuals close to maturity.
- **Recoverable injury**: tissue and other physical damage or physiological effects, that are recoverable but which may place animals at lower levels of fitness, may render them more open to predation, impaired feeding and growth, or lack of breeding success, until recovery takes place.

- **TTS**: short-term changes in hearing sensitivity may, or may not, reduce fitness and survival. Temporary impairment of hearing may affect the ability of animals to capture prey and avoid predators and also cause deterioration in communication between individuals affecting growth, survival, and reproductive success. After termination of a sound that causes TTS, normal hearing ability returns over a period that is variable, depending on many factors, including the intensity and duration of sound exposure.

Table 4.4: Criteria for Onset of Injury to Fish and Sea Turtles due to Impulsive Piling (Popper *et al.*, 2014)

Type of animal	Parameter	Mortality and potential mortal injury	Recoverable injury	TTS
Group 1 Fish: no swim bladder (particle motion detection)	SEL, dB re 1 µPa^{2}s	>219	>216	>186
	SPL$_{Peak}$, dB re 1 µPa	>213	>213	-
Group 2 Fish: where swim bladder is not involved in hearing (particle motion detection)	SEL, dB re 1 µPa^{2}s	210	203	>186
	SPL$_{Peak}$, dB re 1 µPa	>207	>207	-
Groups 3 and 4 Fish: where swim bladder is involved in hearing (primarily pressure detection)	SEL, dB re 1 µPa^{2}s	207	203	186
	SPL$_{Peak}$, dB re 1 µPa	>207	>207	-
Sea turtles	SEL, dB re 1 µPa^{2}s	210	(Near) High (Intermediate) Low (Far) Low	(Near) High (Intermediate) Low (Far) Low
	SPL$_{Peak}$, dB re 1 µPa	>207		
Eggs and larvae	SEL, dB re 1 µPa^{2}s	>210	(Near) Moderate (Intermediate) Low (Far) Low	(Near) Moderate (Intermediate) Low (Far) Low
	SPL$_{Peak}$, dB re 1 µPa	>207		

4.4.4 The criteria used in this underwater sound assessment for non-impulsive piling and other continuous sound sources, such as vessels, are given in Table 4.5. The only numerical criteria for these sources are for recoverable injury and TTS for Groups 3 and 4 Fish.

Table 4.5: Criteria for Onset of Injury to Fish and Sea Turtles due to Non-Impulsive Sound (Popper *et al.*, 2014)

Type of animal	Mortality and potential mortal injury	Recoverable injury	TTS
Group 1 Fish: no swim bladder (particle motion detection)	(Near) Low (Intermediate) Low (Far) Low	(Near) Low (Intermediate) Low (Far) Low	(Near) Moderate (Intermediate) Low (Far) Low
Group 2 Fish: where swim bladder is not involved in hearing (particle motion detection)	(Near) Low (Intermediate) Low (Far) Low	(Near) Low (Intermediate) Low (Far) Low	(Near) Moderate (Intermediate) Low (Far) Low
Groups 3 and 4 Fish: where swim bladder is involved in hearing (primarily pressure detection)	(Near) Low (Intermediate) Low (Far) Low	170 dB re 1μPa (rms) for 48 hours	158 dB re 1μPa (rms) for 12 hours
Sea turtles	(Near) Low (Intermediate) Low (Far) Low	(Near) Low (Intermediate) Low (Far) Low	(Near) Moderate (Intermediate) Low (Far) Low
Eggs and larvae	(Near) Low (Intermediate) Low (Far) Low	(Near) Low (Intermediate) Low (Far) Low	(Near) Low (Intermediate) Low (Far) Low

4.4.5 The criteria used in this underwater sound assessment for explosives are given in Table 4.6.

Table 4.6: Criteria for Onset of Injury to Fish and Sea Turtles due to Sound From Explosives (Popper *et al.*, 2014)

Type of animal	Parameter	Mortality and potential mortal injury	Recoverable injury	TTS
Group 1 Fish: no swim bladder (particle motion detection)	Peak, dB re 1μPa	229 - 234	(Near) High (Intermediate) Low (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Group 2 Fish: where swim bladder is not involved in hearing (particle motion detection)	Peak, dB re 1μPa	229 - 234	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Group 3 and 4 Fish: where swim bladder is involved in hearing (primarily pressure detection)	Peak, dB re 1μPa	229 - 234	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) High (Far) Low

4.4.6 It should be noted that there are no thresholds in Popper *et al.* (2014) in relation to sound from HF sonar (>10 kHz). This is because the hearing range of fish species falls well below the frequency range of HF sonar systems. Consequently, the effects of sound from HF sonar-like seabed imaging surveys on fish has not been conducted as part of this study, due to the frequency of the source being beyond the range of hearing and due to the lack of any suitable thresholds.

4.4.7 Behavioural reaction of fish to sound has been found to vary between species based on their hearing sensitivity. Typically, fish sense sound via particle motion in the inner ear which is detected from sound-induced motions in the fish's body (see Section 8 for further details on particle motion). The detection of sound pressure is restricted to those fish which have air filled swim bladders; however, particle motion (induced by sound) can be detected by fish without swim bladders[8].

4.4.8 Highly sensitive species such as herring have elaborate specialisations of their auditory apparatus, known as an otic bulla – a gas filled sphere, connected to the swim bladder, which enhances hearing ability. The gas filled swim bladder in species such as cod and salmon may be involved in their hearing capabilities, so although there is no direct link to the inner ear, these species are able to detect lower sound frequencies and as such are considered to be of medium sensitivity to sound. Flat fish and elasmobranchs have no swim bladders and as such are considered to be relatively less sensitive to sound pressure.

4.4.9 The most recent criteria for disturbance are considered to be those contained in Popper *et al.* (2014) which set out qualitative criteria for disturbance due to different sources of sound. The risk of behavioural effects is categorised in relative terms as 'high', 'moderate' or 'low' at three distances from the source: 'near' (i.e. in the tens of metres), 'intermediate' (i.e. in the hundreds of metres) or 'far' (i.e. in the thousands of metres), as shown in Table 4.7.

Table 4.7: Criteria for Onset of Behavioural Effects in Fish and Sea Turtles for Impulsive and Non-Impulsive Sound (Popper *et al.*, 2014)

Type of animal	**Relative risk of behavioural effects**		
	Impulsive piling	**Explosives**	**Non-impulsive sound**
Group 1 Fish: no swim bladder (particle motion detection)	(Near) High (Intermediate) Moderate (Far) Low	(Near) High (Intermediate) Moderate (Far) Low	(Near) Moderate (Intermediate) Moderate (Far) Low
Group 2 Fish: where swim bladder is not involved in hearing (particle motion detection)	(Near) High (Intermediate) Moderate (Far) Low	(Near) High (Intermediate) High (Far) Low	(Near) Moderate (Intermediate) Moderate (Far) Low

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[8] It should be noted that the presence of a swim bladder does not necessarily mean that the fish can detect pressure. Some fish have swim bladders that are not involved in the hearing mechanism and can only detect particle motion.

Type of animal	Relative risk of behavioural effects		
	Impulsive piling	**Explosives**	**Non-impulsive sound**
Groups 3 and 4 Fish: where swim bladder is involved in hearing (primarily pressure detection)	(Near) High (Intermediate) High (Far) Moderate	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Sea turtles	(Near) High (Intermediate) Moderate (Far) Low	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Eggs and larvae	(Near) Moderate (Intermediate) Low (Far) Low	(Near) High (Intermediate) Low (Far) Low	(Near) Moderate (Intermediate) Moderate (Far) Low

4.4.10 It is important to note that the Popper *et al.* (2014) criteria for disturbance due to sound are qualitative rather than quantitative. Consequently, a source of sound of a particular type (e.g. piling) would be predicted to result in the same potential impact, no matter the level of sound produced or the propagation characteristics.

4.4.11 Therefore, the criteria presented in the Washington State Department of Transport Biological Assessment Preparation for Transport Projects Advanced Training Manual (WSDOT, 2011) are used in this assessment for predicting the distances at which behavioural effects may occur due to sound from impulsive piling. The manual suggests an unweighted sound pressure level of 150 dB re 1 µPa (rms) as the criterion for onset of behavioural effects, based on work by Hastings (2002). Sound pressure levels in excess of 150 dB re 1 µPa (rms) are expected to cause temporary behavioural changes, such as elicitation of a startle response, disruption of feeding, or avoidance of an area. The document notes that levels exceeding this threshold are not expected to cause direct permanent injury but may indirectly affect the individual fish (such as by impairing predator detection). It is important to note that this threshold is for onset of potential effects, and not necessarily an ‘adverse effect’ threshold.

4.5 Use of Impulsive Sound Thresholds at Large Ranges

4.5.1 For any sound of a given amplitude and frequency content, impulsive sound has a greater potential to cause auditory injury than a similar magnitude non-impulsive sound (Southall *et al.*, 2007; 2019; 2021; NMFS, 2018; von Benda-Beckmann *et al.*, 2022). For highly impulsive sounds such as those generated by impact piling, UXO detonations and seismic source arrays, the interaction with the seafloor and the water column is complex. In these cases, due to a combination of dispersion (i.e. where the waveform elongates), multiple reflections from the sea surface and seafloor and molecular absorption of HF energy, the sound is unlikely to still be impulsive in character once it has propagated some distance (Hastie *et al.*, 2019; Martin *et al.*, 2020; Southall *et* *al.*, 2019; Southall, 2021). This transition in the acoustic characteristics therefore has implications with respect to which threshold values should be used (impulsive vs. non-impulsive criteria) and, consequently, the distances at which potential injury effects may occur.

4.5.2 This acoustic wave elongation effect is particularly pronounced at larger ranges of several kilometres and, in particular, it is considered highly unlikely that predicted PTS or TTS ranges for impulsive sound which are found to be in the tens of kilometres are realistic (Southall, 2021). However, the precise range at which the transition from impulsive to non-impulsive sound occurs is difficult to define precisely, not least because the transition also depends on the response of the marine mammals' ear. Consequently, there is currently no consensus as to the range at which this transition occurs or indeed the measure of impulsivity which can be used to determine which threshold should be applied (Southall, 2021) although evidence for impact pile driving and seismic source arrays does indicate that some measures of impulsivity change markedly within 10 km of the source (Hastie *et al.*, 2019). Additionally, the draft NMFS (2018) guidance suggested 3 km as a transition range, but this was removed from the final document.

4.5.3 This is an area of ongoing research and there are a number of potential methods for determining the cross-over point being investigated, such as the kurtosis metric, and the loss of HF energy from the spectrum (above 10 kHz, e.g. Southall, 2021). In the meantime, it is considered that any predicted injury ranges in the tens of kilometres are almost certainly an overly precautionary interpretation of existing criteria (Southall, 2021).

4.5.4 Because disturbance ranges are likely to extend beyond the range at which auditory injury could occur, this transition from impulsive to continuous sound is likely to be even more important (e.g. Southall *et al.*, 2021). For example, where dose-response relationships have been derived based on exposure to impulsive sounds, particularly where these have been derived based on experiments relatively close to the impulsive source, then extrapolation of the dose-response relationship to larger ranges could be misleading. This is particularly true where the dose-response relationship has been derived using parameters such as unweighted single pulse SEL or $\mathrm{rms}_{(T90)}$ SPL, which does not take into account the characteristics (e.g. frequency content of impulsivity) of the sound. Consequently, great caution should be used when interpreting potential disturbance ranges in the order of tens of kilometres, which should be considered alongside an understanding of potential background sound levels in order to understand the distances at which sounds related to an impulsive source may be detected.

5 Source Sound Levels

5.1 General

5.1.1 Underwater sound source level is usually quantified using a dB scale with values generally referenced to 1 μPa pressure amplitude as if measured at a distance of 1 m from a hypothetical, infinitesimally small point source (sometimes referred to as the Source Level, SL). This quantity is often referred to as an equivalent monopole source level. In practice, it is not usually possible to measure sound at 1 m from a large structure, which, in reality, is more akin to a distributed sound source, but the source level metric allows comparisons and reporting of different source sound emissions on a like for like basis, as well as a standard input parameter for sound propagation models. In reality, for a large sound source such as a monopile, seismic source array or vessel, the source level value at this conceptual point at 1 m from the (theoretical, infinitesimally small) acoustic centre does not exist. Furthermore, the energy is distributed across the source and does not all emanate from this imagined acoustic centre point. Therefore, the stated SPL at 1 m does not occur at any point in space for these large sources. In the acoustic near field (i.e. close to the source), the sound pressure level will be significantly lower than the value predicted by the source level.

5.1.2 A wealth of experimental data and literature-based information is available for quantifying the sound emission from different construction operations. This information, which allows us to predict with a good degree of accuracy the sound generated by a source at discrete frequencies in one-third octave bands, will be employed to characterise their acoustic emission in the underwater environment. Sections 5.3 to 5.6 detail the types of sound sources present during different activities, their potential signatures in different frequency bands, and acoustic levels.

5.2 Types of sound sources

5.2.1 The sound sources and activities investigated in this report are summarised in Table 5.1.

Table 5.1: Summary of the Sound Generating Activities Considered in the Assessment

Phase	Source/activity
Pre-Construction	Geophysical site investigation activities including: • Multibeam Echosounder (MBES); • Sidescan Sonar (SSS); • Single Beam Echosounder (SBES); • Sub-Bottom Profilers (SBP) (chirper and pinger); and • Ultra-High Resolution Seismic (UHRS) (sparker). Geotechnical site investigation activities including: • Drilling of boreholes; and • Vibro-cores. Use of geophysical/geotechnical survey vessels. Clearance of UXOs including potential use of low order and low yield techniques as well as possible high order detonation.

Phase	Source/activity
Construction	Impact driven or drilled piled jacket and monopile foundations for fixed Wind Turbines and OSPs. Vessels used for a range of construction activities including boulder clearance, sandwave clearance, drilling and trenching. Range of construction vessels including: • Main installation and support vessels; • Tug/Anchor handlers; • Cable lay installation and support vessels; • Guard vessels; • Survey vessels (e.g. for geophysical or geotechnical surveys) • Seabed preparation vessels for boulder removal, grapnel, pre-sweep/levelling; • Crew transfer vessels (CTVs); • Scour protection installation vessels; and • Cable protection installation vessels.
O&M	Operational sound from Wind Turbines. Operational and maintenance vessels, including: • CTVs/workboats; • Jack up vessels; • Cable repair vessels; and • Excavators or backhoe dredger.
Decommissioning	Vessels for a range of decommissioning activities, assumed as per vessel activity described for construction phase.

5.2.2 The above sources for each project phase are considered in more detail in the following sections.

5.3 Pre-construction phase

Geophysical surveys

5.3.1 Several sonar-like survey source types will potentially be used for the pre-construction site investigation geophysical surveys. During the survey a transmitter emits an acoustic signal directly toward the seabed (or alongside, at an angle to the seabed, in the case of side scan techniques). The equipment likely to be used can typically work at a range of signal frequencies, depending on the distance to the bottom and the required resolution. The signal is highly directional and acts as a beam, with the energy narrowly concentrated within a few degrees of the direction in which it is aimed. The signal is emitted in pulses, the length of which can be varied as per the survey requirements. The assumed pulse rate, pulse width and beam width used in the assessment are based on a review of typical units used in other similar surveys. It should be noted that sonar-like survey sources are classed as non-impulsive sound because they generally comprise a single (or multiple discrete) frequency (e.g. a sine wave or swept sine wave) as opposed to a broadband signal with high kurtosis, high peak pressures and rapid rise times.

5.3.2 The characteristics assumed for each device modelled in this assessment are summarised in Table 5.2. For the purpose of potential impacts, these sources are considered to be continuous (non-impulsive).

Table 5.2: Typical Sonar-Like Survey Equipment Parameters Used in Assessment

Survey Type	Frequency	Source level, dB re 1 µPa re 1 m (rms)	Pulse Rate (s^{-1})	Pulse Width (ms)	Beam Width
MBES	400 kHz	225	60	0.5	0.9° x 1.9°
SSS	230 kHz (LF) 550 kHz (HF)	210	15	15	0.54° (LF) 0.36° (HF)
Parametric SBP	100 kHz (primary) 4, 5, 6, 8, 10, 12 kHz selectable secondary frequencies	248	50	0.07 – 1.5	2.0°

5.3.3 The assumed pulse rate has been used to calculate the SEL, which is normalised to one second, from the SPL_{rms}. Directivity corrections were calculated based on the transducer dimensions and ping frequency and taken from manufacturer's datasheets. It is important to note that directivity will vary significantly with frequency, but that these directivity values have been used in line with the modelling assumptions stated above.

5.3.4 Directivity corrections have been applied to the source sound level data based on directivity characteristics for the proposed sources. Directivity factors were derived based on source take-off angle for an animal on the sea floor. This results in a larger correction (reduction in level) due to directivity at distances further from the source than for receivers close to the source.

5.3.5 At distances closer to the source (i.e. less than the water depth), no directivity correction is made because the animal could be directly underneath the source. As the source to receiver range increases, the take-off angle between the source and animal becomes larger. Hence, when the range to source is large in comparison to the water depth, the effects of the source's directivity will have a much greater bearing on the received sound level. Once the range to source becomes larger than the water column depth then the source directivity effects will become increasingly important.

5.3.6 Unlike the sonar-like survey sources, the UHRS source is likely to utilise a sparker, which produces an impulsive, broadband source signal. The parameters used in the underwater sound modelling for UHRS are summarised in Table 5.3.

Table 5.3: Typical UHRS Survey Equipment Parameters Used in Assessment

Source	Peak frequency (kHz)	Source level (dB re 1µPa re 1m) (peak)	Source SEL (dB re $1\mu Pa^2 s$ re 1m)	Source level (dB re 1µPa re 1m) (rms)	T90 (ms)
UHRS (sparker)	0.05 to 4	219	182	170 to 200	0.7

Geotechnical Surveys

5.3.7 Measurements of a vibro-core test (Reiser *et al.*, 2011) show underwater source SPL of approximately 187 dB re 1 µPa re 1 m (rms). The SEL has been calculated based on a one-hour sample time which, it is understood, is the typical maximum time required for each sample. The vessel would then move on to the next location and take the next sample with approximately one-hour break between each operation. The vibro-core sound is considered to be continuous (non-impulsive).

5.3.8 During vibro-core sampling, a vibrating tube is driven into the sediment, the vibrations causing the surrounding sediment to liquify and allowing the tube to more easily penetrate.

Table 5.4: Vibro-core Source Levels Used in the Assessment

Parameter	Source level	Unit
SEL (unweighted) – based on one-hour operation for single core sample	223	dB re 1 µPa^{2}s re 1 m
RMS$_{(T90)}$	187	dB re 1 µPa re 1 m
Peak	190	dB re 1 µPa re 1 m

5.3.9 The frequency spectral shape for vibro-coring is presented in Figure 5.1.

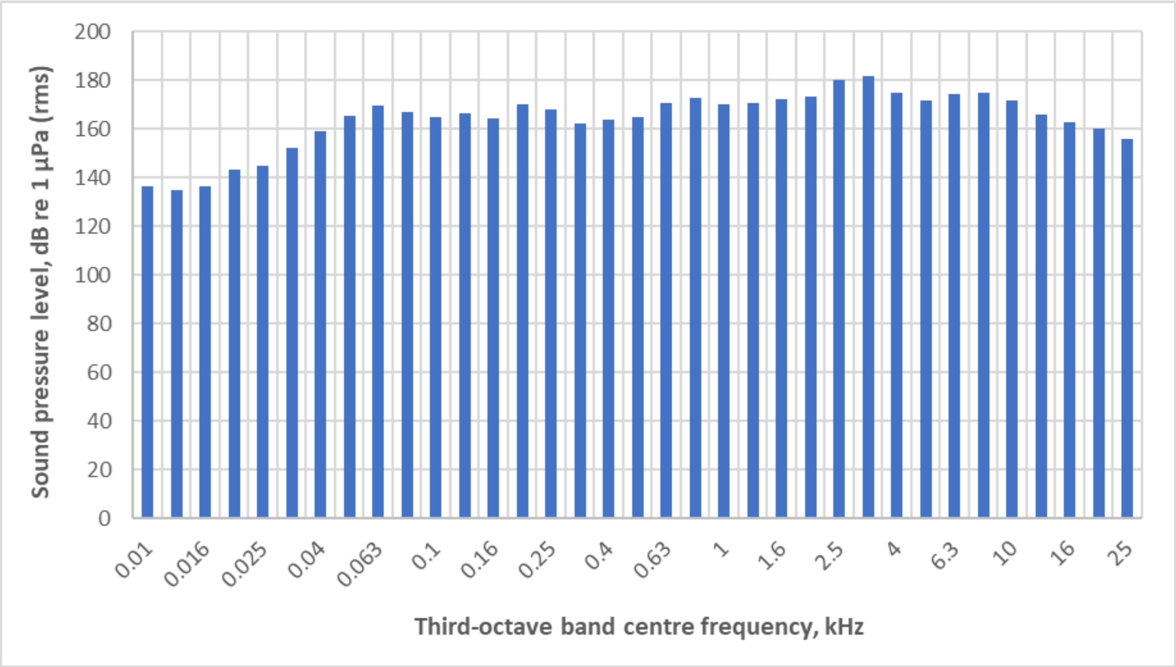

Figure 5.1: Frequency Spectral Shape Used for Vibro-coring

5.3.10 Source levels for borehole drilling ahead of standard penetration testing was reported in Erbe and McPherson (2017), with source levels of 142 dB to 145 dB re 1 µPa re 1 m (rms). A set of one-third octave band levels, calculated from the spectrum presented in the paper are shown in Figure 5.2. In contrast to vibro-core, boreholes are drilled into the seabed to allow samples to be taken of deeper layers of seafloor sediment.

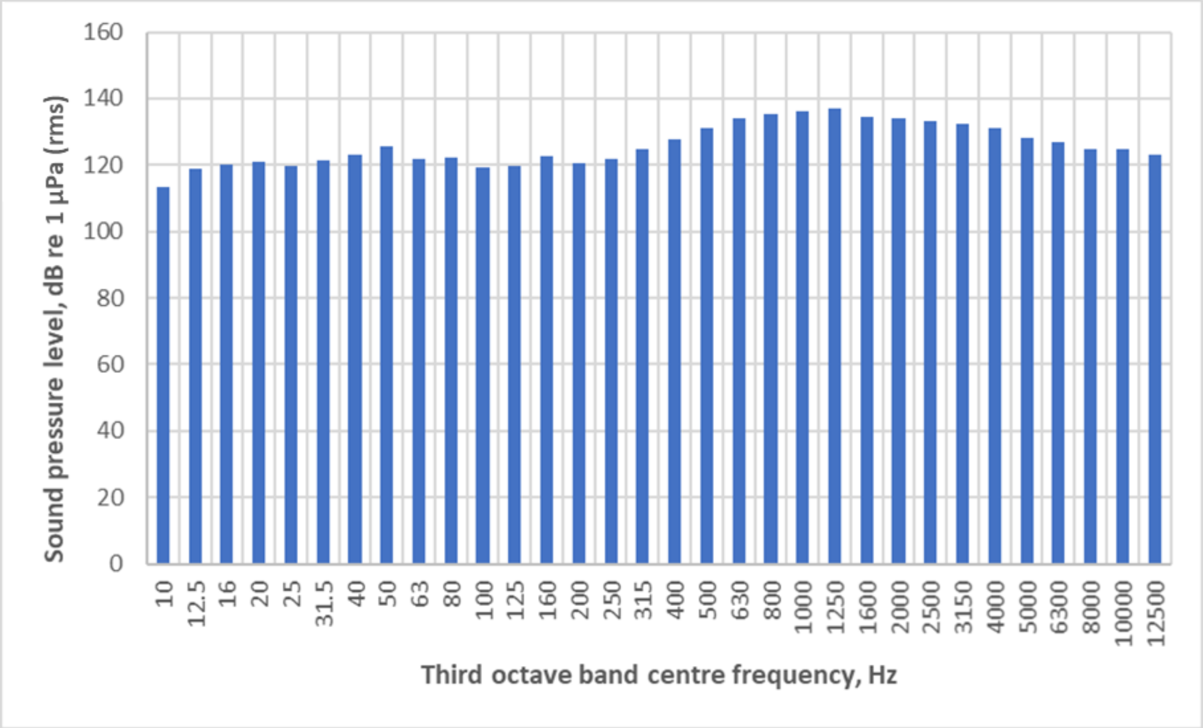

Figure 5.2: Borehole Drilling Source Level Spectrum Shape Used in the Assessment

5.3.11 As for other non-impulsive sources (e.g. vessels), the impact assessment criteria used is the SEL metric for a receptor moving away from the source.

UXO Clearance

5.3.12 The precise details and locations of potential UXOs is unknown at this time. For the purposes of this assessment, it has been assumed that the Maximum Design Scenario (MDS) will be clearance of UXO with a Net Explosive Quantity (NEQ) of 720 kg cleared by either low order techniques by default, or high order techniques if necessary. Low order techniques are not always possible and are dependent upon the individual situations surrounding each UXO.

5.3.13 There are a number of low order and low yield techniques available for the clearance of UXO, with the development of new techniques being a subject of ongoing research. For example, one such technique (deflagration) uses a single charge of 30 g to 80 g NEQ which is placed in close proximity to the UXO to target a specific entry point. When detonated, a shaped charge penetrates the casing of the UXO to introduce a small, clinical plasma jet into the main explosive filling. The intention is to excite the explosive molecules within the main filling to generate enough pressure to burst the UXO casing, producing a deflagration of the main filling and neutralising the UXO.

5.3.14 Controlled experiments showed low order deflagration to result in a substantial reduction in acoustic output over traditional high order methods, with SPL_{peak} and SEL being typically significantly lower for the deflagration of the same size munition, and with the acoustic output being proportional to the size of the shaped charge, rather than the size of the UXO itself (Robinson *et al.*, 2020). Using this low order deflagration method, the probability of a low order outcome is high; however, there is a small inherent risk with these clearance methods that the UXO will detonate or deflagrate violently resulting in higher sound level emissions.

5.3.15 It is possible that there will be residual explosive material remaining on the seabed following the use of low order techniques for UXO disposal. In this case, and only for debris of sufficient size to be a risk to fishing activities, recovery will be performed which includes the potential use of a small (500 g) ‘clearing shot’.

5.3.16 As a last resort, if it is not possible to carry out low order or low yield clearance techniques, it may be necessary to carry out a high order detonation of the UXO.

5.3.17 The underwater sound modelling has been undertaken for a range of charge configurations as set out in Table 5.5.

Table 5.5: Details of UXO and their Relevant Charge Sizes Employed for Modelling

Charge Size (kg NEQ)	Notes/Assumptions
Low Order and Low-Yield Donor Charge Configurations	
0.08 kg	Maximum size of donor charge used for low order technique.
0.5 kg	Maximum size of clearing shot to neutralise any residual explosive material.
Potential UXOs (High Order Disposal)	
227 kg	Realistic worst case UXO charge weight, based on British World War Two (WW2) mine Mk XIV.
720 kg	Maximum estimated UXO size that is anticipated to be encountered, based on a 1,000 kg German WW2 mine BM1000.

5.4 Construction Phase

Impact Piling

5.4.1 The sound generated and radiated by a pile as it is driven into the ground is complex, due to the many components which constitute the generation and radiation mechanisms. Larger pile sizes can require a higher energy in order to drive them into the seabed, and different seabed and underlying substrate types can require use of different installation techniques including varying the hammer energies and the number of hammer strikes. In addition, the seabed characteristics can affect how sound propagates from the pile through the sub-surface geology, thus fundamentally affecting the acoustic field around the activity. The type of hammer method used (i.e. the force-impulse characteristics) can also affect the sound characteristics.

5.4.2 The estimation of source levels for sound propagation modelling of piling is an important aspect of the modelling methodology. Ideally, use can be made of data measurements for similar piles, installed using a similar hammer in similar conditions. However, since noise modelling for proposed OWFs often proposes the use of piles and hammers for which there is no currently available measured data, it is often necessary to utilise an alternative method to estimate the source level inputs to the model. One such method used in some previous modelling assessments is the use of energy conversion factors, which involves estimating the proportion of the hammer energy which is transmitted into the water column as sound. However, the subject of sound generation due to impact piling is an active area of research and the evidence base is constantly being updated by new measurements, research and published papers. It is therefore important to ensure that the methodology used for determining the source levels of piling take into account the most recent research.

5.4.3 The method of scaling of measured data during pile driving for similar operations to the Array Area was used in order to determine source levels. The evidence base is constantly being updated by new measurements, research and published papers. A recent peer reviewed paper (von Pein *et al.*, 2022) presents a methodology for the dependencies of the SEL on strike energy, diameter, ram weight, and water depth that can be used for scaling measured or computed SELs from one project to another. The method has been shown to be usable within practical ranges of accuracy, especially if the measurement uncertainties are taken into account. The paper suggests that scaling should be performed over either a small number of very similar piling situations or over a larger data set with according averaging. This is a recently published method for deriving the source level which provides a more scientifically robust method compared to using an energy conversion factor (the conversion factor method simply assumes that a percentage of the hammer energy is converted into sound irrespective of parameters such as pile size, water depth and hammer specifications). Since the von Pein *et al.* (2022) methodology takes into account several site-specific and pile-specific factors, in addition to hammer energy, and because it is based on a scientifically rigorous and peer reviewed study, it is therefore considered to be a significant improvement on the use of simple conversion factors alone. This methodology is further endorsed by the recent study undertaken by Jasco on behalf of Marine Scotland (now Marine Directorate), which recommends use of scaling methods instead of those relying on conversion factors (Wood *et al.,* 2023).

5.4.4 Using the equation below (von Pein *et al.,* 2022), a broadband source level value is calculated for the sound emitted during impact pile driving operation in each operation window:

$$SEL_1 = SEL_0 + 10log_{10}\left(\frac{E_1}{E_0}\right) + 16.7log_{10}\left(\frac{d_1}{d_0}\right) - 10log_{10}\left(\frac{m_{r,1}}{m_{r,0}}\right) + 750\left[\frac{10log_{10}(|R_0|^2)}{2\,cot(\varphi)}\left(\frac{1}{h_1} - \frac{1}{h_0}\right)\right]$$

5.4.5 In this equation, *E* is the hammer energy employed in Joules, *d* is the pile diameter, m_r is the ram mass in kg, *h* is the water depth in m, $|R_0|$ is the reflection coefficient and φ is the propagation angle (approximately 17° for a Mach wave generated by impact piling). The equation allows measured pile sound data from one site (denoted by subscript 0) to be scaled to another site (denoted by subscript 1).

5.4.6 To account for the pile penetration and use of submerged piling rigs, a correction is applied through the piling sequence based on Lippert *et al.* (2017) by considering the quotient of wetted pile length L_w and water depth h_w using the following equation:

$$\Delta SEL = 8.3log_{10}(L_w/h_w)$$

5.4.7 This methodology therefore takes into account the following factors:

- pile diameter;
- pile length;
- pile penetration;
- water depth;
- rated maximum hammer energy of the proposed hammer;
- hammer energy being used;
- ram mass for the hammer; and
- acoustical parameters of the soil and water.

5.4.8 The peak SPL (SPL_{peak}) can be calculated from SEL values via the empirical fitting between pile driving SEL and peak SPL data, given in Lippert *et al.* (2015), as:

$$SPL_{peak} = 1.43 \times SEL - 44.0.$$

5.4.9 Root mean square (rms) sound pressure levels were calculated assuming a typical T90 pulse duration (i.e. the period that contains 90% of the total cumulative sound energy) of 100 ms. It should be noted that in reality the rms T90 period will increase significantly with distance which means that any ranges based on rms sound pressure levels at ranges of more than a few kilometres are likely to be significant overestimates and should therefore be treated as highly conservative.

5.4.10 The piling scenarios for the Array Area include the following phases:

- initiation (including slow start);
- soft start;
- ramp up; and
- full power piling.

5.4.11 These phases and the various associated parameters and durations are shown in Table 5.6 to Table 5.8 below.

5.4.12 The impact piling scenarios that have been modelled for the Array Area are as follows (it is worth noting that these are based on the MDS and the actual expected values of hammer energy and duration will be lower):

- Monopile Wind Turbine foundations using a maximum hammer energy of 6,250 kJ for a duration of up to 8.6 hours, related to the MDS associated with the largest diameter and longest piles (15 m diameter, 123 m length, see Table 5.6).
- Piled jacket foundations for Wind Turbines and OSP using a maximum hammer energy of 4,500 kJ for a duration of up to 16.2 hours, related to the MDS associated with the largest diameter and longest foundations (5 m diameter, 90 m length, see Table 5.7).
- Monopile Wind Turbine foundations using a maximum hammer energy of 6,000 kJ for a duration of up to 4.3 hours, associated with the realistic installation scenario for the largest diameter and piles (15 m diameter, 123 m length, Table 5.8).

Table 5.6: Impact Piling Schedule Used in the Assessment - Monopile Wind Turbine Foundations

Activity/stage	Duration, minutes	Hammer energy, kJ	Strike rate (strikes per minute)	Number of strikes
Initiation	1	200	5	5
Soft start	20	937.5	30	600
Ramp up	30	937.5 to 6,000	40	1,200
Full power piling	465	6,250	50	23,250
Total piling duration, mins	516			
Total piling duration, hours	8.6			
Total no. of strikes	25,055			
Modelled SEL at 750 m, dB	181.0			

Table 5.7: Impact Piling Schedule Used in the Assessment – Jacket Wind Turbine Foundations and OSPs

Activity/stage	Duration, minutes	Hammer energy, kJ	Strike rate (strikes per minute)	Number of strikes
Initiation	1	675	5	5
Soft start	20	675	30	600
Ramp up	30	675 to 4,500	40	1,200
Full power piling	921	4,500	50	46,050
Total piling duration, mins	972			
Total piling duration, hours	16.2			
Total no. of strikes	47,855			
Modelled SEL at 750 m, dB	176.7			

Table 5.8: Impact Piling Schedule Used in the Assessment - Monopile Wind Turbine Foundations, Realistic Installation Scenario

Activity/stage	Duration, minutes	Hammer energy, kJ	Strike rate (strikes per minute)	Number of strikes
Initiation	1	200	5	5
Soft start	20	937.5	30	600
Ramp up	30	937.5 to 6,000	40	1,200
Full power piling	207	6,000	50	10,350
Total piling duration, mins	258			
Total piling duration, hours	4.3			
Total no. of strikes	12,155			
Modelled SEL at 750 m, dB	180.8			

5.4.13 The piling of Wind Turbine foundations described above was also modelled with the inclusion of an Acoustic Deterrent Device (ADD) before commencement of piling. Use of an ADD was modelled for a duration of 15 minutes prior to commencement of piling, all other stages of piling remained the same, and the ADD itself was assumed to not contribute towards any animal injury effects (Boisseau *et al.*, 2021). This effectively allows the animal 15 minutes to move away from the sound source before the start of piling. It should be noted that the use of an ADD decreases the effective cumulative SEL PTS and TTS range because the animal is assumed to be further from the pile before being exposed to piling sound. In the case of SPL_{peak} PTS and TTS thresholds (i.e. potential for instantaneous auditory injury) the potential radius at which the threshold could be exceeded remains the same, although it is possible that the animal will swim outside the injury range before piling commences, effectively reducing the peak SPL injury range to zero.

5.4.14 There is a possibility that during the piling operations it will be necessary for two pile installation vessels to operate concurrently. For the concurrent piling scenarios, two separate MDS assumptions were identified, as follows:

- Separation distance of 1 km (the minimum distance between foundations) as an MDS for injury.
- Separation distance of up to 20 km as an MDS for disturbance.

5.4.15 The reason the MDS separation distances for injury and disturbance differ is that the scenario which results in the greatest potential for injury is when two piling spreads are operating in close proximity, meaning that the animal is exposed to the combined sound generated from both piling activities at relatively high levels and at short distances from the piling. Conversely, the maximum area of disturbance occurs when both piling activities are operating at a further distance apart in the Array Area and their respective disturbance ranges are just overlapping.

Drilled piles

5.4.16 For drilled piling, source sound levels have been based on pile drilling for the Oyster 800 project (Kongsberg, 2011). The source levels used in the assessment are summarised in Table 5.9.

5.4.17 Rotary drilling is non-impulsive in character and therefore the non-impulsive injury and behavioural thresholds have been adopted for the assessment.

Table 5.9: Drilled Pile Sound Source Levels Used in Assessment (Unweighted)

Parameter	Source Level at 1 m
SEL per second of operation @ 1 m, dB re 1 μPa^{2}s	163
Peak sound pressure level @ 1 m, dB re 1 μPa	166
RMS$_{(T90)}$ sound pressure level @ 1 m, dB re 1 μPa	163

5.4.18 The other sound sources potentially active during the construction phase are related to cable installation (i.e. trenching and cable laying activities), and their related operations such as the jack up rigs. The source levels used in this assessment are presented in Table 5.10.

Table 5.10: Source Levels of Other Construction Phase Sources

Sources	Data source	RMS (dB re 1 μPa)
Cable laying	Wyatt (2008)	180
Cable trenching/cutting	Nedwell *et al.* (2003)	178
Jack up rig	Nedwell and Edwards (2004)	163

5.5 Operation and Maintenance Phase

Operational Sound from Wind Turbines

5.5.1 Operational sound due to the operational Wind Turbines is assessed qualitatively in Section 7.3.

Routine Maintenance

5.5.2 There are very few activities during the O&M phase that generate significant amounts of underwater sound. These sound generating activities are anticipated at this stage to be characterised by vessel movements.

5.6 Vessels (All Phases)

5.6.1 The sound emissions from the types of vessels that may be used for the Array Area are quantified in Table 5.11, based on a review of publicly available data. Sound from the vessels themselves (e.g. propeller, thrusters and sonar (if used)) primarily dominates the emission level, hence sound from activities such as seabed preparation, trenching and rock placement (if required) have not been included separately.

5.6.2 In Table 5.11, SELs have been estimated for each source based on 24 hours continuous operation, although it is important to note that it is highly unlikely that any marine mammal or fish would stay at a stationary location or within a fixed radius of a vessel (or any other sound source) for 24 hours. Consequently, the acoustic modelling has been undertaken based on an animal swimming away from the source (or the source moving away from an animal).

5.6.3 Source levels for vessels depend on the vessel size and speed as well as propeller design and other factors. There can be considerable variation in magnitude and character between vessels even within the same class. Therefore, source data for the assessment has been based on MDS assumptions (i.e. using data toward the higher end of the scale for the relevant class of ship as a proxy). In the case of the cable laying vessel, no publicly available information was available for a similar vessel and therefore measurements on a suction dredger using Dynamic Positioning (DP) thrusters were used as a proxy. This is considered an appropriate proxy because it is a similar size of vessel using DP and therefore likely to have a similar acoustic footprint.

Table 5.11: Source Sound Level Data for Site Preparation, Construction, Operation and Maintenance and Decommissioning Vessels

Item	**Description/ Assumptions**	**Data Source**	**Source SPL at 1 m**	
			RMS, dB re 1 µPa	SEL (24h), dB re 1 µPa²s
Sandwave clearance	‘Gerardus Mercator’ trailer hopper suction dredger using DP as proxy	Wyatt *et al.* (2020)	180	229
Boulder clearance, offshore construction vessel, excavator, backhoe dredger	Backhoe dredger used as proxy	Nedwell *et al.* (2008)	163	212
Main installation vessels (Barge/DP vessel) cargo vessels	‘Gerardus Mercator’ trailer hopper suction dredger using DP as proxy	Wyatt *et al.* (2020)	180	229
Jack up rig/jack up vessel	Jack up rig	Evans (1996)	163	212
Tug/anchor handlers	Tug used as proxy	Richardson (1995)	172	221
Cable laying, installation vessels	‘Gerardus Mercator’ trailer hopper suction dredger using DP as proxy	Wyatt *et al.* (2020)	180	229
Rock placement vessels	‘Gerardus Mercator’ trailer hopper suction dredger using DP as proxy	Wyatt *et al.* (2020)	180	229

Item	Description/ Assumptions	Data Source	Source SPL at 1 m	
			RMS, dB re 1 µPa	SEL (24h), dB re 1 µPa^{2}s
Guard vessels, workboats	Tug used as proxy	Richardson (1995)	172	221
Survey vessels, geophysical/geotechnical survey vessels	Offshore support vessel used as proxy	McCauley (1998)	179	228
CTVs, Service operation vessels, support vessels, construction support vessels, trenching support vessels, UXO clearance vessel, pre-lay grapnel run (PLGR) vessel, Diving Support Vessels	Offshore support vessel used as proxy	McCauley (1998)	179	228
Scour/cable protection, seabed preparation, installation vessels, rock dumping vessels, cable repair vessels	Offshore support vessel used as proxy	McCauley (1998)	179	228

6 Propagation Modelling

6.1 Propagation of Sound Underwater

6.1.1 As the distance from the sound source increases the level of received or recorded sound reduces, primarily due to the spreading of the sound energy with distance, in combination with attenuation due to absorption of sound energy by molecules in the water. This latter mechanism is more important for higher frequency sound than for lower frequencies.

6.1.2 The way that the sound spreads (geometrical divergence) will depend upon several factors such as water column depth, pressure, temperature gradients, salinity as well as water surface and bottom (i.e. seabed) conditions. Thus, even for a given locality, there are temporal variations to the way that sound will propagate. However, in simple terms, the sound energy may spread out in a spherical pattern (close to the source) or a cylindrical pattern (much further from the source), although other factors mean that decay in sound energy may be somewhere between these two simplistic cases. The distance at which cylindrical spreading dominates is highly dependent on water depth. Sound propagation in shallow water depths will be dominated by cylindrical spreading as opposed to spherical spreading.

6.1.3 In acoustically shallow waters[9] in particular, the propagation mechanism is influenced by multiple interactions with the seabed and the water surface (Lurton, 2002; Etter, 2013; Urick, 1983; Brekhovskikh *et al.,* 2003; Kinsler *et al.*, 1999). Whereas in deeper waters, the sound will propagate further without encountering the surface or seabed.

6.1.4 At the sea surface, the majority of the sound is reflected into the water due to the difference in acoustic impedance (i.e. product of sound speed and density) between air and water. However, the scattering of sound at the surface of the sea can be an important factor in the propagation of sound. In an ideal case (i.e. for a perfectly smooth sea surface), the majority of sound energy will be reflected into the sea. However, for rough seas, much of the sound energy is scattered (e.g. Eckart, 1953; Fortuin, 1970; Marsh *et al*., 1961; Urick and Hoover, 1956). Scattering can also occur due to bubbles near the surface such as those generated by wind, fish or due to suspended solids in the water such as particulates and marine life. Scattering is more pronounced for higher frequencies than for low frequencies and is dependent on the sea state (i.e. wave height). However, the various factors affecting this mechanism are complex.

6.1.5 Because surface scattering results in differences in reflected sound, its effect will be more important at longer ranges from the sound source and in

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[9] Acoustically, shallow water conditions exist whenever the propagation is characterised by multiple reflections with both the sea surface and bottom (Etter, 2013). Consequently, the depth at which water can be classified as acoustically deep or shallow depends upon numerous factors including the sound speed gradient, water depth, frequency of the sound and distance between the source and receiver.

acoustically shallow water (i.e. where there are multiple reflections between the source and receiver). The degree of scattering will depend upon the sea state/wind speed, water depth, frequency of the sound, temperature gradient, grazing angle and range from source. It should be noted that variations in propagation due to scattering will vary temporally within an area primarily due to different sea-states/wind speeds at different times. However, over shorter ranges (e.g. several hundred meters or less) the sound will experience fewer reflections and so the effect of scattering should not be significant.

6.1.6 When sound waves encounter the seabed, the amount of sound reflected will depend on the geoacoustic properties of the bottom (e.g. grain size, porosity, density, sound speed, absorption coefficient and roughness) as well as the grazing angle and frequency of the sound (Cole, 1965; Hamilton, 1970; Mackenzie, 1960; McKinney and Anderson, 1964; Etter, 2013; Lurton, 2002; Urick, 1983). Thus, seabeds comprising primarily mud or other acoustically soft sediments will reflect less sound than acoustically harder bottoms such as rock or sand. This will also depend on the profile of the bottom (e.g. the depth of the sediment layer and how the geoacoustic properties vary with depth below the seafloor). The effect is less pronounced at low frequencies (a few kHz and below). A scattering effect (similar to that which occurs at the surface) also occurs at the seabed (Essen, 1994; Greaves and Stephen, 2003; McKinney and Anderson, 1964; Kuo, 1992), particularly on rough substrates (e.g. pebbles).

6.1.7 The waveguide effect should also be considered, which defines the shallow water columns that do not allow the propagation of LF sound (Urick, 1983; Etter, 2013). The cut off frequency of the lowest mode in a channel can be calculated based on the water depth and knowledge of the sediment geoacoustic properties but, for example, the cut off frequency as a function of water depth (based on the equations set out in Urick, 1983) is shown in Figure 6.1 for a range of seabed types. Any sound below this frequency will not propagate far due to energy losses through multiple reflections.

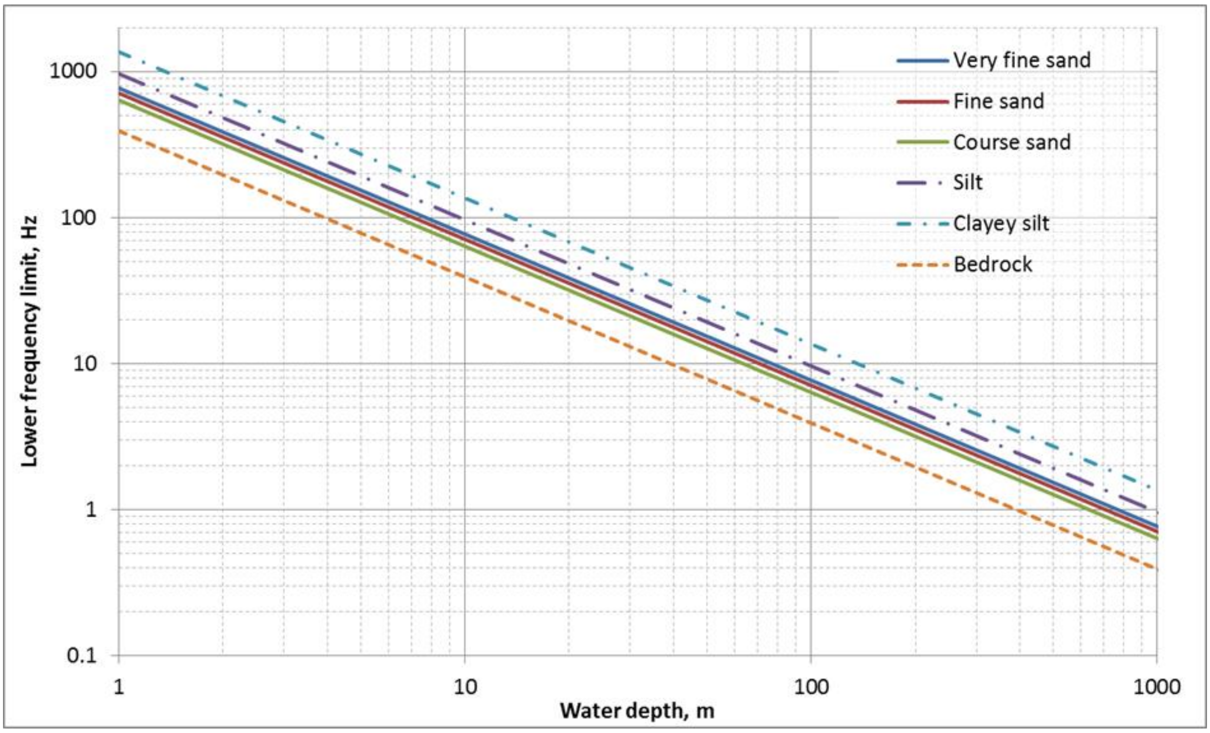

Figure 6.1: Lower Cut-Off Frequency as a Function of Depth for a Range of Seabed Types

6.1.8 Changes in the water temperature and the hydrostatic pressure with depth mean that the speed of sound varies throughout the water column. This can lead to significant variations in sound propagation and can also lead to sound channels, particularly for HF sound (Lurton, 2002). Sound can propagate in a duct-like manner within these channels, effectively focussing the sound, and conversely, they can also lead to shadow zones. The frequency at which this occurs depends on the characteristics of the sound channel and since the temperature gradient can vary throughout the year there will be potential variation in sound propagation depending on the season.

6.1.9 Sound energy is also absorbed due to interactions at the molecular level converting the acoustic energy into heat (Urick, 1983). This is another frequency-dependent effect with higher frequencies experiencing much higher losses than lower frequencies.

6.2 Modelling Approach

6.2.1 There are several methods available for modelling the propagation of sound between a source and receiver ranging from simple models which assume geometric spreading effects according to a 10 log (R) or 20 log (R) relationship (as discussed above, and where R is the range from source) to full acoustic models (e.g. ray tracing, normal mode, parabolic equation, wavenumber integration and energy flux models). In addition, semi-empirical models are available, in which complexity and accuracy are somewhere in between these two extremes.

6.2.2 In choosing the correct propagation model to employ, it is important to ensure that it is fit for purpose and produces results with a suitable degree of accuracy for the application in question, taking into account the context, as detailed in "Monitoring Guidance for Underwater Noise in European Seas Part III", National Physical Laboratory Guidance (Dekeling *et al.*, 2014) and in Farcas *et al.* (2016). Thus, in some situations (e.g. low risk of auditory injury due to underwater sound, where range dependent bathymetry is not an issue, i.e. for non-impulsive sound) a simple (N log R) model might be sufficient, particularly where other uncertainties (such as uncertainties in source level or the impact thresholds) outweigh the uncertainties due to modelling. On the other hand, some situations (e.g. very high source levels, impulsive sound, complex source and propagation path characteristics, highly sensitive receivers, and low uncertainties in assessment criteria) warrant a more complex modelling methodology.

6.2.3 The first step in choosing a propagation model is therefore to examine these various factors, such as:

- balancing of errors/uncertainties;
- range dependant bathymetry;
- frequency dependence; and
- source characteristics.

6.3 Modelling Approach for Vessels and Continuous Sources

6.3.1 For the sound field model, relevant survey parameters were chosen based on a combination of data provided by the Applicant combined with the information gathered from the publicly available literature. These parameters were fed into an appropriate propagation model routine, in this case the Weston Energy Flux model, which is suited to the region and the frequencies of interest (for more information refer to Weston, 1971; 1980a; 1980b). The frequency-dependent loss of acoustic energy with distance (TL) values were then evaluated along different transects around the chosen source points. The frequencies of interest in the present study are from 20 Hz to 80 kHz, with different sound sources operating in different frequency bands.

6.3.2 The propagation loss is calculated using one of four regions, depending on the distance of the receiver location from the source, and related to the frequency and the seafloor conditions such as depth and its composition.

6.3.3 The spherical spreading region exists in the immediate vicinity of the source, which is followed by a region where the propagation follows a cylindrical spread out until the grazing angle is equal to the critical grazing angle. Above the critical grazing angle in the mode stripping region an additional loss factor is introduced which is due to seafloor reflection loss, where higher modes are attenuated faster due to their larger grazing angles. In the final region, the single mode region, all modes but the lowest have been fully attenuated.

6.4 Modelling Approach for Impact Piling

6.4.1 In the case of offshore pile installation using an impact hammer, the sound source can be thought of as a 'line-source' extending through the water column (or in the case of installations using a submersible hammer, a line-source through a lower portion of the water column). The hammer strike at the top of the pile produces a compression wave in the pile resulting in radial displacement of the pile walls which is transmitted into the surround media (water and sediments) as sound waves. These compressional waves travel through the pile at circa 5,000 m/s, resulting in a conically shaped wavefront in the water column.

6.4.2 Underwater acoustic propagation modelling for this project was undertaken using a distributed line-source array line-source energy flux model. The line-source energy flux model is based on an implementation of the energy flux model for a directional source set out in de Jong *et al.* (2019).

6.4.3 The line-source energy flux model (de Jong *et al.,* 2019) includes the effect of directionality of the cone shaped wavefront associated with piling sound (circa 17 degrees). This results in damped cylindrical spreading at shorter ranges and mode stripping behaviour at more distant ranges. At even more distant ranges, once the 'mode stripping' has eliminated the contribution of all waveguide modes except the lowest mode, propagation is evaluated according to a single mode regime.

6.4.4 For estimation of propagation loss of acoustic energy at different distances away from the sound source location (in different directions), the following steps were considered:

- The bathymetry information around this chosen source points will be extracted from the GEBCO database in 72 different transects.
- A geoacoustic model of the different seafloor layers in the survey region will be calculated based on the British Geological Survey (BGS) borehole database and European Marine Observation and Data Network (EMODnet) sediment database.
- A calibrated line-source propagation model will be employed to estimate the transmission loss matrices for different frequencies of interest (from 25 Hz to 80 kHz) along the 72 different transects.
- Source levels for the line-source array will be determined based on a back-calculation from the received sound level and spectrum shape at 750 m (based on the scaling laws set out in von Pein *et al.* (2022)).
- The calculated source level values were combined with the transmission loss results to achieve a frequency and range dependant RL of acoustic energy around the chosen source position.
- The potential auditory injury impact distances for different marine mammal groups were calculated using relevant metrics and weighting functions (from (Southall *et al.* 2019) and NMFS (2024)) and a simplistic animal movement model was employed (directly away from the sound source) where appropriate. No weighting functions were applied for the assessment of marine mammal disturbance using single pulse SEL, and for the assessment of effects on fish.

6.4.5 The level of detail presented in terms of sound modelling needs to be considered in relation to the level of uncertainty for animal injury and disturbance thresholds. Uncertainty in the sound level predictions will be higher over larger propagation distances (i.e. in relation to disturbance thresholds) and much lower over shorter distances (i.e. in relation to injury thresholds). Nevertheless, it is considered that the uncertainty in animal injury and disturbance thresholds is likely to be higher than uncertainty in sound predictions. This is further compounded by differences in individual animal response, sensitivity, and behaviour. It would therefore be wholly misleading to present any injury or disturbance ranges as a clear line beyond which no effect can occur, and it would be equally misleading to present any sound modelling results in such a way.

6.5 Seiche Line-Source Model Calibration

6.5.1 The Seiche Limited line array model has been benchmarked against the COMPILE benchmark workshop for numerical models for pile driving acoustics (Lippert *et al.*, 2016). The COMPILE workshop included modelling results from a number of different organisations in an attempt to compare the performance of acoustic models for piling against pre-defined input parameters. The models included in the benchmarking exercise included those developed by Seoul National University, Netherlands Organisation for Applied Scientific Research, Hamburg University of Technology, Jasco Applied Sciences, Curtin University and Bundeswehr Technical Centre for Ships and Naval Weapons, Maritime Technology and Research (WTD 71).

6.5.2 A comparison between the Seiche model and the benchmark workshop model results is presented in Figure 6.2. The results of the benchmarking exercise show good correlation with the other models with the results most closely matching the Netherlands Organisation for Applied Scientific Research (TNO) model. The Seiche model predicts slightly higher received levels compared to the other models at 20 km range for this particular benchmark scenario (10 m water depth, sand substrate). Nevertheless, it is considered that the results of the benchmarking exercise demonstrate a good degree of agreement with other sound propagation models for piling.

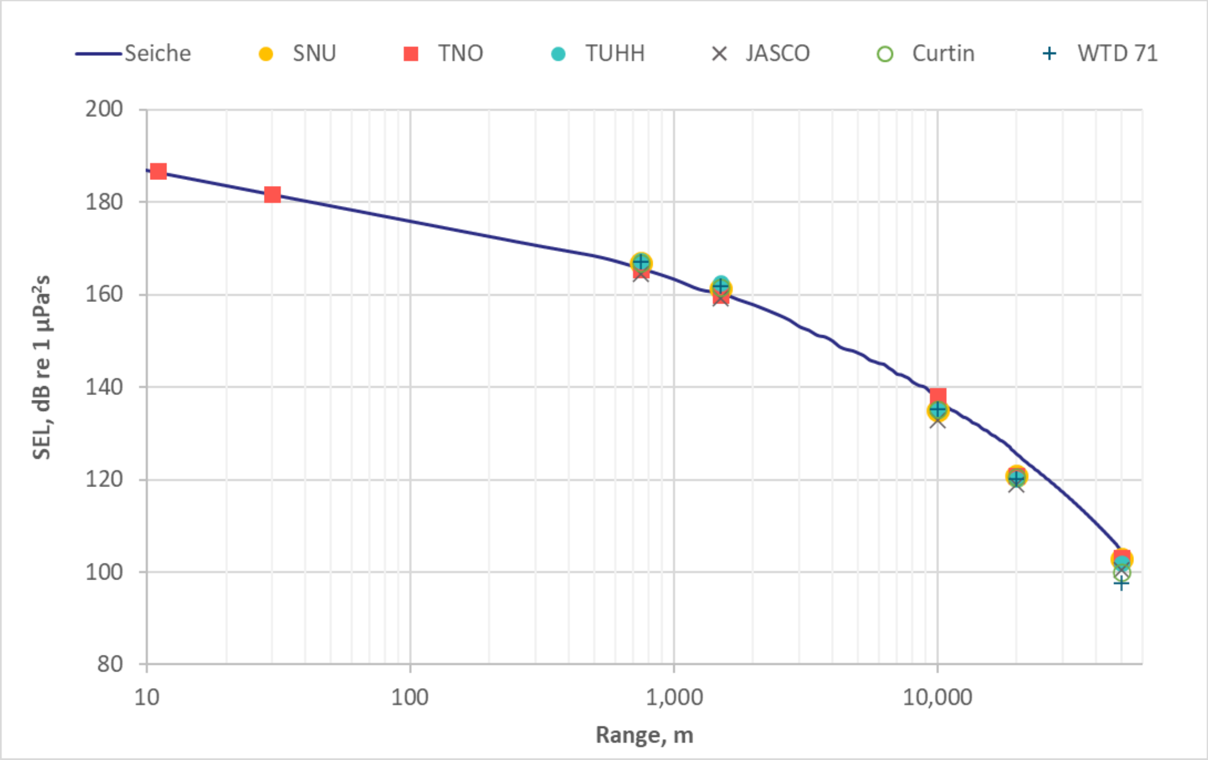

Figure 6.2: Comparison of Seiche Underwater Acoustic Model Against COMPILE Benchmarks

6.6 Exposure Calculations

6.6.1 As well as calculating the unweighted sound levels at various distances from different source, it is also necessary to calculate the received acoustic signal in terms of the SEL metric for a marine mammal using the relevant hearing weighting functions. For the various sound sources, the numerical SEL value is equal to the SPL_{rms} value integrated over a one second window as the sources are continuous and non-impulsive. These SEL values are employed for calculation of SEL_{cum} (cumulative SEL) metric for different marine mammal groups to assess potential impact ranges.

6.6.2 Simplified exposure modelling could assume that the animal is either static and at a fixed distance away from the sound source, or that the animal is swimming at a constant speed in a perpendicular direction away from a sound source. For fixed receiver calculations, it has generally been assumed (in literature) that an animal will stay at a known distance from the sound source for a period of 24 hours. As the animal does not move, the sound will be constant over the integration period of 24 hours (assuming the source does not change its operational characteristics over this time). This, however, would give an unrealistic level of exposure, as animals are highly unlikely to remain stationary when exposed to loud sound, and are therefore expected to swim away from the source. The approximation used in these calculations, therefore, is that the animals move directly away from the source. Nevertheless, in the case of fish exposure, calculations have also been undertaken based on a static receiver assumption.

6.6.3 It should be noted that the sound exposure calculations are based on the simplistic assumption that the sound source is active continuously (or intermittently based on source activation timings) over a 24-hour period; however, the real-world situation is more complex. The SEL calculations presented in this study do not account for any breaks in activity, such as repositioning of the piling vessel, or downtime due to mechanics, logistics or weather.

6.6.4 Furthermore, the sound criteria described in the Southall *et al.* (2019) and NMFS (2024) guidelines assume that the animal does not recover hearing between periods of activity. It is likely that both the intervals between operations could allow some recovery from temporary hearing threshold shifts for animals exposed to the sound (von Benda-Beckmann *et al.* 2022) and, therefore, the assessment of SEL is conservative.

6.6.5 In order to carry out the moving marine mammal calculation, it has been assumed that a mammal will swim away from the sound source at the onset of activities. For impulsive sounds of pile driving, the calculation considers each pulse to be established separately resulting in a series of discrete SEL values of decreasing magnitude (see Figure 6.3).

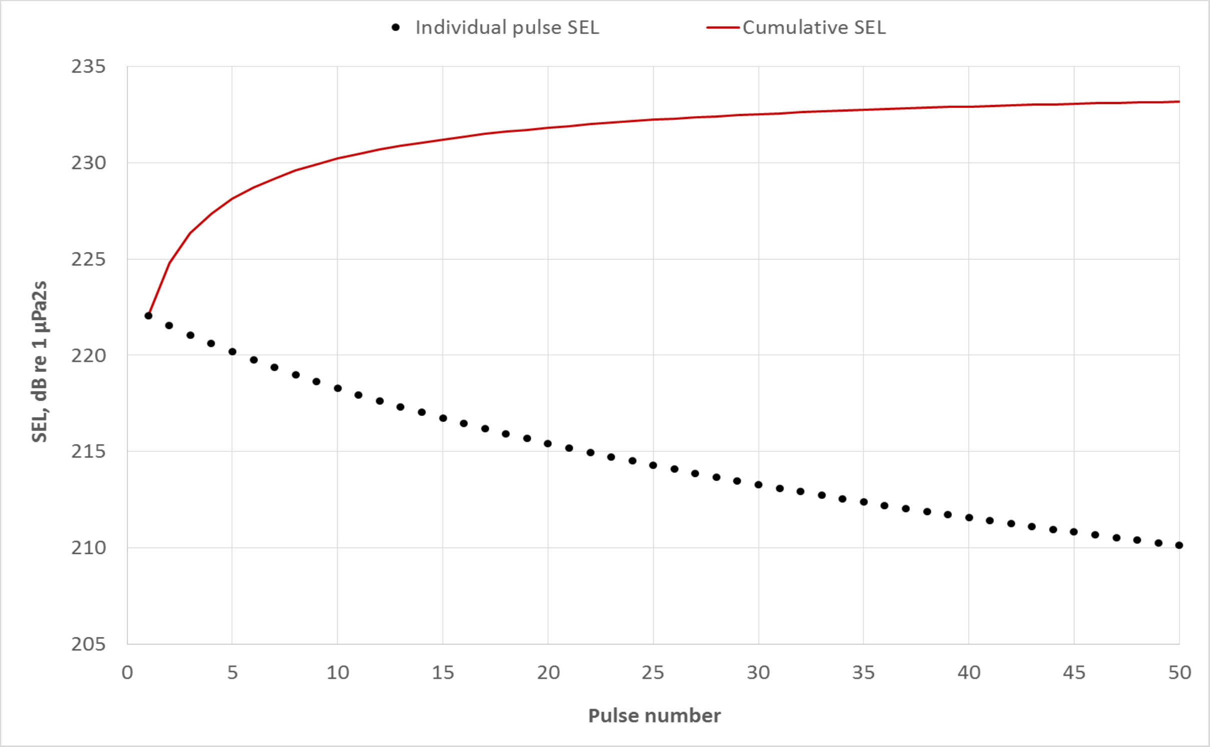

Figure 6.3: A Comparison of Discrete SEL per Pulse, and Cumulative SEL Values

6.6.6 As an animal swims away from the sound source, the sound it experiences will become progressively lower (more attenuated); the SEL_{cum} is derived by logarithmically adding the SEL to which the mammal is exposed as it travels away from the source. This calculation was used to estimate the approximate minimum start distance for an animal in order for it not to be exposed to sufficient sound energy to result in the onset of potential auditory injury. It should be noted that the sound exposure calculations are based on the simplistic assumption that the animal will continue to swim away at a fairly constant relative speed. The real-world situation is more complex, and the animal is likely to move in a more complex manner.

6.6.7 The assumed swim speeds for animals likely to be present across the Proposed Development are set out in Table 6.1.

Table 6.1: Assessment Swim Speeds of Marine Mammals and Fish That are Likely to Occur Within the North Sea for the Purpose of Exposure Modelling

Species	Hearing group	Swim speed (m/s)	Source reference
Harbour seal	PCW	1.8	Thompson *et al.* (2015)
Grey seal	PCW	1.8	Thompson *et al.* (2015)
Harbour porpoise	VHF	1.5	Otani *et al.* (2000)
Minke whale	LF	2.3	Boisseau *et al.* (2021)
Bottlenose dolphin	HF	1.52	Bailey *et al.* (2010)
White-beaked dolphin	HF	1.52	Bailey *et al.* (2010)
Short beaked common dolphin *Delphinus delphis*	HF	1.52	Bailey *et al.* (2010)
Risso's dolphin *Grampus griseus*	HF	1.52	Bailey *et al.* (2010)
Basking shark	Group 1 fish	1.0	Sims *et al.* (2000)
All fish hearing groups (excluding basking sharks)	Group 1 to 4 fish	0 and 0.5	Popper *et al.* (2014)

6.6.8 As an additional sensitivity analysis, modelling was carried out for fish assuming a swim speed of 0 m/s (i.e. stationary).

6.6.9 To perform the cumulative exposure calculation, the first step is to parameterise the marine mammal hearing weighted sound exposure levels (or unweighted in the case of fish) for single strikes of a given energy via the 95th percentile line of best fit against the calculated received levels from the model. This function is then used to predict the exposure level for each strike in the planned hammer schedule (periods of slow start, ramp up and full power).

6.6.10 In addition to the single-source pile driving, simplified situations of simultaneous pile driving from two piling rigs have been considered. The response has been approximated as moving directly away from the point on a line equidistant between the two sources. For simplicity, the sources are considered to be omnidirectional and the piling schedules (soft start, ramp up, etc.) are synchronised, entering each stage of the schedule at the same time.

6.7 UXO sound modelling

High order detonation

6.7.1 Acoustic modelling for UXO clearance has been undertaken using the methodology described in Soloway and Dahl (2014). The equation provides a simple relationship between distance from an explosion and the weight of the charge (or equivalent TNT weight) but does not take into account bottom topography or sediment characteristics.

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

Where *W* is the equivalent TNT charge weight and *R* is the distance from source to receiver.

6.7.2 Since the charge is assumed to be freely standing in mid-water, unlike a UXO which would be resting on the seabed and could potentially be buried, degraded or subject to other significant attenuation, this estimation of the source level can be considered conservative.

6.7.3 According to Soloway and Dahl (2014), the SEL can be estimated by the following equation:

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

6.7.4 In order to compare to the marine mammal hearing weighted thresholds, it is necessary to apply the frequency-dependent weighting functions at each distance from the source. This was accomplished by determining a transfer function between unweighted and weighted SEL values at various distances based on an assumed spectrum shape (see Figure 6.4) and taking into account molecular absorption at various ranges. Furthermore, because there is potential for more than one UXO clearance event per day (a maximum of two per day is assumed) then it is also necessary to take this into account in the exposure calculation.

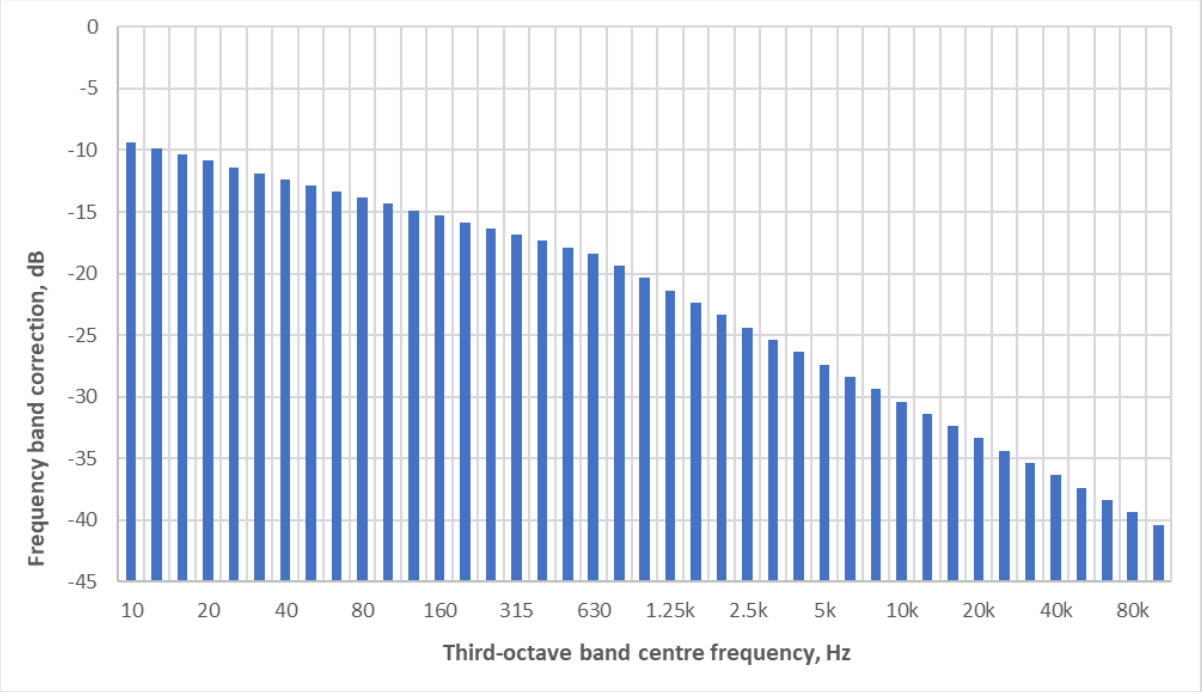

Figure 6.4: Assumed Explosive Spectrum Shape Used to Estimate Hearing Weighting Corrections to SEL

Low order techniques

6.7.5 According to Robinson *et al.* (2020), low order deflagration (a specific method of low order UXO clearance) results in a much lower amplitude of peak sound pressure than high order detonations. The study concluded that peak sound pressure during deflagration is due only to the size of the shaped charge used to initiate deflagration and, consequently, that the acoustic output can be predicted for deflagration as long as the size of the shaped charge is known.

6.7.6 Acoustic modelling for low order techniques (such as deflagration) has therefore been based on the methodology described above for high order detonations, using a smaller donor charge size.

7 Sound Modelling Results

7.1 Pre-construction Phase

7.1.1 The estimated ranges for auditory injury to marine mammals due to various proposed activities undertaken during the pre-construction site investigation surveying phase of the operations are presented in this section. These include geophysical and geotechnical survey activities, UXO clearance and supported vessel activities.

7.1.2 The potential ranges presented for injury and behavioural response are not a hard and fast 'line' where an impact will occur on one side and not on the other. Potential impact is more probabilistic than that; dose dependency in auditory injury onset, individual variations and uncertainties regarding behavioural response and swim speed/direction all mean that it is much more complex than drawing a contour around a location. These ranges are designed to provide an indication of the potential spatial extent of the impact.

Geophysical and Geotechnical Surveys

7.1.3 Geophysical surveying includes many sonar-like sound sources and the resulting injury and disturbance ranges for marine mammals are presented in Table 7.1 and Table 7.2, based on a comparison to the non-impulsive thresholds set out in Southall *et al.* (2019) and NMFS (2024) respectively. Table 7.3 and Table 7.4 presents the results for geotechnical investigations.

7.1.4 The potential impact distances from these operations vary based on their frequencies of operation and source levels and are rounded to the nearest 5 m. Sonar-like systems have very strong directivity which effectively means that there is only potential for injury when a marine mammal is directly underneath the sound source. Once the animal moves outside of the main beam, there is significantly reduced potential for injury. The same is true in many cases for TTS where an animal is only exposed to enough energy to cause TTS when inside the direct beam of the sonar-like source. For this reason, many of the TTS and PTS/AUD INJ ranges are similar (i.e. limited by the depth of the water). Disturbance thresholds are as summarised in Table 4.3 for impulsive and non-impulsive sources, noting that impulsive sources have both a strong and a mild disturbance threshold.

Table 7.1: Potential Impact Ranges (m) for Marine Mammals During the Various Geophysical Investigation Activities Based on Comparison to Southall *et al.* (2019) SEL Thresholds (N/E – Threshold not Exceeded)

Source	Potential impact range (m)										
	LF		HF		VHF		PCW		OCW		All Groups
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
MBES*	75	10	248	150	300	255	115	20	N/E	N/E	490
SSS LF*	130	15	255	215	281	255	185	40	32	N/E	530
SSS HF*	21	N/E	157	61	254	205	40	N/E	N/E	N/E	283
SBP (chirp/ pinger)*	90	86	205	88	700	295	90	86	86	72	1,275
UHRS (sparker)**	214	N/E	N/E	N/E	296	17	35	N/E	N/E	N/E	Mild 80 Strong 552

*Non-impulsive threshold
**Impulsive threshold

Table 7.2: Potential Impact Ranges (m) for Marine Mammals During the Various Geophysical Investigation Activities Based on Comparison to NMFS (2024) SEL Thresholds (N/E – Threshold not Exceeded)

Source	Potential impact range (m)										
	LF		HF		VHF		PCW		OCW		All Groups
	TTS	AUD INJ	TTS	AUD INJ	TTS	AUD INJ	TTS	AUD INJ	TTS	AUD INJ	Disturbance
MBES*	N/E	N/E	75	8	251	165	N/E	N/E	N/E	N/E	490
SSS LF*	N/E	N/E	215	60	300	251	72	5	N/E	N/E	530
SSS HF*	N/E	N/E	N/E	N/E	135	45	N/E	N/E	N/E	N/E	283
SBP (chirp/ pinger)*	83	25	120	86	525	170	90	86	86	83	1,275
UHRS (sparker)**	213	N/E	N/E	N/E	541	17	130	N/E	9	N/E	Mild 80 Strong 552

*Non-impulsive threshold
**Impulsive threshold

Table 7.3: Potential Impact Ranges for Geotechnical Site Investigation Activities Based on Comparison to Southall *et al.* (2019) SEL Thresholds (N/E – Threshold not Exceeded)

Source	Potential impact range (m)										
	LF		HF		VHF		PCW		OCW		All Groups
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
Vibro-coring	N/E	N/E	N/E	N/E	346	N/E	N/E	N/E	N/E	N/E	9,154
Borehole drilling	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	294

Table 7.4: Potential Impact Ranges for Geotechnical Site Investigation Activities Based on Comparison to NMFS (2024) SEL Thresholds (N/E – Threshold not Exceeded)

Source	Potential impact range (m)										
	LF		HF		VHF		PCW		OCW		All Groups
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
Vibro-coring	6.5	N/E	N/E	N/E	N/E	N/E	N/E	N/E	5	N/E	9,154
Borehole drilling	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	294

Table 7.5: Estimated Recoverable Injury and TTS Ranges for Geotechnical Site Investigation Activities for Group 3 and 4 Fish

Source	Injury Zone Radius (m)	
	Recoverable injury 170 dB re 1 µPa (rms) for 48 hrs	TTS 158 dB re 1 µPa (rms) for 12 hrs
Vibro-coring	10	53
Borehole drilling	N/E	N/E

UXO Clearance

7.1.5 The predicted injury ranges for low order disposal are presented in Table 7.6 and Table 7.7, and for high order clearance in Table 7.9 and Table 7.10. All UXO injury and disturbance ranges are based on a comparison to the relevant impulsive sound thresholds as set out in Section 4.2.

7.1.6 It should be noted that, due to a combination of dispersion (i.e. where the waveform elongates), multiple reflections from the sea surface and seabed and molecular absorption of HF energy, the sound is unlikely to still be impulsive in character once it has propagated more than a few kilometres. Consequently, great caution should be used when interpreting any results with predicted injury ranges in the order of tens of kilometres. Furthermore, the modelling assumes that the UXO acts like a charge suspended in open water whereas in reality it is likely to be partially buried in the sediment. In addition, it is possible that the explosive material will have deteriorated over time meaning that the predicted sound levels are likely to be over-estimated. In combination, these factors mean that the results should be treated as precautionary potential impact ranges which are likely to be significantly lower than predicted.

Table 7.6: Potential Impact Ranges for Low Order and Low Yield UXO Clearance Activities, in Terms of the Southall *et al.* (2019) Thresholds (N/E – Threshold not Exceeded)

	PTS Range (m)		TTS Range (m)	
	SPL_{peak}	SEL	SPL_{peak}	SEL
0.08 kg Low Order Donor Charge				
LF	122	47	224	660
HF	40	2	73	23
VHF	685	191	1,265	1,495
PCW	135	9	247	125
OCW	32	N/E	60	6
0.5 kg Clearing Shot				
LF	223	115	415	1,585
HF	73	4	134	56
VHF	1,265	425	2,325	2,435
PCW	247	22	455	301
OCW	60	N/E	110	14

Table 7.7: Potential Impact Ranges for Low Order and Low Yield UXO Clearance Activities, in Terms of the NMFS (2024) Thresholds (N/E – Threshold not Exceeded)

	PTS Range (m)		TTS Range (m)	
	SPL_{peak}	SEL	SPL_{peak}	SEL
0.08 kg Low Order Donor Charge				
LF	90	51	165	715
HF	40	N/E	73	6
VHF	685	175	1,265	1,480
PCW	81	16	149	222
OCW	40	5	73	75
0.5 kg Clearing Shot				
LF	165	125	303	1,725
HF	73	N/E	134	14
VHF	1,265	395	2,325	2,475
PCW	149	39	274	535
OCW	73	13	134	181

Table 7.8: Potential Impact Ranges for Low Order and Low Yield UXO Clearance Activities, in Terms of the Popper *et al.* (2014) Thresholds for Fish

	Range of Mortality and Potential Injury (m)
	SPL$_{peak}$
0.08 kg Low Order Donor Charge	
Fish	27 - 44
0.5 kg Clearing Shot	
Fish	49 - 81

Table 7.9: Potential Impact Ranges for High Order Clearance of UXOs, in Terms of the Southall *et al.* (2019) Thresholds

	PTS Range (m)		TTS Range (m)	
	SPL$_{peak}$	SEL	SPL$_{peak}$	SEL
227 kg UXO – High Order Explosion				
LF	1,715	2,220	3,160	21,660
HF	560	79	1,030	845
VHF	9,685	2,865	17,850	7,400
PCW	1,900	420	3,500	4,105
OCW	460	19	840	261
720 kg UXO – High Order Explosion				
LF	2,520	3,795	4,640	31,885
HF	825	136	1,515	12,75
VHF	14,230	3,655	26,225	8,660
PCW	2,790	720	5,140	6,020
OCW	670	33	1,235	450

Table 7.10: Potential Impact Ranges for High Order Clearance of UXOs, in Terms of the NMFS (2024) Thresholds

	PTS Range (m)		TTS Range (m)	
	SPL$_{peak}$	SEL	SPL$_{peak}$	SEL
227 kg UXO – High Order Explosion				
LF	1,265	2,415	2,330	23,210
HF	560	79	1,030	985
VHF	9,685	2,935	17,850	7,730
PCW	1,140	740	2,105	6,300
OCW	560	253	1,030	2,450
720 kg UXO – High Order Explosion				
LF	1,855	4,120	3,420	34,275
HF	825	138	1,515	1,595

	PTS Range (m)		TTS Range (m)	
VHF	14,230	3,780	26,225	9,010
PCW	1,675	1,245	3,090	8,785
OCW	825	435	1,515	3,575

Table 7.11: Potential Impact Ranges for High Order Clearance of UXOs, in Terms of the Popper *et al.* (2014) Thresholds for Fish

	Range of Mortality and Potential Injury (m)
	SPL_{peak}
227 kg UXO – High Order Explosion	
Fish	375 - 620
720 kg UXO – High Order Explosion	
Fish	550 - 910

7.2 Construction Phase

Impact Piling

7.2.1 The impact piling scenarios modelled were as follows:

- single piling rig – monopile Wind Turbine foundations;
- single piling rig – pin pile jacket foundations for Wind Turbines and OSPs;
- single piling rig – monopile Wind Turbine foundation, realistic installation scenario;
- consecutive piling – installation of two consecutive piles by a single rig, up to a maximum of 24 hours – monopile Wind Turbine foundations;
- consecutive piling – installation of two consecutive piles by a single rig, up to a maximum of 24 hours - pin pile jacket foundations for Wind Turbines and OSPs;
- consecutive piling – installation of two consecutive piles by a single rig, up to a maximum of 24 hours - monopile Wind Turbine foundation, realistic installation scenario;
- two piling rigs concurrent piling – monopile Wind Turbine foundations;
- two piling rigs concurrent piling – pin pile jacket foundations for Wind Turbines and OSPs; and
- two piling rigs concurrent piling – monopile Wind Turbine foundation, realistic installation scenario.

7.2.2 All cases are presented both with and without the use of 15 minutes of ADD prior to installation.

7.2.3 Impact ranges were modelled for two locations within the array, incorporating the deepest parts, however, only the worst-case injury ranges have been reported in this section: in this case the greatest injury ranges occurred at the north location.

7.2.4 All impact piling injury ranges are based on a comparison to the relevant impulsive sound thresholds as set out in Section 4.2. Disturbance effects are presented in Volume 2, Chapter 10: Marine Mammals using the dose-response approach described in Section 4.3.

7.2.5 The injury ranges for peak sound pressure are based on both the sound from the first strike a receptor may experience at the closest point during each phase of the pile installation, as well as for the maximum hammer energy over the entire installation.

7.2.6 It should be noted that peak sound pressure is a time domain parameter and does not necessarily add together to produce higher received peak sound pressure levels. Even if two piling hammers were to strike their piles synchronously (i.e. to the exact millisecond) the sound waves will arrive at different locations at different times. Consequently, the peak pressure ranges for simultaneous piling do not differ from the peak injury ranges identified for single piling.

7.2.7 During impact piling the interaction with the seabed and the water column is complex. In these cases, a combination of dispersion (i.e. where the waveform shape elongates), and multiple reflections from the sea surface and bottom and molecular absorption of HF energy, the sound will lose its impulsive shape after some distance (generally in order of several kilometres).

7.2.8 A recent article by Southall (2021) discusses this aspect in detail, and notes that "*…when onset criteria levels were applied to relatively high-intensity impulsive sources (e.g. pile driving), TTS onset was predicted in some instances at ranges of tens of kilometres from the sources. In reality, acoustic propagation over such ranges transforms impulsive characteristics in time and frequency (see Hastie et al., 2019; Amaral et al., 2020; Martin et al., 2020). Changes to received signals include less rapid signal onset, longer total duration, reduced crest factor, reduced kurtosis, and narrower bandwidth (reduced HF content). A better means of accounting for these changes can avoid overly precautionary conclusions, although how to do so is proving vexing*". The point is reinforced later in the discussion which points out that "*…it should be recognized that the use of impulsive exposure criteria for receivers at greater ranges (tens of kilometres) is almost certainly an overly precautionary interpretation of existing criteria*". (See discussion in Section 4.5).

7.2.9 Consequently, great caution should be used when interpreting any results with predicted injury ranges in the order of tens of kilometres.

Single Piling Rig – Monopile Wind Turbine Foundations

7.2.10 Distances are presented at which sound levels decrease to below PTS/AUD INJ and TTS threshold values in terms of SEL_{cum} and SPL_{peak}.

Table 7.12: Potential Marine Mammal Injury Ranges for Single Pile Installation of Monopile Foundations, Based on the Southall *et al.* (2019) Cumulative SEL Metric (N/E – Threshold not exceeded)

Species/Group	Threshold, SEL (dB re 1 µPa²s)	Range (m)	
		No ADD	15 min ADD
LF	PTS – 183 dB re 1 µPa²s	13,360	11,251
	TTS – 168 dB re 1 µPa²s	21,973	19,922
HF	PTS – 185 dB re 1 µPa²s	N/E	N/E
	TTS – 170 dB re 1 µPa²s	25	N/E
VHF	PTS – 155 dB re 1 µPa²s	1,993	646
	TTS – 140 dB re 1 µPa²s	16,407	15,118
PCW	PTS – 185 dB re 1 µPa²s	23	N/E
	TTS – 170 dB re 1 µPa²s	14,766	13,126
OCW	PTS – 203 dB re 1 µPa²s	N/E	N/E
	TTS – 188 dB re 1 µPa²s	N/E	N/E

Table 7.13: Potential Marine Mammal Injury Ranges for Single Pile Installation of Monopile Foundations, Based on the NMFS (2024) Cumulative SEL Metric (N/E – Threshold not Exceeded)

Species/Group	Threshold, SEL (dB re 1 µPa²s)	Range (m)	
		No ADD	15 min ADD
LF	AUD INJ – 183 dB re 1 µPa²s	14,063	12,129
	TTS – 168 dB re 1 µPa²s	22,266	20,274
HF	AUD INJ – 193 dB re 1 µPa²s	N/E	N/E
	TTS – 178 dB re 1 µPa²s	411	N/E
VHF	AUD INJ – 159 dB re 1 µPa²s	2,462	1,173
	TTS – 144 dB re 1 µPa²s	17,579	16,172
PCW	AUD INJ – 183 dB re 1 µPa²s	470	N/E
	TTS – 168 dB re 1 µPa²s	17,461	15,938
OCW	AUD INJ – 185 dB re 1 µPa²s	11,719	10,548
	TTS – 170 dB re 1 µPa²s	21,973	20,625

Table 7.14: Potential Marine Mammal Injury Ranges for Pile Installation of Monopile Foundations, Based on the Southall *et al.* (2019) Peak SPL Metric

Species/Group	Threshold, SPL_{peak}, dB re 1 µPa	Range (m)	
		First Strike	Highest Energy
LF	PTS – 219 dB re 1 µPa (pk)	115	568
	TTS – 213 dB re 1 µPa (pk)	180	888
HF	PTS – 230 dB re 1 µPa (pk)	51	250
	TTS – 224 dB re 1 µPa (pk)	79	391
VHF	PTS – 202 dB re 1 µPa (pk)	410	2,016
	TTS – 196 dB re 1 µPa (pk)	641	3,156
PCW	PTS – 218 dB re 1 µPa (pk)	124	612
	TTS – 212 dB re 1 µPa (pk)	194	957
OCW	PTS – 232 dB re 1 µPa (pk)	44	215
	TTS – 226 dB re 1 µPa (pk)	68	337

Table 7.15: Potential Marine Mammal Injury Ranges for Pile Installation of Monopile Foundations, Based on the NMFS (2024) Peak SPL Metric

Species/Group	Threshold, SPL_{peak}, dB re 1 µPa	Range (m)	
		First Strike	Highest Energy
LF	AUD INJ – 222 dB re 1 µPa (pk)	92	454
	TTS – 216 dB re 1 µPa (pk)	144	711
HF	AUD INJ – 230 dB re 1 µPa (pk)	51	250
	TTS – 224 dB re 1 µPa (pk)	79	391
VHF	AUD INJ – 202 dB re 1 µPa (pk)	410	2,016
	TTS – 196 dB re 1 µPa (pk)	641	3,156
PCW	AUD INJ – 223 dB re 1 µPa (pk)	85	422
	TTS – 217 dB re 1 µPa (pk)	133	660
OCW	AUD INJ – 230 dB re 1 µPa (pk)	51	250
	TTS – 224 dB re 1 µPa (pk)	79	391

Table 7.16: Potential Injury and Disturbance Ranges for Single Monopile Installation Based on the Cumulative SEL Metric for Moving Fish (N/E – Threshold not Exceeded)

Hearing Group	Response	Threshold, SEL (dB re 1 µPa²s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	22,266
Basking shark	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	19,805
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	177
	Recoverable injury	203	3,926
	TTS	186	22,266
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	1,056
	Recoverable injury	203	3,926
	TTS	186	22,266
Sea Turtles	Mortality	210	177
Fish eggs and larvae	Mortality	210	3,780
All Fish Groups	Disturbance	150 dB re 1µPa (rms)	60,451

Table 7.17: Potential Injury and Disturbance Ranges for Single Monopile Installation Based on the Cumulative SEL Metric for Static Fish

Hearing Group	Response	Threshold, SEL (dB re 1 µPa²s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	1,436
	Recoverable injury	216	1,993
	TTS	186	25,000
Basking shark	Mortality	219	1,436
	Recoverable injury	216	1,993
	TTS	186	25,000
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	3,780
	Recoverable injury	203	10,430
	TTS	186	25,000

Hearing Group	**Response**	**Threshold, SEL (dB re 1 μPa²s)**	**Range (m)**
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	5,860
	Recoverable injury	203	10,430
	TTS	186	25,000
Sea Turtles	Mortality	210	3,780
Fish eggs and larvae	Mortality	210	3,780
All Fish Groups	Disturbance	150 dB re 1μPa (rms)	60,451

Table 7.18: Potential Injury Ranges for Monopile Installation Based on the Peak SPL Metric

Hearing Group	**Response**	**Threshold, SPL_{peak} (dB re 1 μPa)**	**Range (m)**	
			First Strike	**Highest Energy**
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	213	180	888
	Recoverable injury	213	180	888
Basking shark	Mortality	213	180	888
	Recoverable injury	213	180	888
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	207	282	1,389
	Recoverable injury	207	282	1,389
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	282	1,389
	Recoverable injury	207	282	1,389
Sea Turtles	Mortality	207	282	1,389
Fish eggs and larvae	Mortality	207	282	1,389

Single Piling Rig – Jacket Foundations

7.2.11 Distances are presented at which sound levels decrease to below PTS/AUD INJ and TTS threshold values in terms of cumulative SEL and peak sound pressure level.

Table 7.19: Potential Marine Mammal Injury Ranges for Single Pile Installation of Jacket Piles, Based on the Southall *et al.* (2019) Cumulative SEL Metric (N/E – Threshold not Exceeded)

Species/Group	Threshold, SEL (dB re 1 µPa²s)	Range (m)	
		No ADD	15 min ADD
LF	PTS – 183 dB re 1 µPa²s	11,016	8,907
	TTS – 168 dB re 1 µPa²s	21,328	19,219
HF	PTS – 185 dB re 1 µPa²s	N/E	N/E
	TTS – 170 dB re 1 µPa²s	21	N/E
VHF	PTS – 155 dB re 1 µPa²s	997	N/E
	TTS – 140 dB re 1 µPa²s	15,762	14,473
PCW	PTS – 185 dB re 1 µPa²s	25	N/E
	TTS – 170 dB re 1 µPa²s	15,000	13,360
OCW	PTS – 203 dB re 1 µPa²s	N/E	N/E
	TTS – 188 dB re 1 µPa²s	13	N/E

Table 7.20: Potential Marine Mammal Injury Ranges for Single Pile Installation of Jacket Piles, Based on the NMFS (2024) cumulative SEL Metric (N/E – Threshold not Exceeded)

Species/Group	Threshold, SEL (dB re 1 µPa²s)	Range (m)	
		No ADD	15 min ADD
LF	AUD INJ – 183 dB re 1 µPa²s	11,719	9,610
	TTS – 168 dB re 1 µPa²s	21,504	19,453
HF	AUD INJ – 193 dB re 1 µPa²s	N/E	N/E
	TTS – 178 dB re 1 µPa²s	704	N/E
VHF	AUD INJ – 159 dB re 1 µPa²s	1,349	N/E
	TTS – 144 dB re 1 µPa²s	16,875	15,469
PCW	AUD INJ – 183 dB re 1 µPa²s	821	N/E
	TTS – 168 dB re 1 µPa²s	18,282	16,699
OCW	AUD INJ – 185 dB re 1 µPa²s	10,782	9,376
	TTS – 170 dB re 1 µPa²s	21,797	20,450

Table 7.21: Potential Marine Mammal Injury Ranges for Pile Installation of Jacket Piles, Based on the Southall *et al.* (2019) Peak SPL Metric

Species/Group	Threshold, SPL_{peak}, dB re 1 µPa	Range (m)	
		First Strike	Highest Energy
LF	PTS – 219 dB re 1 µPa (pk)	130	336
	TTS – 213 dB re 1 µPa (pk)	211	544
HF	PTS – 230 dB re 1 µPa (pk)	54	139
	TTS – 224 dB re 1 µPa (pk)	87	225
VHF	PTS – 202 dB re 1 µPa (pk)	511	1,320
	TTS – 196 dB re 1 µPa (pk)	828	2,139
PCW	PTS – 218 dB re 1 µPa (pk)	141	364
	TTS – 212 dB re 1 µPa (pk)	229	590
OCW	PTS – 232 dB re 1 µPa (pk)	46	118
	TTS – 226 dB re 1 µPa (pk)	74	192

Table 7.22: Potential Marine Mammal Injury Ranges for Pile Installation of Jacket Piles, Based on the NMFS (2024) Peak SPL Metric

Species/Group	Threshold, SPL_{peak}, dB re 1 µPa	Range (m)	
		First Strike	Highest Energy
LF	AUD INJ – 222 dB re 1 µPa (pk)	103	264
	TTS – 216 dB re 1 µPa (pk)	166	428
HF	AUD INJ – 230 dB re 1 µPa (pk)	54	139
	TTS – 224 dB re 1 µPa (pk)	87	225
VHF	AUD INJ – 202 dB re 1 µPa (pk)	511	1,320
	TTS – 196 dB re 1 µPa (pk)	828	2,139
PCW	AUD INJ – 223 dB re 1 µPa (pk)	95	244
	TTS – 217 dB re 1 µPa (pk)	153	395
OCW	AUD INJ – 230 dB re 1 µPa (pk)	54	139
	TTS – 224 dB re 1 µPa (pk)	87	225

Table 7.23: Potential Injury and Disturbance Ranges for Single Jacket Pile Installation Based on the Cumulative SEL Metric for Moving Fish (N/E – Threshold not Exceeded)

Hearing Group	Response	Threshold, SEL (dB re 1 µPa²s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	20,977
Basking shark	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	17,579
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	13
	Recoverable injury	203	1,173
	TTS	186	20,977
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	96
	Recoverable injury	203	1,173
	TTS	186	20,977
Sea Turtles	Mortality	210	13
Fish eggs and larvae	Mortality	210	2,931
All Fish Groups	Disturbance	150 dB re 1µPa (rms)	55,359

Table 7.24: Potential Injury and Disturbance Ranges for Single Jacket Pile Installation Based on the Cumulative SEL Metric for Static Fish

Hearing Group	Response	Threshold, SEL (dB re 1 µPa²s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	1,026
	Recoverable injury	216	1,495
	TTS	186	25,000
Basking shark	Mortality	219	1,026
	Recoverable injury	216	1,495
	TTS	186	25,000
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	2,931
	Recoverable injury	203	7,384
	TTS	186	25,000
Group 3 and 4 Fish: Swim bladder involved in hearing	Mortality	207	3,985
	Recoverable injury	203	7,384

Hearing Group	Response	Threshold, SEL (dB re 1 μPa²s)	Range (m)
(primarily pressure detection)	TTS	186	25,000
Sea Turtles	Mortality	210	2,931
Fish eggs and larvae	Mortality	210	2,931
All Fish Groups	Disturbance	150 dB re 1μPa (rms)	55,359

Table 7.25: Potential Injury Ranges for Fish of Jacket Pile Installation Based on the Peak SPL Metric

Hearing Group	Response	Threshold, SPL_{peak} (dB re 1 μPa)	Range (m)	
			First Strike	Highest Energy
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	213	211	544
	Recoverable injury	213	211	544
Basking shark	Mortality	213	211	544
	Recoverable injury	213	211	544
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	207	342	882
	Recoverable injury	207	342	882
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	342	882
	Recoverable injury	207	342	882
Sea Turtles	Mortality	207	342	882
Fish eggs and larvae	Mortality	207	342	882

Single Piling Rig – Monopile Foundations, Realistic Installation Scenario

7.2.12 Distances are presented at which sound levels decrease to below PTS/AUD INJ and TTS threshold values in terms of cumulative SEL and peak sound pressure level.

Table 7.26: Potential Marine Mammal Injury Ranges for the Realistic Single Pile Installation of Monopile Foundations, Based on the Southall *et al.* (2019) Cumulative SEL Metric (N/E – Threshold not Exceeded)

Species/Group	Threshold, SEL (dB re 1 μPa²s)	Range (m)	
		No ADD	15 min ADD
LF	PTS – 183 dB re 1 μPa²s	13,126	11,133
	TTS – 168 dB re 1 μPa²s	21,973	19,922
HF	PTS – 185 dB re 1 μPa²s	N/E	N/E
	TTS – 170 dB re 1 μPa²s	25	N/E
VHF	PTS – 155 dB re 1 μPa²s	1,993	587
	TTS – 140 dB re 1 μPa²s	16,407	15,000
PCW	PTS – 185 dB re 1 μPa²s	23	N/E
	TTS – 170 dB re 1 μPa²s	14,532	12,891
OCW	PTS – 203 dB re 1 μPa²s	N/E	N/E
	TTS – 188 dB re 1 μPa²s	N/E	N/E

Table 7.27: Potential Marine Mammal Injury Ranges for the Realistic Single Pile Installation of Monopile Foundations, Based on the NMFS (2024) Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 μPa²s)	Range (m)	
		No ADD	15 min ADD
LF	AUD INJ – 183 dB re 1 μPa²s	14,063	11,954
	TTS – 168 dB re 1 μPa²s	22,266	20,274
HF	AUD INJ – 193 dB re 1 μPa²s	N/E	N/E
	TTS – 178 dB re 1 μPa²s	265	N/E
VHF	AUD INJ – 159 dB re 1 μPa²s	2,403	1,056
	TTS – 144 dB re 1 μPa²s	17,520	16,172
PCW	AUD INJ – 183 dB re 1 μPa²s	411	N/E
	TTS – 168 dB re 1 μPa²s	17,402	15,821
OCW	AUD INJ – 185 dB re 1 μPa²s	11,719	10,313
	TTS – 170 dB re 1 μPa²s	21,973	20,625

Table 7.28: Potential Marine Mammal Injury Ranges for the Realistic Pile Installation of Monopile Foundations, Based on the Southall *et al.* (2019) Peak SPL Metric

Species/Group	Threshold, SPL_{peak}, dB re 1 µPa	Range (m)	
		First Strike	Highest Energy
LF	PTS – 219 dB re 1 µPa (pk)	115	558
	TTS – 213 dB re 1 µPa (pk)	180	872
HF	PTS – 230 dB re 1 µPa (pk)	51	245
	TTS – 224 dB re 1 µPa (pk)	79	384
VHF	PTS – 202 dB re 1 µPa (pk)	410	1,978
	TTS – 196 dB re 1 µPa (pk)	641	3,096
PCW	PTS – 218 dB re 1 µPa (pk)	124	601
	TTS – 212 dB re 1 µPa (pk)	194	939
OCW	PTS – 232 dB re 1 µPa (pk)	44	211
	TTS – 226 dB re 1 µPa (pk)	68	331

Table 7.29: Potential Marine Mammal injury ranges for the Realistic Pile Installation of Monopile Foundations, Based on the NMFS (2024) Peak SPL Metric

Species/Group	Threshold, SPL_{peak}, dB re 1 µPa	Range (m)	
		First Strike	Highest Energy
LF	AUD INJ – 222 dB re 1 µPa (pk)	92	446
	TTS – 216 dB re 1 µPa (pk)	144	697
HF	AUD INJ – 230 dB re 1 µPa (pk)	51	245
	TTS – 224 dB re 1 µPa (pk)	79	384
VHF	AUD INJ – 202 dB re 1 µPa (pk)	410	1,978
	TTS – 196 dB re 1 µPa (pk)	641	3,096
PCW	AUD INJ – 223 dB re 1 µPa (pk)	85	414
	TTS – 217 dB re 1 µPa (pk)	133	647
OCW	AUD INJ – 230 dB re 1 µPa (pk)	51	245
	TTS – 224 dB re 1 µPa (pk)	79	384

Table 7.30: Potential Injury and Disturbance Ranges for Monopile Realistic Installation Based on the Cumulative SEL Metric for Moving Fish (N/E – Threshold Not Exceeded)

Hearing Group	Response	Threshold, SEL (dB re 1 μPa^{2}s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	22,149
Basking shark	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	19,688
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	118
	Recoverable injury	203	2,579
	TTS	186	22,149
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	763
	Recoverable injury	203	2,579
	TTS	186	22,149
Sea Turtles	Mortality	210	118
Fish eggs and larvae	Mortality	210	2,696
All Fish Groups	Disturbance	150 dB re 1μPa (rms)	59,735

Table 7.31: Potential Injury and Disturbance Ranges for Single Monopile Realistic Installation Based on the Cumulative SEL Metric for Static Fish

Hearing Group	Response	Threshold, SEL (dB re 1 μPa^{2}s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	909
	Recoverable injury	216	1,349
	TTS	186	25,000
Basking shark	Mortality	219	909
	Recoverable injury	216	1,349
	TTS	186	25,000
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	2,696
	Recoverable injury	203	6,329
	TTS	186	25,000
Group 3 and 4 Fish: Swim bladder involved	Mortality	207	3,634
	Recoverable injury	203	6,329

Hearing Group	Response	Threshold, SEL (dB re 1 μPa^{2}s)	Range (m)
in hearing (primarily pressure detection)	TTS	186	25,000
Sea Turtles	Mortality	210	2,696
Fish eggs and larvae	Mortality	210	2,696
All Fish Groups	Disturbance	150 dB re 1μPa (rms)	59,735

Table 7.32: Potential Injury Ranges for Fish of Monopile Realistic Installation Based on the Peak SPL Metric

Hearing Group	Response	Threshold, SPL$_{peak}$ (dB re 1 μPa)	Range (m)	
			First Strike	Highest Energy
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	213	180	872
	Recoverable injury	213	180	872
Basking shark	Mortality	213	180	872
	Recoverable injury	213	180	872
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	207	282	1,363
	Recoverable injury	207	282	1,363
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	282	1,363
	Recoverable injury	207	282	1,363
Sea Turtles	Mortality	207	282	1,363
Fish eggs and larvae	Mortality	207	282	1,363

Consecutive Piling – Monopile Wind Turbine Foundations

7.2.13 There is a potential during construction for the installation of two piles consecutively during a single 24-hour period. The potential cumulative SEL injury ranges for marine mammals and fish due to impact pile driving of piles are modelled as following the same piling schedules with phases occurring consecutively.

7.2.14 Distances are presented at which sound levels decrease to below PTS/AUD INJ and TTS threshold values in terms of cumulative SEL.

Table 7.33: Potential Marine Mammal Injury Ranges for Consecutive Pile Installation of Monopile Foundations, Based on the Southall *et al.* (2019) Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 µPa²s)	Range (m)	
		No ADD	15 min ADD
LF	PTS – 183 dB re 1 µPa²s	13,360	11,251
	TTS – 168 dB re 1 µPa²s	21,973	19,922
HF	PTS – 185 dB re 1 µPa²s	N/E	N/E
	TTS – 170 dB re 1 µPa²s	25	N/E
VHF	PTS – 155 dB re 1 µPa²s	1,993	646
	TTS – 140 dB re 1 µPa²s	16,407	15,118
PCW	PTS – 185 dB re 1 µPa²s	23	N/E
	TTS – 170 dB re 1 µPa²s	14,766	13,126
OCW	PTS – 203 dB re 1 µPa²s	N/E	N/E
	TTS – 188 dB re 1 µPa²s	N/E	N/E

Table 7.34: Potential Marine Mammal Injury Ranges for Consecutive Pile Installation of Monopile Foundations, Based on the NMFS (2024) Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 µPa²s)	Range (m)	
		No ADD	15 min ADD
LF	AUD INJ – 183 dB re 1 µPa²s	14,063	12,129
	TTS – 168 dB re 1 µPa²s	22,266	20,274
HF	AUD INJ – 193 dB re 1 µPa²s	N/E	N/E
	TTS – 178 dB re 1 µPa²s	528	N/E
VHF	AUD INJ – 159 dB re 1 µPa²s	2,462	1,173
	TTS – 144 dB re 1 µPa²s	17,579	16,172
PCW	AUD INJ – 183 dB re 1 µPa²s	470	N/E
	TTS – 168 dB re 1 µPa²s	17,461	15,938
OCW	AUD INJ – 185 dB re 1 µPa²s	11,719	10,548
	TTS – 170 dB re 1 µPa²s	21,973	20,625

Table 7.35: Potential Injury and Disturbance Ranges for Consecutive Monopile Installation Based on the Cumulative SEL Metric for Moving Fish (N/E – Threshold Not Exceeded)

Hearing Group	Response	Threshold, SEL (dB re 1 µPa²s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	22,266
Basking shark	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	19,805
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	206
	Recoverable injury	203	4,220
	TTS	186	22,266
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	1,114
	Recoverable injury	203	4,220
	TTS	186	22,266
Sea Turtles	Mortality	210	206
Fish eggs and larvae	Mortality	210	6,095
All Fish Groups	Disturbance	150 dB re 1µPa (rms)	60,451

Table 7.36: Potential Injury and Disturbance Ranges for Consecutive Monopile Installation Based on the Cumulative SEL Metric for Static Fish

Hearing Group	Response	Threshold, SEL (dB re 1 µPa²s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	2,052
	Recoverable injury	216	2,872
	TTS	186	25,000
Basking shark	Mortality	219	2,052
	Recoverable injury	216	2,872
	TTS	186	25,000
Group 2 Fish: Swim bladder not involved in	Mortality	210	6,095
	Recoverable injury	203	15,469

Hearing Group	Response	Threshold, SEL (dB re 1 µPa²s)	Range (m)
hearing (particle motion detection)	TTS	186	25,000
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	9,376
	Recoverable injury	203	15,469
	TTS	186	25,000
Sea Turtles	Mortality	210	6,095
Fish eggs and larvae	Mortality	210	6,095
All Fish Groups	Disturbance	150 dB re 1µPa (rms)	60,451

Consecutive Piling – Jacket Foundations

7.2.15 Distances are presented at which sound levels decrease to below PTS/TTS threshold values in terms of cumulative SEL.

Table 7.37: Potential Marine Mammal Injury Ranges for Consecutive Pile Installation of Jacket Piles, Based on the Southall *et al.* (2019) Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 µPa²s)	Range (m)	
		No ADD	**15 min ADD**
LF	PTS – 183 dB re 1 µPa²s	11,016	8,907
	TTS – 168 dB re 1 µPa²s	21,328	19,219
HF	PTS – 185 dB re 1 µPa²s	N/E	N/E
	TTS – 170 dB re 1 µPa²s	21	N/E
VHF	PTS – 155 dB re 1 µPa²s	997	N/E
	TTS – 140 dB re 1 µPa²s	15,762	14,473
PCW	PTS – 185 dB re 1 µPa²s	25	N/E
	TTS – 170 dB re 1 µPa²s	15,000	13,360
OCW	PTS – 203 dB re 1 µPa²s	N/E	N/E
	TTS – 188 dB re 1 µPa²s	14	N/E

Table 7.38: Potential Marine Mammal Injury Ranges for Consecutive Pile Installation of Jacket Piles, Based on the NMFS (2024) Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 µPa²s)	Range (m)	
		No ADD	**15 min ADD**
LF	AUD INJ – 183 dB re 1 µPa²s	11,719	9,610
	TTS – 168 dB re 1 µPa²s	21,504	19,453

Species/Group	Threshold, SEL (dB re 1 µPa^{2}s)	Range (m)	
		No ADD	15 min ADD
HF	AUD INJ – 193 dB re 1 µPa^{2}s	N/E	N/E
	TTS – 178 dB re 1 µPa^{2}s	821	N/E
VHF	AUD INJ – 159 dB re 1 µPa^{2}s	1,349	N/E
	TTS – 144 dB re 1 µPa^{2}s	16,875	15,469
PCW	AUD INJ – 183 dB re 1 µPa^{2}s	821	N/E
	TTS – 168 dB re 1 µPa^{2}s	18,282	16,699
OCW	AUD INJ – 185 dB re 1 µPa^{2}s	10,782	9,376
	TTS – 170 dB re 1 µPa^{2}s	21,797	20,450

Table 7.39: Potential Injury and Disturbance Ranges for Consecutive Jacket Pile Installation Based on the Cumulative SEL Metric for Moving Fish (N/E – Threshold Not Exceeded)

Hearing Group	Response	Threshold, SEL (dB re 1 µPa^{2}s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	20,977
Basking shark	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	17,579
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	13
	Recoverable injury	203	1,173
	TTS	186	20,977
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	96
	Recoverable injury	203	1,173
	TTS	186	20,977
Sea Turtles	Mortality	210	13
Fish eggs and larvae	Mortality	210	3,048
All Fish Groups	Disturbance	150 dB re 1µPa (rms)	55,359

Table 7.40: Potential Injury and Disturbance Ranges for Consecutive Jacket Pile Installation Based on the Cumulative SEL Metric for Static Fish

Hearing Group	Response	Threshold, SEL (dB re 1 µPa²s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	1,085
	Recoverable injury	216	1,554
	TTS	186	25,000
Basking shark	Mortality	219	1,085
	Recoverable injury	216	1,554
	TTS	186	25,000
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	3,048
	Recoverable injury	203	7,735
	TTS	186	25,000
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	4,102
	Recoverable injury	203	7,735
	TTS	186	25,000
Sea Turtles	Mortality	210	3,048
Fish eggs and larvae	Mortality	210	3,048
All Fish Groups	Disturbance	150 dB re 1µPa (rms)	55,359

Consecutive Piling - Monopile Foundations, Realistic Installation Scenario

7.2.16 Distances are presented at which sound levels decrease to below PTS/TTS threshold values in terms of cumulative SEL.

Table 7.41: Potential Marine Mammal Injury Ranges for the Realistic Consecutive Pile Installation of Monopile Foundations, Based on the Southall *et al.* (2019) Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 µPa²s)	Range (m)	
		No ADD	15 min ADD
LF	PTS – 183 dB re 1 µPa²s	13,126	11,133
	TTS – 168 dB re 1 µPa²s	21,973	19,922
HF	PTS – 185 dB re 1 µPa²s	N/E	N/E
	TTS – 170 dB re 1 µPa²s	25	N/E
VHF	PTS – 155 dB re 1 µPa²s	1,993	587
	TTS – 140 dB re 1 µPa²s	16,407	15,000
PCW	PTS – 185 dB re 1 µPa²s	23	N/E

Species/Group	Threshold, SEL (dB re 1 μPa^{2}s)	Range (m)	
		No ADD	15 min ADD
	TTS – 170 dB re 1 μPa^{2}s	14,532	12,891
OCW	PTS – 203 dB re 1 μPa^{2}s	N/E	N/E
	TTS – 188 dB re 1 μPa^{2}s	N/E	N/E

Table 7.42: Potential Marine Mammal Injury Ranges for the Realistic Consecutive Pile Installation of Monopile Foundations, Based on the NMFS (2024) Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 μPa^{2}s)	Range (m)	
		No ADD	15 min ADD
LF	AUD INJ – 183 dB re 1 μPa^{2}s	14,063	11,954
	TTS – 168 dB re 1 μPa^{2}s	22,266	20,274
HF	AUD INJ – 193 dB re 1 μPa^{2}s	N/E	N/E
	TTS – 178 dB re 1 μPa^{2}s	367	N/E
VHF	AUD INJ – 159 dB re 1 μPa^{2}s	2,403	1,056
	TTS – 144 dB re 1 μPa^{2}s	17,520	16,172
PCW	AUD INJ – 183 dB re 1 μPa^{2}s	411	N/E
	TTS – 168 dB re 1 μPa^{2}s	17,402	15,821
OCW	AUD INJ – 185 dB re 1 μPa^{2}s	11,719	10,313
	TTS – 170 dB re 1 μPa^{2}s	21,973	20,625

Table 7.43: Potential Injury and Disturbance Ranges for Consecutive Monopile Realistic Installation Based on the Cumulative SEL Metric for Moving Fish (N/E – Threshold Not Exceeded)

Hearing Group	Response	Threshold, SEL (dB re 1 μPa^{2}s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	22,149
Basking shark	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	19,688
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	118
	Recoverable injury	203	2,579
	TTS	186	22,149

Hearing Group	Response	Threshold, SEL (dB re 1 μPa^{2}s)	Range (m)
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	763
	Recoverable injury	203	2,579
	TTS	186	22,149
Sea Turtles	Mortality	210	118
Fish eggs and larvae	Mortality	210	2,696
All Fish Groups	Disturbance	150 dB re 1μPa (rms)	59,735

Table 7.44: Potential Injury and Disturbance Ranges for Consecutive Monopile Realistic Installation Based on the Cumulative SEL Metric for Static Fish

Hearing Group	Response	Threshold, SEL (dB re 1 μPa^{2}s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	1,407
	Recoverable injury	216	1,949
	TTS	186	25,000
Basking shark	Mortality	219	1,407
	Recoverable injury	216	1,949
	TTS	186	25,000
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	3,751
	Recoverable injury	203	10,313
	TTS	186	25,000
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	5,626
	Recoverable injury	203	10,313
	TTS	186	25,000
Sea Turtles	Mortality	210	3,751
Fish eggs and larvae	Mortality	210	3,751
All Fish Groups	Disturbance	150 dB re 1μPa (rms)	59,735

Concurrent Piling – Monopile Foundations

7.2.17 Construction may occur utilising two pile installation vessels operating concurrently. The potential cumulative SEL injury ranges for marine mammals and fish due to impact pile driving of piles are modelled as following the same piling plans with all phases starting at the same time. For injury the MDS is considered to be that of two adjacent piles, separated by a distance of 1 km due to the maximal overlap of sound propagation contours leading to the maximum generated sound levels. Conversely, for disturbance the maximum separation between two piling locations would lead to the larger area ensonified at any one time and therefore the greatest disturbance.

7.2.18 In this section, modelling of injury ranges has been undertaken for two adjacent piles. As for the single piling case, the MDS has been reported here.

7.2.19 Distances are presented at which sound levels decrease to below PTS/AUD INJ and TTS threshold values in terms of cumulative SEL.

Table 7.45: Potential Marine Mammal Injury Ranges for Concurrent Pile Installation of Monopile Foundations, With a Separation of 1 km, Based on the Southall *et al.* (2019) Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 μPa^{2}s)	Range (m)	
		No ADD	15 min ADD
LF	PTS – 183 dB re 1 μPa^{2}s	16,993	12,891
	TTS – 168 dB re 1 μPa^{2}s	23,613	20,684
HF	PTS – 185 dB re 1 μPa^{2}s	N/E	N/E
	TTS – 170 dB re 1 μPa^{2}s	440	N/E
VHF	PTS – 155 dB re 1 μPa^{2}s	5,626	1,759
	TTS – 140 dB re 1 μPa^{2}s	19,746	16,641
PCW	PTS – 185 dB re 1 μPa^{2}s	1,876	N/E
	TTS – 170 dB re 1 μPa^{2}s	18,985	15,235
OCW	PTS – 203 dB re 1 μPa^{2}s	N/E	N/E
	TTS – 188 dB re 1 μPa^{2}s	118	N/E

Table 7.46: Potential Marine Mammal Injury Ranges for Concurrent Pile Installation of Monopile Foundations, With a Separation of 1 km, Based on the NMFS (2024) Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 μPa^{2}s)	Range (m)	
		No ADD	15 min ADD
LF	AUD INJ – 183 dB re 1 μPa^{2}s	17,402	13,594
	TTS – 168 dB re 1 μPa^{2}s	23,789	20,977
HF	AUD INJ – 193 dB re 1 μPa^{2}s	N/E	N/E
	TTS – 178 dB re 1 μPa^{2}s	5,391	N/E
VHF	AUD INJ – 159 dB re 1 μPa^{2}s	6,798	2,579
	TTS – 144 dB re 1 μPa^{2}s	20,274	17,579
PCW	AUD INJ – 183 dB re 1 μPa^{2}s	5,626	N/E
	TTS – 168 dB re 1 μPa^{2}s	20,274	17,227

Species/Group	Threshold, SEL (dB re 1 µPa²s)	Range (m)	
		No ADD	15 min ADD
OCW	AUD INJ – 185 dB re 1 µPa²s	18,047	13,360
	TTS – 170 dB re 1 µPa²s	23,438	21,153

Table 7.47: Potential Injury and Disturbance Ranges for Concurrent Monopile Installation, With a Separation of 1 km, Based on the Cumulative SEL Metric for Moving Fish

Hearing Group	Response	Threshold, SEL (dB re 1 µPa²s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	5
	Recoverable injury	216	12
	TTS	186	23,086
Basking shark	Mortality	219	4
	Recoverable injury	216	6
	TTS	186	21,211
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	1,056
	Recoverable injury	203	7,969
	TTS	186	23,086
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	2,813
	Recoverable injury	203	7,969
	TTS	186	23,086
Sea Turtles	Mortality	210	1,056
Fish eggs and larvae	Mortality	210	5,860
All Fish Groups	Disturbance	150 dB re 1µPa (rms)	73,451

Table 7.48: Potential Injury and Disturbance Ranges for Concurrent Monopile Installation, With a Separation of 1 km, Based on the Cumulative SEL Metric for Static Fish

Hearing Group	Response	Threshold, SEL (dB re 1 µPa²s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	1,993
	Recoverable injury	216	2,813
	TTS	186	25,000
Basking shark	Mortality	219	1,993
	Recoverable injury	216	2,813
	TTS	186	25,000

Hearing Group	Response	Threshold, SEL (dB re 1 µPa²s)	Range (m)
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	5,860
	Recoverable injury	203	15,235
	TTS	186	25,000
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	9,141
	Recoverable injury	203	15,235
	TTS	186	25,000
Sea Turtles	Mortality	210	5,860
Fish eggs and larvae	Mortality	210	5,860
All Fish Groups	Disturbance	150 dB re 1µPa (rms)	73,451

Concurrent Piling – Jacket Foundations

7.2.20 Distances are presented at which sound levels decrease to below PTS/AUD INJ and TTS threshold values in terms of cumulative SEL.

Table 7.49: Potential Marine Mammal Injury Ranges for Concurrent Pile Installation of Jacket Piles, With a Separation of 1 km, Based on the Southall *et al.* (2019) Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 µPa²s)	Range (m)	
		No ADD	**15 min ADD**
LF	PTS – 183 dB re 1 µPa²s	16,290	11,954
	TTS – 168 dB re 1 µPa²s	23,321	20,274
HF	PTS – 185 dB re 1 µPa²s	N/E	N/E
	TTS – 170 dB re 1 µPa²s	235	N/E
VHF	PTS – 155 dB re 1 µPa²s	4,923	938
	TTS – 140 dB re 1 µPa²s	19,922	16,993
PCW	PTS – 185 dB re 1 µPa²s	3,282	N/E
	TTS – 170 dB re 1 µPa²s	19,688	16,407
OCW	PTS – 203 dB re 1 µPa²s	N/E	N/E
	TTS – 188 dB re 1 µPa²s	880	N/E

Table 7.50: Potential Marine Mammal Injury Ranges for Concurrent Pile Installation of Jacket Piles, With a Separation of 1 km, Based on the NMFS (2024) Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 µPa²s)	Range (m)	
		No ADD	15 min ADD
LF	AUD INJ – 183 dB re 1 µPa²s	16,641	12,422
	TTS – 168 dB re 1 µPa²s	23,496	20,508
HF	AUD INJ – 193 dB re 1 µPa²s	10	N/E
	TTS – 178 dB re 1 µPa²s	8,438	2,110
VHF	AUD INJ – 159 dB re 1 µPa²s	6,329	1,876
	TTS – 144 dB re 1 µPa²s	20,332	17,696
PCW	AUD INJ – 183 dB re 1 µPa²s	8,907	2,345
	TTS – 168 dB re 1 µPa²s	21,153	18,282
OCW	AUD INJ – 185 dB re 1 µPa²s	18,282	13,829
	TTS – 170 dB re 1 µPa²s	23,584	21,270

Table 7.51: Potential Injury and Disturbance Ranges for Concurrent Jacket Pile Installation, With a Separation of 1 km, Based on the Cumulative SEL Metric for Moving Fish (N/E – Threshold Not Exceeded)

Hearing Group	Response	Threshold, SEL (dB re 1 µPa²s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	22,559
Basking shark	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	20,274
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	206
	Recoverable injury	203	4,220
	TTS	186	22,559
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily	Mortality	207	1,056
	Recoverable injury	203	4,220
	TTS	186	22,559

Hearing Group	Response	Threshold, SEL (dB re 1 μPa²s)	Range (m)
pressure detection)			
Sea Turtles	Mortality	210	206
Fish eggs and larvae	Mortality	210	4,337
All Fish Groups	Disturbance	150 dB re 1μPa (rms)	70,356

Table 7.52: Potential Injury and Disturbance Ranges for Concurrent Jacket Pile Installation, With a Separation of 1 km, Based on the Cumulative SEL Metric for Static Fish

Hearing Group	Response	Threshold, SEL (dB re 1 μPa²s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	1,612
	Recoverable injury	216	2,286
	TTS	186	25,000
Basking shark	Mortality	219	1,612
	Recoverable injury	216	2,286
	TTS	186	25,000
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	4,337
	Recoverable injury	203	11,954
	TTS	186	25,000
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	7,032
	Recoverable injury	203	11,954
	TTS	186	25,000
Sea Turtles	Mortality	210	4,337
Fish eggs and larvae	Mortality	210	4,337
All Fish Groups	Disturbance	150 dB re 1μPa (rms)	70,356

Concurrent Piling – Monopile Foundations, Realistic Installation Scenario

7.2.21 Distances are presented at which sound levels decrease to below PTS/AUD INJ and TTS threshold values in terms of cumulative SEL.

Table 7.53: Potential Marine Mammal Injury Ranges for the Concurrent Realistic Pile Installation of Monopile Foundations, With a Separation of 1 km, Based on the Southall *et al.* (2019) Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 µPa²s)	Range (m)	
		No ADD	15 min ADD
LF	PTS – 183 dB re 1 µPa²s	16,407	11,954
	TTS – 168 dB re 1 µPa²s	23,379	20,274
HF	PTS – 185 dB re 1 µPa²s	N/E	N/E
	TTS – 170 dB re 1 µPa²s	221	N/E
VHF	PTS – 155 dB re 1 µPa²s	4,571	1,056
	TTS – 140 dB re 1 µPa²s	19,219	15,938
PCW	PTS – 185 dB re 1 µPa²s	1,056	N/E
	TTS – 170 dB re 1 µPa²s	18,399	14,063
OCW	PTS – 203 dB re 1 µPa²s	N/E	N/E
	TTS – 188 dB re 1 µPa²s	17	N/E

Table 7.54: Potential Marine Mammal Injury Ranges for the Concurrent Realistic Pile Installation of Monopile Foundations, With a Separation of 1 km, Based on the NMFS (2024) Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 µPa²s)	Range (m)	
		No ADD	15 min ADD
LF	AUD INJ – 183 dB re 1 µPa²s	16,875	12,832
	TTS – 168 dB re 1 µPa²s	23,598	20,625
HF	AUD INJ – 193 dB re 1 µPa²s	N/E	N/E
	TTS – 178 dB re 1 µPa²s	2,579	N/E
VHF	AUD INJ – 159 dB re 1 µPa²s	5,626	1,700
	TTS – 144 dB re 1 µPa²s	19,864	16,875
PCW	AUD INJ – 183 dB re 1 µPa²s	3,751	N/E
	TTS – 168 dB re 1 µPa²s	19,805	16,582
OCW	AUD INJ – 185 dB re 1 µPa²s	16,875	11,719
	TTS – 170 dB re 1 µPa²s	23,057	20,874

Table 7.55: Potential Injury and Disturbance Ranges for Concurrent Monopile Realistic Installation, With a Separation of 1 km, Based on the Cumulative SEL Metric for Moving Fish (N/E – Threshold Not Exceeded)

Hearing Group	Response	Threshold, SEL (dB re 1 μPa²s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	22,852
Basking shark	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	20,830
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	587
	Recoverable injury	203	4,923
	TTS	186	22,852
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	1,642
	Recoverable injury	203	4,923
	TTS	186	22,852
Sea Turtles	Mortality	210	587
Fish eggs and larvae	Mortality	210	3,399
All Fish Groups	Disturbance	150 dB re 1μPa (rms)	72,395

Table 7.56: Potential Injury and Disturbance Ranges for Concurrent Monopile Realistic Installation, With a Separation of 1 km, Based on the Cumulative SEL Metric for Static Fish

Hearing Group	Response	Threshold, SEL (dB re 1 μPa²s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	1,261
	Recoverable injury	216	1,759
	TTS	186	25,000
Basking shark	Mortality	219	1,261
	Recoverable injury	216	1,759
	TTS	186	25,000

Hearing Group	Response	Threshold, SEL (dB re 1 µPa²s)	Range (m)
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	3,399
	Recoverable injury	203	8,907
	TTS	186	25,000
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	4,806
	Recoverable injury	203	8,907
	TTS	186	25,000
Sea Turtles	Mortality	210	3,399
Fish eggs and larvae	Mortality	210	3,399
All Fish Groups	Disturbance	150 dB re 1µPa (rms)	72,395

Other Construction Phase Sources

7.2.22 The potential impact ranges from other construction related activities (such as cable trenching, cable laying and supporting jack up rigs) on different marine mammal groups are presented in Table 7.57 and Table 7.58 for the Southall *et al.* (2019) and NMFS (2024) respectively. The potential impact ranges for fish are presented in Table 7.59.

Table 7.57: Estimated PTS, TTS and Disturbance Ranges From Other Construction Phase Sources for Marine Mammals, Assessed Against the Southall *et al.* (2019) Thresholds (N/E – Threshold Not Exceeded)

Source	Potential impact range (m)										
	LF		HF		VHF		PCW		OCW		All Groups
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
Cable laying	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	4,540
Cable trenching/ cutting	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	4,493
Jack up rig	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E
Drilled piling	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	407

Table 7.58: Estimated AUD INJ, TTS and Disturbance Ranges From Other Construction Phase Sources for Marine Mammals, Assessed Against the NMFS, (2024) Thresholds (N/E – Threshold Not Exceeded)

Source	Potential impact range (m)										
	LF		HF		VHF		PCW		OCW		All Groups
	TTS	AUD INJ	TTS	AUD INJ	TTS	AUD INJ	TTS	AUD INJ	TTS	PTS AUD INJ	Disturbance
Cable laying	N/E	N/E	N/E	N/E	54	N/E	N/E	N/E	N/E	N/E	4,540
Cable trenching/ cutting	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	4,493
Jack up rig	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E
Drilled piling	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	407

Table 7.59: Estimated Recoverable Injury and TTS Ranges for Other Construction Phase Source for Group 3 and 4 Fish (N/E – Threshold Not Exceeded)

Source	Potential Injury Zone Radius (m)	
	Recoverable injury 170 dB re 1 µPa (rms) for 48 hrs	TTS 158 dB re 1 µPa (rms) for 12 hrs
Cable laying	N/E	16
Cable trenching/cutting	N/E	8
Jack up rig	N/E	N/E
Drilled piling	N/E	N/E

7.3 Operation and Maintenance

7.3.1 Structure-borne underwater sound from operational offshore Wind Turbines derives in the main from the moving mechanical parts in the nacelle, which is generally found to be of frequencies below 1 kHz (Pangerc *et al.*, 2016).

7.3.2 Vibration of the Wind Turbine's gear box and generator is transmitted down the tower and radiated as sound from the tower wall. Sound radiation by surface waves is difficult to quantitatively predict, in particular for the boundary regions, and is highly dependent upon the conditions of both the Wind Turbine itself, including generator and tower condition, and on the seawater conditions. There have been few empirical investigations of operational OWFs, and as such measurement data is also scarce. Due to the general lack of investigation into the subject, Wind Turbines of a variety of foundation types have been included in this section.

7.3.3 The distances and exposures of marine mammals and fish reported by studies that investigate the impact of operational OWFs present a range of values, but the majority conclude that in the order of hundreds of metres distance from the Wind Turbines, sound levels would likely be audible but not at a level sufficient to cause injury or behavioural changes (see Table 7.60 for references). Norro *et al.* (2011) compared measurements of a range of different foundation types and Wind Turbine ratings in the Belgian part of the North Sea, as well as comparing those to other European waters. A summary of these studies is shown in Table 7.60. The authors found a slight increase in SPL compared to the ambient sound measured before the construction of the wind farms. They concluded that even the highest increases found within the dataset (20 to 25 dB re 1 µPa) are unlikely to cause a significant impact and are significantly lower than those during the construction phase. They do however caution that this sound is of a much longer duration over the operational lifespan of the wind farm, and that little is known of the long-term impacts to aquatic life.

Table 7.60: Desktop Study of Operational Noise From Fixed Wind Turbines

Paper	Turbine	Foundation Type	Location	Notes
Betke, 2006	Vestas V80-2 MW 70 m hub height	Monopiles	Horns Rev	Peak at 118 dB re 1 µPa @ 150 Hz Measured at 100 m
Nedwell *et al.*, 2007	Vestas V80-2 MW	Monopiles	North Hoyle	Inside wind farm 128 dB re 1 µPa Outside 120 dB re. 1 µPa No tonal components
	Vestas V80-2 MW 68 m hub height	Steel monopiles 4.8 m diameter	Scroby Sands	Inside wind farm 130 dB re 1 µPa Outside 132 dB re. 1 µPa States that the background level is higher inside the wind farm, perhaps due to shallow water No tonal component
	Vestas V90-3 MW 70 m hub height	Monopiles	Kentish Flats	Inside wind farm 114 dB re 1 µPa Outside 113 dB re. 1 µPa Clear tonal components dependent upon separation
	Vestas V90-3 MW 75 m hub height	Steel monopiles 4.75 m diameter	Barrow	Inside wind farm 124 dB re 1 µPa Outside 122 dB re. 1 µPa No tonal components. No consistent relationship between distance and level, thought due to wind sound
Norro *et al.*, 2011	Senvion (Repower) 5 MW 95 m hub height	Gravity base	Thorntonbank	Increase of 8 dB above background

Paper	Turbine	Foundation Type	Location	Notes
	Vestas V90-3 MW 72 m hub height	Steel monopile foundations	Belwind Bligh Bank	Increase of 20 dB to 25 dB above background
Marmo *et al*,. (2013)	6 MW	Monopile, jacket and gravity foundations	Scottish Waters	Monopile foundations produced highest SPL at lower frequencies (<200 Hz), with levels of 149 dB re 1 µPa within 5m of the foundation at 560 Hz
Jansen and De Jong, 2016	Vestas V80-2 MW	Steel monopiles 4 m diameter	Princess Amalia wind farm	Noted to be next to busy shipping lanes - no difference in level between 100 m and 3.8 km
Pangerc *et al.*, 2016	Siemens SWT-3.6-120	Monopile	UK waters (specific site not named)	"*The broadband sound pressure level measured at 100 m was around 126 dB re 1 µPa. This reduced to around 117 dB at 800 m, indicating attenuation with distance but also showing detectability at relatively large ranges.*"
Yoon *et al.*, 2023	3 MW	Jacket-type foundations	Southwest OWF, Korea	Measured operational noise over 10 days – found tonal frequencies varying with rotor speed, with peak levels at around 198 Hz increasing by around 20 dB at rated rotor speed
Holme *et al.*, 2024	6.3 MW and 8.3 MW	Not specified	North Sea	Found no significant relation between broadband underwater noise levels and turbine activity up to 70 m from Wind Turbines
Botero-Bolivar *et al.*, 2025	5 MW, 10 MW and 22 MW	Not specified	Various	Modelled underwater aerodynamic noise for large Wind Turbines – found that noise emissions from large offshore farms could pose environmental concerns for marine life (a group of 100 Wind Turbines can raise underwater noise levels by about 15dB for 5 MW Wind Turbines and up to 25 dB for 22 MW Wind Turbines)

7.4 Vessels (All Phases)

7.4.1 Estimated ranges for injury to marine mammals due to the continuous sound sources (vessels) during different phases of the construction and O&M are presented below.

7.4.2 It should be borne in mind that there is a considerable degree of uncertainty and variability in the onset of disturbance and therefore any disturbance ranges should be treated as potentially over precautionary. Another important consideration is that vessels and construction sound will be temporary and transitory, as opposed to permanent and fixed. In this respect, construction sound is unlikely to differ significantly from vessel traffic already in the area.

7.4.3 The estimated median ranges for onset of TTS and PTS/AUD INJ for different marine mammal groups exposure to the sound characteristics of different vessel traffic are shown in Table 7.61 and Table 7.62 for marine mammals and in Table 7.63 for fish. The exposure metrics for different marine mammal and swim speeds (as detailed in Table 6.1) were employed.

Table 7.61: Estimated PTS and TTS Ranges From Vessels for Marine Mammals, Assessed Against the Southall *et al.* (2019) Thresholds (N/E – Threshold Not Exceeded)

Source/ Vessel	**Range (m)**										
	LF		**HF**		**VHF**		**PCW**		**OCW**		**All Groups**
	TTS	**PTS**	**TTS**	**PTS**	**TTS**	**PTS**	**TTS**	**PTS**	**TTS**	**PTS**	**Disturbance**
Sandwave clearance	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	4,743
Boulder clearance, offshore construction vessel	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	474
Installation vessel, construction vessel (DP)	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	4,743
Jack up rig	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E
Tug/anchor handlers	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	4,436
Rock placement vessel and cable installation vessels	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	4,743
Guard vessels	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	4,436
Survey vessel and support vessels	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	5,597
CTV	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	5,597

Source/ Vessel	Range (m)										
	LF		HF		VHF		PCW		OCW		All Groups
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
Scour/ Cable Protection/ Seabed Preparation/ Installation Vessels	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	5,597

Table 7.62: Estimated AUD INJ and TTS Ranges From Vessels for Marine Mammals, Assessed Against the NMFS, (2024) Thresholds (N/E – Threshold not Exceeded)

Source/Vessel	Range (m)										
	LF		HF		VHF		PCW		OCW		All Groups
	TTS	AUD INJ	TTS	AUD INJ	TTS	AUD INJ	TTS	AUD INJ	TTS	AUD INJ	Disturbance
Sandwave clearance	N/E	N/E	N/E	N/E	54	N/E	N/E	N/E	N/E	N/E	4,743
Boulder clearance, offshore construction vessel	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	474
Installation vessel, construction vessel (DP)	N/E	N/E	N/E	N/E	54	N/E	N/E	N/E	N/E	N/E	4,743
Jack up rig	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E
Tug/anchor handlers	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	4,436
Rock placement vessel and cable installation vessels	N/E	N/E	N/E	N/E	54	N/E	N/E	N/E	N/E	N/E	4,743
Guard vessels	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	4,436
Survey vessel and support vessels	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	5,597
CTV	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	5,597
Scour/Cable Protection/ Seabed Preparation/	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	5,597

Source/Vessel	**Range (m)**										
	LF		**HF**		**VHF**		**PCW**		**OCW**		**All Groups**
	TTS	**AUD INJ**	**TTS**	**AUD INJ**	**TTS**	**AUD INJ**	**TTS**	**AUD INJ**	**TTS**	**AUD INJ**	**Disturbance**
Installation Vessels											

Table 7.63: Estimated Recoverable Injury and TTS ranges from Vessels for Group 3 and 4 Fish (N/E – Threshold not Exceeded)

Source	**Injury Zone Radius (m)**	
	Recoverable injury **170 dB re 1 µPa (rms) for 48 hrs**	**TTS** **158 dB re 1 µPa (rms) for 12 hrs**
Sandwave clearance	N/E	16
Construction vessel (DP)	N/E	N/E
Installation vessel, construction vessel (DP)	N/E	16
Jack up rig	N/E	N/E
Tug/anchor handlers	N/E	9
Rock placement vessel and cable installation vessels	N/E	16
Guard vessels	N/E	9
Survey vessel and support vessels	N/E	11
CTV	N/E	11
Scour/Cable Protection/ Seabed Preparation/ Installation Vessels	N/E	11

8 Particle Motion

8.1 Introduction

8.1.1 This Subsea Noise Technical Report provides an analysis of the effects of sound on marine species. However, there are uncertainties in relation to the presence of compression and interface waves at the water/ground substrate boundary during piling, and the potential effect on fish and invertebrates. Although the risk of injury to fish with and without swim bladders is addressed through the use of SEL and SPL_{peak} pressure thresholds (Popper *et al.*, 2014), it is possible that some fish are only sensitive to particle motion. These fish could experience high levels of particle motion in close proximity to piling. However, the Popper *et al.* (2014) paper primarily addresses high amplitude sounds and high dynamic pressure, rather than particle motion.

8.1.2 The majority of measurements during piling for OWFs are undertaken using hydrophones in the water column which includes contributions from both direct radiated sound from the pile into the water, as well as ground borne radiated sound, and there are uncertainties with respect to how effectively the ground borne energy couples into the sea. If measurements were taken in an evanescent (non-propagating) field then high particle motion would not be reflected in the associated dynamic pressure measurements, particularly if those measurements were taken in shallow water and the energy is below the cut off frequency. Consequently, it is possible that the effects on benthic fauna close to the pile could be under-estimated, particularly for species primarily sensitive to vibration of the seafloor sediment.

8.1.3 To put this issue into perspective, in Popper *et al.* (2014), the authors state that "*extreme levels of particle motion arising from various impulsive sources may also have the potential to injure tissues, although this has yet to be demonstrated for any source*". It would therefore appear that there is currently a lack of criteria for (or detailed measurements of) particle motion during piling operations for this issue to be currently assessed. Thus, in terms of potential damage to fish, Volume 2, Chapter 9: Fish and Shellfish Ecology has addressed the impact as far as is practicable with the existing state of knowledge, based primarily on exposure to sound pressure.

8.1.4 The purpose of this section is to provide an overview of the acoustic aspects of particle motion. Potential effects on marine species are dealt with in the marine ecology topic chapters of the EIA (predominantly Volume 2, Chapter 9: Fish and Shellfish Ecology and Volume 2, Chapter 13: Commercial Fisheries).

8.2 Overview of Particle Motion

8.2.1 Particle motion is defined as the motion of an infinitesimally small part of the medium relative to the rest of the medium, that is caused by a sound wave (Popper *et al.*, 2014). Unlike the pressure variation caused by the wave, which is a scalar quantity and therefore has no direction, the particle motion is a three-dimensional (3-D) vector quantity (i.e. directional). Particle motion can be described by the velocity, acceleration, and displacement of the particle. These are related by the following equations (Nedelec *et al.*, 2016):

$$a = u \times 2\pi f$$

$$\xi = \frac{u}{2\pi f}$$

where a = acceleration (m/s^2), u = particle velocity (m/s), $2\pi f$ = angular frequency, and ξ = displacement (m).

8.2.2 In the same way as the unit for sound pressure is referenced to the Pa, likewise in the case of particle motion, the dB unit is referenced to either the displacement, velocity or acceleration as appropriate. Therefore, units will be in the form of dB re m, m/s or m/s^2.

8.2.3 Particle motion can also be related to measured sound pressure and can be approximated from the sound pressure in simplified circumstances such as a plane wave. For a plane wave, or a wave for which a plane wave is a good approximation of its behaviour (a wave in the free field), the following relationship holds:

$$u = \frac{P}{\rho c}$$

where P = acoustic pressure (Pa), ρ = density of the water (kgm^{-3}), and c =sound speed (ms^{-1}). The quantity ρc is also known as the characteristic acoustic impedance.

8.2.4 The following relationship holds true for the near field of a point source. The source must be far from any boundaries that could lead to the wave not propagating due to cut off frequency, or reflections that could interfere with the propagation of the wave:

$$\xi = \frac{p}{2\pi f \rho c}\left[1 + \left(\frac{\lambda}{2\pi r}\right)^2\right]^{1/2}$$

where r = distance to sound source (m). All other symbols are consistent throughout the equations presented here.

8.2.5 A plane wave is a wave that can be considered to have a flat wavefront. This generally occurs far from both the source of the wave and any sources of reflected waves. The term 'far' is relative to the wavelength of the sound and the size of the source as both will change the distance at which the wave can be considered a plane wave. In shallow coastal and sea-shelf habitats these far field conditions are not often met at the acoustic frequencies relevant to fish and invertebrates. This means that there is usually not a reliable way to derive particle motion from sound pressure measurement in these habitats. Technically a relationship between particle motion and sound pressure can be derived for more complicated wavefronts (e.g. by assuming that the wavefront has an idealised geometry). However, this is not necessarily reliable, and, in most cases where plane waves cannot be assumed, the only reliable solution is to measure directly (Nedelec *et al.*, 2016).

8.2.6 In those situations where it is appropriate to assume that waves generated by a monopole are plane waves (i.e. in the acoustic far field), it is possible to approximate the magnitude of the particle motion. It is important to understand where it is appropriate to make these assumptions. Spherical spreading occurs when sound propagates from a source without any interference and the applicability of the plane wave assumption is based on the frequency of interest and the waveguide (i.e. the duct formed by the surface and bottom of the water column), which encapsulates the water depth, distance to source, source type, and the sound speed in water and sediment. The values that are key for this assumption are the wavelength of the lowest frequency of interest (λ) and the cut off frequency (f_0) based on the waveguide. These values can be calculated from the following equations (Nedelec *et al.*, 2021):

$$\lambda = \frac{c_w}{f}$$

$$f_0 = \frac{c_w}{4D\sqrt{1-\left(\frac{c_w}{c_b}\right)^2}}$$

where f_0 is the cut off frequency, D is the water depth, c_w is the sound speed in water, and c_b is the sound speed in sediment.

8.2.7 If the distance to the sound source is greater than one wavelength and the lowest frequency is greater than the cut off frequency, then it is possible to estimate the magnitude of the particle motion from an SPL measurement. However, it must be noted that this only applies to a travelling plane wave and as such the signal to noise ratio must be high enough to consider other sounds negligible (Nedelec *et al.*, 2021).

8.2.8 It should also be borne in mind that sound produced from piling is, in reality, not a monopole source. The pile acts as a line-source throughout the water column and in the sediment and produces a complex Mach wavefront. Consequently, the above simplifications may not be appropriate to assess the particle motion produced by piling.

8.3 Hearing in Fish and Invertebrates

8.3.1 All fish, and many invertebrates, detect the particle motion of a sound wave with mechanosensory organs such as the inner ear, statocyst or lateral line (Nedelec *et al.*, 2021). The ability to hear their surroundings gives fish, and many invertebrates, an abundance of information about their environment. This ability is unaffected by light levels and is omnidirectional, allowing for the most abundant information about the environment. Of all the senses that fish, and many invertebrates, use to assess their surroundings, hearing is the most versatile in a marine environment. In particular, their hearing is able to give rapid feedback with relatively long distance 3-D information (Popper and Hawkins, 2019).

8.3.2 The detection of sound and characterisation of the immediate soundscape is something that is key to the way that fish and many vertebrates live. This ability allows them to detect the direction of predators, and subsequently avoid them, or detect prey and move towards them. Furthermore, this ability can be used to recognise others within their own species and select a mate. Although not all fishes, or invertebrates, produce sound for communication, they are all known to use it for awareness of their surroundings. As such, any interference with this ability could impact the survival of the fish (Popper and Hawkins, 2019).

8.3.3 There have been several studies into the hearing capabilities of fish and invertebrates. However, very few of them have used conditions that are truly representative of the environment that they would encounter in open water. This is due to tank conditions or methodologies used to observe them in an offshore environment. Furthermore, few of these studies have focused on particle motion specifically (Popper and Hawkins, 2019).

8.3.4 Taking this into account it is possible to establish a reasonable assumption for hearing range of various species. Most fish appear to be able to detect sound that falls between 10 Hz and 500 Hz. If the fish or invertebrates are capable of detecting sound pressure, then they may be able to detect sounds at higher frequencies up to approximately 1 kHz or more. There are also a small number of fish that are capable of hearing between 3 Hz and 4 kHz due to various specialisations that they have (Popper and Hawkins, 2019). The values presented here are the upper and lower estimates of each range, there is a degree of variability in each of the values. This is in part due to the complexity of the sound field in a tank or enclosure (Popper *et al.*, 2019). Likewise, invertebrates are also typically sensitive to lower frequencies (Nedelec *et al.*, 2016).

8.4 Effects of Sound and Particle Motion

8.4.1 Potential effects of sound pressure and particle motion on fishes and invertebrates can be summarised as follows (Popper *et al.*, 2014; Popper and Hawkins, 2018; Nedelec *et al.*, 2016):

- death and injury;
- exposure to very high amplitude sounds can cause injury and death in fish and other marine species. In addition, the effect of sudden pressure changes (barotrauma) must be considered:
    - barotrauma is the tissue injury that is caused by a sudden change in pressure resulting in a shock wave effect (e.g. primarily caused by explosions, as opposed to non-shock wave propagation as is typically caused by impulsive piling). Rapid pressure changes can cause the gases in blood to come out of solution and can cause rapid movement in the swim bladder. This can damage other organs and even rupture the swim bladder;
    - sudden changes in pressure (such as that from impulsive sounds) are more likely to cause damage than gradual ones; and
    - extreme levels of particle motion may have the potential to cause tissue damage, but this has not been proven yet (Popper *et al.*, 2014).

- effects on hearing:
    - hearing loss can be permanent or temporary (PTS and TTS) with PTS being caused by damage to the tissue in the auditory pathway (including the swim bladder);
    - TTS results from temporary damage to the hairs in the inner ear or to the auditory nerves. In fish (unlike in mammals) the hairs of the inner ear are constantly added and replaced if damaged. Therefore, loss of hearing due to damage to these hairs may be mitigated over time in fish;
    - while experiencing TTS, fish may have a decrease in fitness in terms of communication, detecting predators or prey, and/or assessing their environment; and
    - masking is an impairment with respect to the relevant sound sources normally detected within the soundscape. The consequences of masking are not fully understood for fish. It is likely that higher levels of masking occur with a higher sound level from the masker.
- effects on behaviour:
    - it is possible that anthropogenic sound will have a detrimental effect on the communication of species between conspecifics, it may also hinder their identification of predator and prey;
    - there have been a variety of behavioural reactions observed from fish, including changes in swimming patterns and startle reactions. These reactions may habituate over repeated exposure to the sound; and
    - there has been very limited research carried out to date in relation to the effects of particle motion on marine invertebrates (Popper and Hawkins, 2018). However, they are expected to have the same types of effect even if the severity is unclear.

8.4.2 Popper *et al.* (2014) categorised fish species into the following identifiable groups:

- fish with no swim bladder or other gas chamber. These fish are less susceptible to barotrauma and only detect particle motion, however, some barotrauma may occur from exposure to sound pressure;
- fish with swim bladders in which hearing does not involve the swim bladder or some other gas volume. These species again only detect particle motion; however, they are susceptible to barotrauma due to the presence of the swim bladder;
- fish in which the swim bladder (or other gas volume) is involved in hearing. These species detect sound pressure as well as particle motion and are susceptible to barotrauma. The frequency sensitivity range of this group is higher than the other groups due to the ability to detect the pressure component of the sound signal as well as the particle motion; and
- fish eggs and larvae.

8.4.3 These groups are known to be able to detect particle motion. However, it is also likely that marine invertebrates are able to detect particle motion (Popper and Hawkins, 2018). Furthermore, some marine invertebrates can detect the vibrations directly from the substrate. This makes them susceptible not only to the particle motion in the water but also the rolling waves, and associated particle motion, in the substrate. It has been observed that benthic marine invertebrates respond directly to anthropogenic sound that has been generated in the substrate or very close to its surface (Hawkins *et al.*, 2021; Aimon *et al.*, 2021). This is particularly important for construction processes like piling that generate a large amount of sound into the substrate. The repercussions of this are that offshore construction activity may affect the benthic habitat, and many benthic invertebrates have a key role in how the substrate is structured. Considerable disturbance of these creatures for a prolonged period could affect habitat quality in addition to any potential impacts associated with sound pressure. It has also been suggested that some species use the sound that travels through the substrate to communicate or to find food sources, loud sounds that mask these sounds could make it difficult for them to operate normally (Popper and Hawkins, 2018).

8.4.4 There have been several studies into the hearing abilities of fish for a relatively small number of species. From these studies, the upper limit of detection for particle motion was found to be between 200 Hz and 400 Hz and the lower limit was 0.1 Hz (Sigray and Anderson, 2011). It is considered likely that all teleost fish have a similar extent of ability to detect particle motion (Radford *et al.*, 2012). Elasmobranchs are also considered to have a similar range of detection for particle motion. For piling, specifically, it is currently considered that most fish would be able to detect particle motion from 750 m away (Thomsen *et al.*, 2015). Marine invertebrates are generally not considered to be sensitive to the pressure wave component of sound as they lack an air filled space in their bodies. Research still needs to be carried out to understand the hearing capabilities of marine invertebrates. The research that has been undertaken so far has primarily focused on crustaceans and molluscs. A need has been identified to develop species specific audiograms to improve the understanding of the detection thresholds.

8.4.5 Hammar *et al.* (2014) discussed the impact of the Kattegat OWF (offshore Sweden) on Atlantic cod in the region. Estimates of operational sound pressure were predicted as 150 dB re 1μPa (rms) at 1 m for the 6 MW Wind Turbines and 250 dB re 1 μPa (rms) for the pile driving based on measurements on the Burbo Bank OWF taken by Parvin and Nedwell (2006). Using these estimates Hammar *et al.* (2014) established that developed Atlantic cod were likely to suffer physical injury within several hundred metres of pile driving. However, studies have shown that fish often group around operational Wind Turbines (Sigray and Andersson, 2011; Engås *et al.*, 1995; Wahlberg and Westerberg, 2005). This suggests that operational sound is not enough to cause them to vacate the area, however it is not clear if it results in higher stress levels in fish in the area.

8.5 Potential Range of Effects Due to Particle Motion

8.5.1 Due to the current state of understanding and existing (validated) modelling methodologies it is not considered feasible at this time to provide a quantitative assessment of the effects of particle motion on marine species for the Proposed Development.

8.5.2 Predicting the levels of particle motion from anthropogenic sound sources is difficult. There is a small amount of measured data available on which to base such predictions and some of these data are not necessarily applicable to full scale industrial procedures such as installation of Wind Turbine foundations. The measurements that do exist mostly come from small scale tank testing. Some of this testing has been conducted in flooded dock style locations with small scale piles. Other recordings have used playback speakers to generate a simulated piling sound (Roberts *et al.*, 2016; Ceraulo *et al.*, 2016). There is some debate about the validity of comparing measurements from tank tests or from playback speakers to full scale piling operations, as the way that particles move within a tank or smaller scale system is different to the full scale in the open ocean. Furthermore, the way that a speaker will agitate the particles is different to that of a cylindrical pile with an exposed length in the water column and sediment. However, there is one commonality between all measurements so far: the particle motion attenuates rapidly close to the source and more slowly further from it (Mueller-Blenkle *et al.*, 2010).

8.5.3 One such experiment was studied by Ceraulo *et al.* (2016), which consisted of measurements during piling at several locations within a flooded dock that incorporated a simulated seabed layer (approximately 3.5 m thick). This allowed the piling to be measured from different ranges. Through this experiment it was found that the sound propagation was close to cylindrical in nature. The levels of particle motion (particle velocity) were found to be 102 dB re 1 nm/s at a distance of 2 m from the pile and this dropped to 86 dB re 1 nm/s at 30 m. There was an interesting observation that the pressure wave appeared to have a cut off frequency at 400 Hz for shallow water and 300 Hz for deep water, although the particle motion does not share this cut off. The study was able to confirm that there is a roughly linear relation between particle motion and pressure although it also found that the particle motion levels were higher than expected.

8.5.4 An added complication in predicting particle motion is the propagation of sound through the substrate. This is particularly prominent in piling operations as the pile being driven into the ground will generate considerable waves through the substrate. This particle motion can impact the benthic species in the area due to behavioural reactions and potential injury. This has been identified as an area that requires more research and should be monitored alongside particle motion within the water column itself. Furthermore, the waves passing through the substrate can add to those in the water column, making the sound field in the water more complex (Mueller-Blenkle *et al.*, 2010).

8.5.5 A study by Thomsen *et al.* (2015) investigated particle motion around the installation of piles at offshore wind sites. The study found that higher hammer energies elicited higher levels of particle motion and that particle motion levels at 750 m from the pile were higher than baseline ambient levels throughout the frequency spectrum, except at very low frequencies. Thomsen *et al.* (2015) showed that with mitigation (a bubble curtain) turned on however, particle motion levels reduced considerably. It should be noted that the range cited of 750 m was likely due to the regulatory requirement for monitoring at 750 m from a pile and this number is therefore somewhat arbitrary in terms of the potential range of effect for particle motion (i.e. it is the most common measurement range for sound pressure rather than being the range over which particle motion effects were thought likely to occur).

8.5.6 Nevertheless, the study concluded that, for most fish, particle motion levels at 750 m are high enough to be detected during pile driving of even a mitigated pile. However, for elasmobranchs, the study concluded that detectability of mitigated piles is likely restricted to relatively short ranges from the source depending on the ambient sound in the area. For invertebrates the study concluded that there is even less information on how they perceive particle motion, but the Thomsen *et al.* (2015) study would indicate that some invertebrates should be able to detect the piling sound at a distance of 750 m, whether mitigated or not.

8.5.7 Taking the above into consideration, it is thought likely that particle motion will be detectable for many fish and invertebrates within the order of 750 m from piling at the Array Area, although it is not feasible to quantify this further at this stage. Furthermore, it is not possible at this time to determine whether the detection of sound by these species at this range is likely to result in an effect, such as behavioural disturbance or injury. Likewise, it is not possible at this time to define the requirements for, or potential effectiveness of, mitigation for particle motion. However, it is likely that potential injury due to particle motion will be confined to a smaller range than disturbance and detectability. Ultimately, until such a time as considerably more data become available, both in terms of measured particle motion during full scale piling and effects on marine species, it is considered that the assessment of effects as set out in this report represents a robust assessment based on the current state of knowledge.

9 Summary

9.1.1 Acoustic modelling has been undertaken to determine distances at which potential effects on marine mammals and fish may occur due to noise from piling activities and other underwater noise generating activities associated with site preparation, construction and O&M of the Proposed Development. Modelling was undertaken for the maximum parameters proposed. The auditory injury results for piling, which is the dominant noise generating activity, are summarised in Table 9.1 without the use of ADD, and related to the metrics and thresholds presented in NMFS (2024) as the most recent guidance. The ranges presented follow the dual metric approach recommended in NMFS (2024), i.e. show the maximum impact range between the SEL_{cum} and SPL_{peak} (of the first strike) metrics. Ranges are also shown for moving fish receptors in terms of the mortality criteria as derived from Popper *et al.* (2014). The ranges presented are for the single pile scenario.

Table 9.1: Summary of Potential Maximum AUD INJ Injury Ranges for Marine Mammals, and Mortality for Fish Due to Impact Piling Based on Highest Range of Peak Pressure or SEL (SEL marked with *) Without the Use of ADD

Species Group	**Range (m)**		
	Single Monopile (Maximum)	**Single Piling Jacket Piles**	**Single Monopile (Realistic)**
Marine Mammals			
LF cetacean	14,063 *	11,719 *	14,063 *
HF cetacean	51	54	51
VHF cetacean	2,462 *	1,349 *	2,403 *
Phocid carnivores	470 *	821 *	411 *
Fish (Moving Away)			
Group 1 Fish: no swim bladder	180	211	180
Group 2 Fish: where swim bladder is not involved in hearing	282	342	282
Group 3 to 4 Fish: where swim bladder is involved in hearing	282	342	282

9.1.2 Underwater noise emissions from the Wind Turbine operations, pre-construction activities, other relevant operational noises, and vessels during the O&M phase are unlikely to be at a level sufficient to cause injury to marine mammals or fish.

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