MORGAN AND MORECAMBE OFFSHORE WIND FARMS: TRANSMISSION ASSETS

Environmental Statement

Volume 1, Annex 5.2: Underwater sound technical report

September 2024
Rev: ES Issue

MOR001-FLO-CON-ENV-RPT-0064
MRCNS-J3303-RPS-10033

PINS Reference: EN020028
APFP Regulations: 5(2)(a)
Document reference: F1.5.2

Document status

Version	Purpose of document	Approved by	Date	Approved by	Date
Rev	For issue	AS	September 2024	IM	September 2024

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Glossary

Term	Meaning
Amplitude	The maximum displacement of a point on a wave from equilibrium.
Anthropogenic	An activity resulting from or relating to the influence of humans.
Applicants	Morgan Offshore Wind Limited (Morgan OWL) and Morecambe Offshore Windfarm Ltd (Morecambe OWL).
Baseline	The status of the environment without the Transmission Assets in place.
Bathymetry	A measure of the depth of water in the ocean.
Carboniferous	A geological period of time from 359 million years ago to 299 million years ago.
Design envelope	A description of the range of possible elements and parameters that make up the Transmission Assets options under consideration, as set out in detail in Volume 1, Chapter 3: Project Description. This envelope is used to define the Transmission Assets for EIA purposes when the exact engineering parameters are not yet known. This is also referred to as the Maximum Design Scenario or Rochdale Envelope approach.
Dose-response relationship	Describes the magnitude of the response of an organism, as a function of exposure to a stimulus or stressor after a certain exposure time.
Effect	The term used to express the consequence of an impact. The significance of effect is determined by correlating magnitude of the impact with the importance, or sensitivity, of the receptor or resource in accordance with defined significance criteria.
EIA Scoping Report	A report setting out the proposed scope of the Environmental Impact Assessment process. The Transmission Assets Scoping Report was submitted to The Planning Inspectorate (on behalf of the Secretary of State) for the Morgan and Morecambe Offshore Windfarms Transmission Assets in October 2022.
Environmental Impact Assessment	The process of identifying and assessing the significant effects likely to arise from a project. This requires consideration of the likely changes to the environment, where these arise as a consequence of a project, through comparison with the existing and projected future baseline conditions.
Generation assets	The generation assets associated with the Morgan Offshore Wind Project and the Morecambe Offshore Windfarm include the offshore wind turbines, inter-array cables, offshore substation platforms and platform link (interconnector) cables to connect offshore substations.
High order	Detonation of an unexploded ordnance as a clearance method.
Impact	Change that is caused by action/proposed development, e.g., land clearing (action) during construction which results in habitat loss (impact).
Impulsive sound	Sound which is broadband, typically transient, brief (less than one second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay.
Kurtosis	A measure of sharpness of the peak of a frequency-distribution curve.

Term	Meaning
Low order	Use of techniques such as deflagration to clear Unexploded Ordnance without resulting in a high order explosion, leading to lower sound levels.
Maximum design scenario	The realistic worst case scenario, selected on a topic-specific and impact specific basis, from a range of potential parameters for the Transmission Assets.
Morecambe Offshore Windfarm: Generation Assets	The offshore generation assets and associated activities for the Morecambe offshore Windfarm.
Morecambe Offshore Windfarm: Transmission Assets	The offshore export cables, landfall and onshore infrastructure required to connect the Morecambe Offshore Windfarm to the National Grid.
Morecambe OWL	Morecambe Offshore Windfarm Limited is a joint venture between Zero-E Offshore Wind S.L.U. (Spain) (a Cobra group company) and Flotation Energy Ltd.
Morgan and Morecambe Offshore Wind Farms: Transmission Assets	The offshore and onshore infrastructure connecting the Morgan Offshore Wind Project and the Morecambe Offshore Windfarm to the national grid. This includes the offshore export cables, landfall site, onshore export cables, onshore substations, 400 kV grid connection cables and associated grid connection infrastructure such as circuit breaker compounds. Also referred to in this report as the Transmission Assets, for ease of reading.
Morgan Offshore Wind Project: Generation Assets	The offshore generation assets and associated activities for the Morgan Offshore Wind Project.
Morgan Offshore Wind Project Transmission Assets	The offshore export cables, landfall and onshore infrastructure required to connect the Morgan Offshore Wind Project to the National Grid.
Morgan OWL	Morgan Offshore Wind Limited is a joint venture between bp Alternative Energy investments Ltd. and Energie Baden-Württemberg AG (EnBW).
Noise	Unwanted sound.
Non impulsive (or continuous) sound	Sound 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.
Offshore export cables	The cables which would bring electricity from the offshore substation platforms to the landfall.
Offshore Order Limits	See Transmission Assets Order Limits: Offshore (below).
Particle motion	Movement of particles within the water or sediment.
Planning Inspectorate	The agency responsible for operating the planning process for applications for development consent under the Planning Act 2008.
Propagation model	Computer model to predict how sound spreads away from a source of sound.

Term	Meaning
Sine wave	A waveform that represents periodic oscillations in which the amplitude of displacement at each point is proportional to the sine of the phase angle of the displacement and that is visualized as a sine curve.
Sound	Vibration of molecules in a liquid or gas.
Sound exposure level	Metric used to measure the cumulative sound energy to which a receiver is exposed over a given time period. This provides a uniform way to make comparisons between sound events of different durations.
Sound pressure	Measure of the resultant change in pressure due to vibration of particles in a fluid or gas.
Spatial extent	Geographical area over which the impact may occur.
Study area	This is an area which is defined for each environmental topic which includes the Transmission Assets Order Limits as well as potential spatial and temporal considerations of the impacts on relevant receptors. The study area for each topic is intended to cover the area within which an impact can be reasonably expected.
Substation	Part of an electrical transmission and distribution system. Substations transform voltage from high to low, or the reverse by means of electrical transformers.
Temporary threshold shift	Change (deterioration) in hearing of an animal which recovers after some time.
Transmission Assets	See Morgan and Morecambe Offshore Wind Farms: Transmission Assets (above).
Transmission Assets Order limits	The area within which all components of the Transmission Assets will be located, including areas required on a temporary basis during construction and/or decommissioning.
Transmission Assets Order Limits: Offshore	The area within which all components of the Transmission Assets seaward of Mean Low Water Springs will be located, including areas required on a temporary basis during construction and/or decommissioning. Also referred to in this report as the Offshore Order Limits, for ease of reading.
Transmission Assets Scoping Boundary	The term used to define the boundary used at the time the Scoping Report was submitted.

Acronyms

Acronym	Meaning
EIA	Environmental Impact Assessment
EnBW	Energie Baden-Württemberg AG
GEBCO	General Bathymetric Chart of the Oceans
HF	High frequency cetaceans
JNCC	Joint Nature Conservation Committee

Acronym	Meaning
LF	Low Frequency Cetaceans
MBES	Multi-Beam Echosounder
MMO	Marine Management Organisation
OCW	Other Carnivores in Water
PEIR	Preliminary Environmental Information Report
PCW	Phocid Carnivores in Water
PTS	Permanent Threshold Shift
RL	Received Level
rms	Root Mean Square
SBES	Single Beam Echosounder
SBP	Sub-Bottom Profiler
SEL	Sound Exposure Level
SL	Source Level
SPL	Sound Pressure Level
SSS	Sidescan Sonar
TL	Transmission Loss
TTS	Temporary Threshold Shift
UHRS	Ultra-High Resolution Seismic
UK	United Kingdom
UXO	Unexploded Ordnance
VHF	Very-high Frequency Cetaceans

Units

Unit	Description
%	Percentage
km	Kilometres
km^2	Square kilometres
dB	Decibel
dBA	A-weighted decibel
Hz	Hertz
kgm^{-3}	Kilograms per cubic metre
μPa	Micro Pascal (10^{-6})

m	Metre
ms^{-1}	Metres per second
ms^{-2}	Metres per second squared
MW	Megawatt (10^6)
s	Second

1 Underwater sound technical report annex

1.1 Introduction

1.1.1.1 This document forms Volume 1, Annex 5.2: Underwater sound technical report of the Environmental Statement (ES) prepared for the Morgan and Morecambe Offshore Wind Farms: Transmission Assets (hereafter referred to as the Transmission Assets).

1.1.1.2 This underwater sound technical report presents the results of a desktop study undertaken by Seiche Ltd. considering the potential effects of underwater sound on the marine environment from the export cable route and associated activities including geophysical and geotechnical surveys and Unexploded Ordnance (UXO) clearance. There is no piling associated with the offshore elements of the Transmission Assets.

1.1.1.3 The location of the Transmission Assets in the Irish Sea is illustrated in **Figure 1.1.** The planned activities at this site fall into four phases: pre-construction, construction, operation and maintenance, and decommissioning.

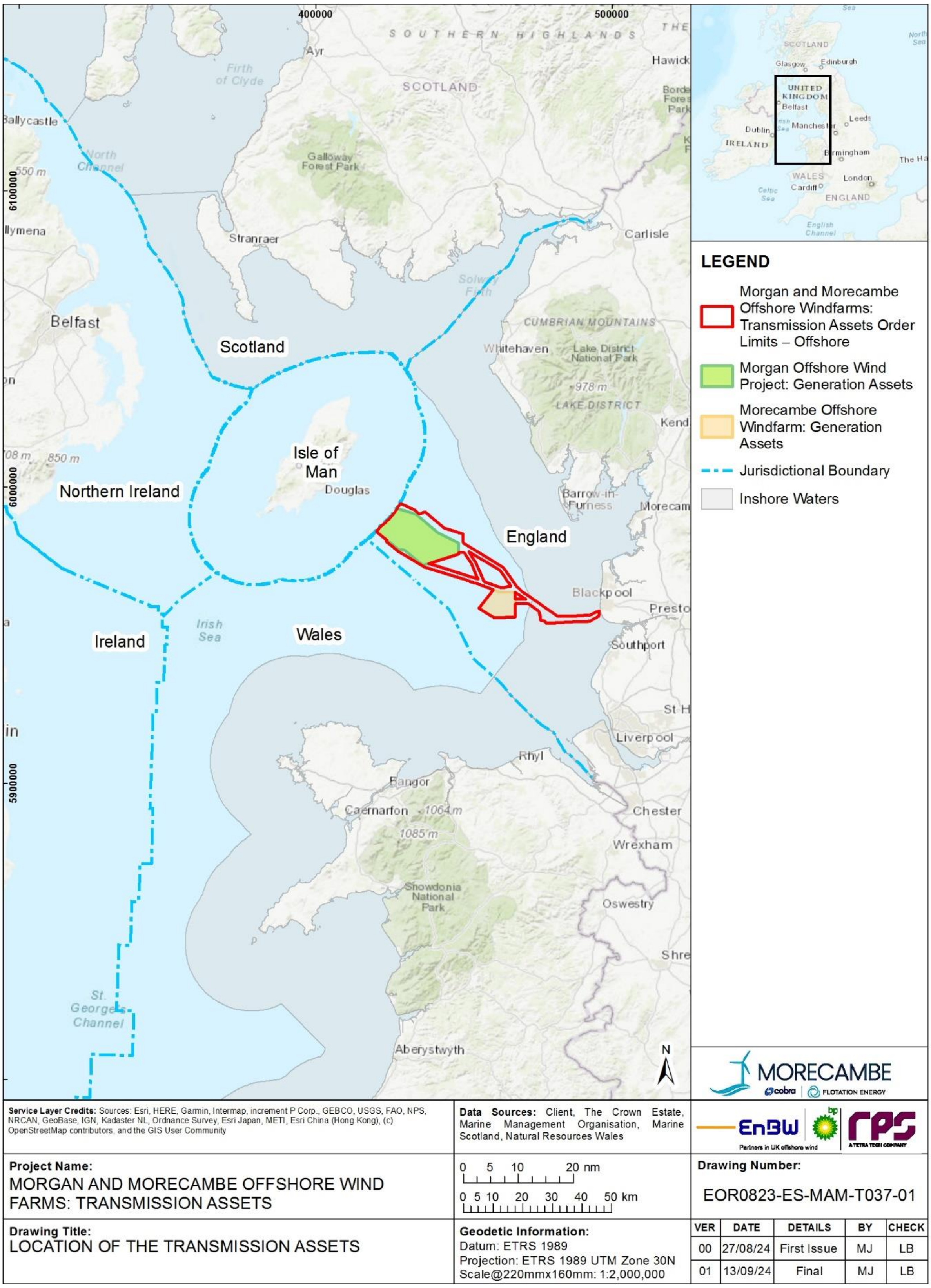

Figure 1.1: Location of the Transmission Assets

1.1.1.4 Sound is readily transmitted into the underwater environment and there is potential for the sound emissions from all development phases of the Transmission Assets to adversely affect marine mammals and fish. At a close range from a sound source generating high enough sound levels, permanent or temporary effects on hearing may occur to marine species, while at a very close range physical injury is possible. At further distances, the introduction of additional sound could potentially cause various short-term effects, for example to behavioural changes and the masking of sounds such as predator and food species[1]. This report provides an overview of the potential effects due to underwater sound from the Transmission Assets on the surrounding marine environment.

1.1.1.5 The primary purpose of this underwater sound technical report is to predict likely distances at which the onset of potential auditory injury (i.e. Permanent Threshold Shifts (PTS) in hearing) and behavioural effects on different marine fauna may occur when exposed to the different anthropogenic sounds that occur during different phases of the Transmission Assets. The results from this underwater sound technical report have been used to inform the following chapters of the ES in order to determine the potential impact of underwater sound on marine life.

- Volume 2, Chapter 3: Fish and shellfish ecology.
- Volume 2, Chapter 4: Marine mammals.
- Volume 2, Chapter 6: Commercial fisheries.

1.1.1.6 Consequently, the sensitivity of species, magnitude of potential impact and significance of effect from underwater sound associated with the Transmission Assets are addressed within the relevant chapters.

1.1.1.7 This technical report uses peer reviewed models to calculate the impact ranges to marine mammals and fish for each phase of the Transmission Assets: pre-construction, construction, operation and maintenance and decommissioning.

1.2 Methodology

1.2.1 Study area

1.2.1.1 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 1.1.1.5** above.

1.2.1.2 The modelled area is 26,269 km^2 and covers the whole Offshore Order Limits. The modelled area extends to up to 120 km from the boundaries north, south, east and west (except where cut off by land). The modelled area includes the waters around the north coast of Wales and Anglesey, the

[1] It should be noted that it is currently unclear whether/how close range or short term impacts may translate to long term population level impacts. This is an area of active research.

north west coast of England, the Isle of Man and extends as far as the east coast of Ireland.

1.2.1.3 Bathymetry data used within the modelling was obtained from the General Bathymetric Chart of the Oceans (GEBCO). The GEBCO 2021 Grid, is a global terrain model for ocean and land, providing elevation data, in metres, on a 15 arc-second interval grid. It showed the water depth (Lowest Astronomical Tide) within the Offshore Order Limits to typically range between 25 m and 40 m deep, reducing to 0 m approaching land, with typical water depths within the area being approximately 35 m.

1.2.2 Consultation

1.2.2.1 A summary of the comments raised during consultation activities undertaken to date specific to underwater sound is presented in **Table 1.1**. It should however be noted that formal responses are provided for **all** consultation responses received and can be accessed in the Consultation Report (document reference E1).

Table 1.1: Summary of key consultation comments raised during consultation activities undertaken for the Transmission Assets relevant to underwater sound

Date	Consultee and type of response	Comments	Response to comment raised and/or where considered in this annex
8 December 2022	Marine Management organisation (MMO) – Response to Environmental Impact Assessment (EIA) Scoping Report	Auditory injury is a primary concern regarding UXO detonation in addition to disturbance.	Auditory injury from UXO clearance activities is assessed in **section 1.8.1**.
8 December 2022	Planning Inspectorate – Response to EIA Scoping Report	Particle motion: content that this matter can be scoped out for marine mammals.	Particle motion has been scoped out as an impact for marine mammals in this Technical Report.
22 November 2023	Natural Resources Wales Advisory – Response to Preliminary Environmental Information Report (PEIR)	Worst case scenario for all species groups	A worst case underwater sound scenario has been assumed for all receptors as described in **section 1.6**.
		Assessment of all sources without the use of Acoustic Deterrent Devices (ADD)	Use of ADDs has not been assessed in this Technical Report.
		Use of impulsive thresholds at long ranges	A review of impulsive thresholds at long ranges is included in **section 1.4.5**.

Date	Consultee and type of response	Comments	Response to comment raised and/or where considered in this annex
22 November 2023	Marine Management Organisation – Response to PEIR	Behavioural response threshold for fishes should be SEL 135 dB re 1µPa^{2}s for impulsive sounds	Behavioural impacts to Fish are assessed in Volume 2, Chapter 3: Fish and shellfish ecology. Since the removal of piling from the project design, the only impulsive sounds assessed are explosives, for which a separate set of thresholds have been derived, and some sonar based sources which operate outside of the frequency range of fish hearing.
		Use Popper *et al.* (2014) thresholds for fishes	This Technical Report used the thresholds defined in Popper *et al.* (2014), which have been reproduced in **section 1.4.6**.
		Further details required on geophysical and geotechnical surveys	Limited details are available at this stage on the specific sources used in geophysical and geotechnical surveys, however more detail has been provided on the modelling of these sources in **section 1.6.3**.
		MMO recommends that the Joint Nature Conservation Committee (JNCC) guidelines (JNCC, 2017) for minimising the risk of injury to marine mammals from geophysical surveys are adopted and included within the ES	Discussion of the application of mitigation strategies is discussed in Volume 2, Chapter 4: Marine mammals.
		Clarification over calculation times for the assessment of vessels on fishes	The assessment times for fishes are 12 or 48 hours dependant on the metric assessed, as described in **section 1.6.7**.
23 November 2023	Natural England – Response to PEIR	Assessment of all sources without the use of ADD	Use of ADDs has not been assessed in this Technical Report.

1.3 Acoustic concepts and terminology

1.3.1.1 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). Because 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. All underwater sound pressure levels in this report are quantified in dB re 1 µPa.

1.3.1.2 There are several descriptors used to characterise a sound wave (in terms of sound pressure). The difference between the lowest pressure variation (rarefaction) and the highest-pressure variation (compression) is called the peak to peak (or 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 1.2**.

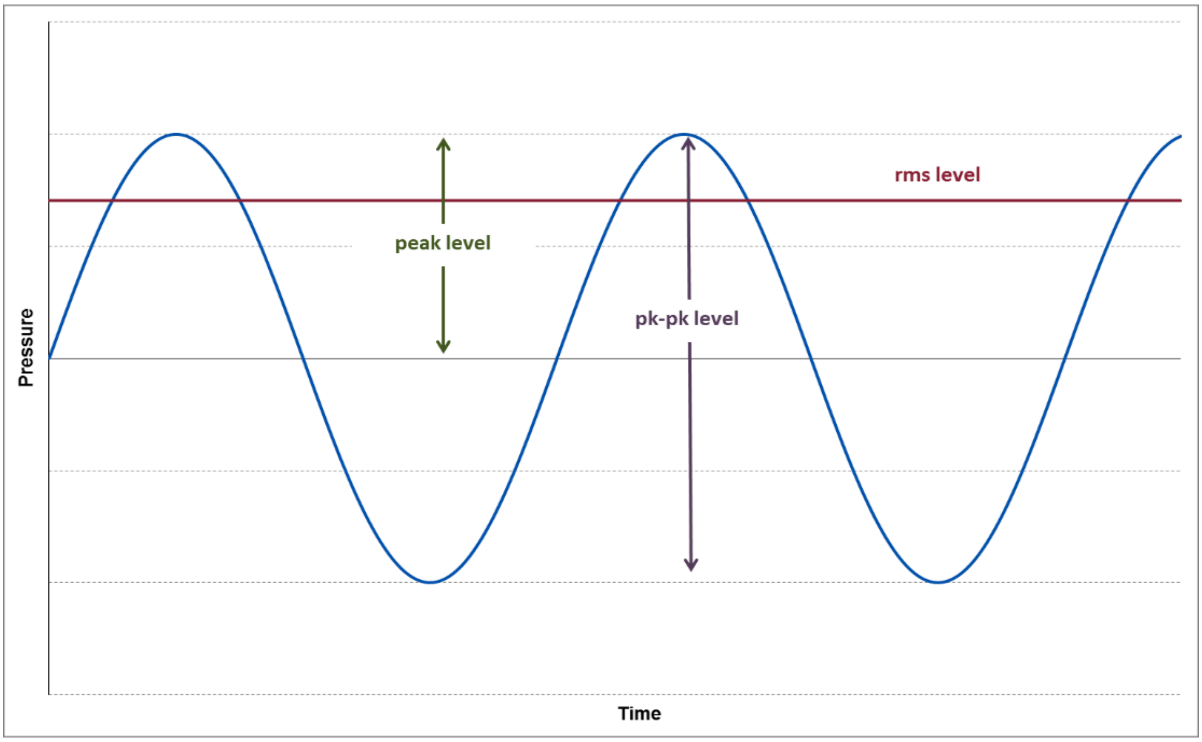

Figure 1.2: Graphical representation of acoustic wave descriptors

1.3.1.3 The SPL_{rms} is defined as:

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

1.3.1.4 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[2]. 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.

1.3.1.5 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 number 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[3]. The SEL is defined as:

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

1.3.1.6 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 meter, 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 a different sensitivity. It is therefore important to understand how an animals hearing varies over its entire frequency range to assess the effects of anthropogenic sound on marine mammals. Consequently, use can be made of frequency weighting scales (M-weighting) 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 1.3**[4].

1.3.1.7 **Third octave bands -** The broadband acoustic power (i.e. containing all the possible frequencies) emitted by a sound source is generally split into and reported in a series of frequency bands. In marine acoustics, the spectrum is

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[2] 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.

[3] 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.

[4] 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.

generally reported in standard one-third octave band frequencies, where an octave represents a doubling in sound frequency[5].

1.3.1.8 **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[6] can be approximated to that of a point source. Source levels do not indicate the real sound pressure level at 1 m.

1.3.1.9 **Transmission Loss (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 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.

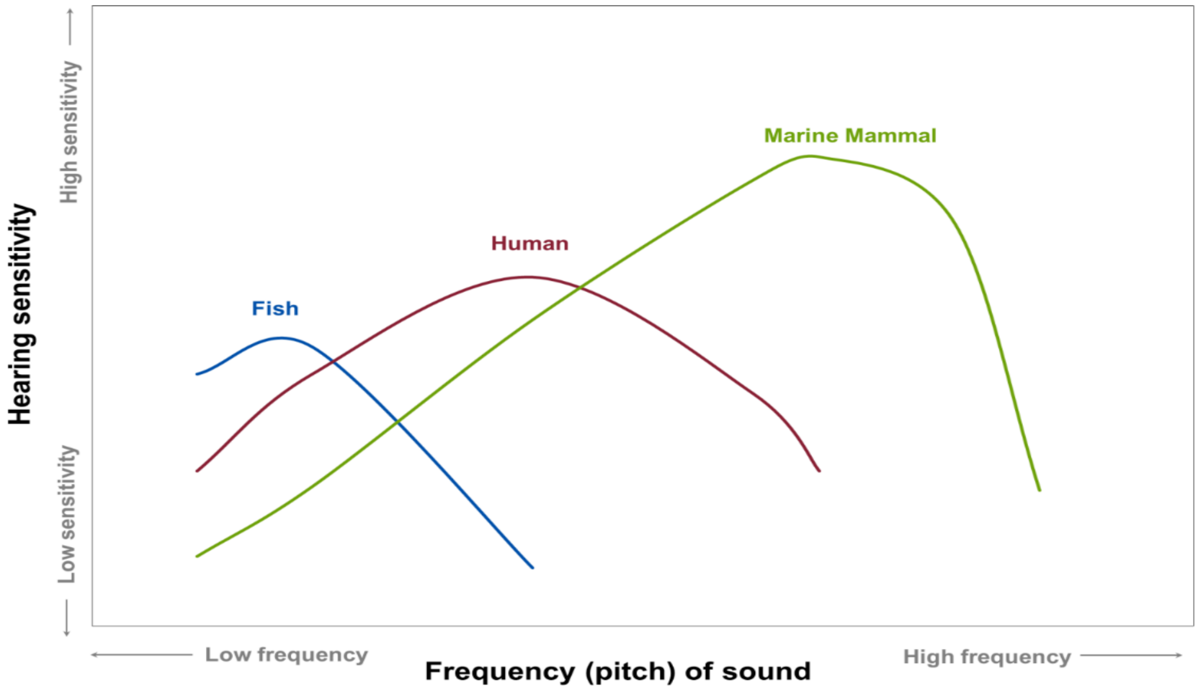

Figure 1.3: Comparison between hearing thresholds of different animals

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[5] 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%.

[6] 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.

1.3.1.10 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-to-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 survey region.

1.3.1.11 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.

1.4 Acoustic assessment criteria

1.4.1 Introduction

1.4.1.1 Underwater sound 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[7] (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; and
- **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 Threshold Shift (TTS) or a PTS. At even closer

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

ranges, and for very high intensity sound sources (e.g. underwater explosions), physical trauma or even death are possible.

1.4.1.2 For this technical report, it is the zones of injury and disturbance (i.e. responsiveness) that are of concern (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.

1.4.2 Injury (physiological damage) to mammals

1.4.2.1 Sound propagation models can be constructed to allow the received sound level at different distances from the source to be calculated. To determine the consequence of these received levels on any marine mammals which might experience such sound emissions, it is necessary to relate the levels to known or estimated potential impact thresholds. The auditory injury (PTS/TTS) threshold criteria proposed by Southall *et al.* (2019) are based on a combination of un-weighted peak pressure levels and mammal hearing weighted SEL. The hearing 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 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 truncatus* and short-beaked common dolphin *Delphinus delphis*);
- **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 *Halichoerus 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).

1.4.2.2 These weightings have therefore been used in this study and are shown in **Figure 1.4**.

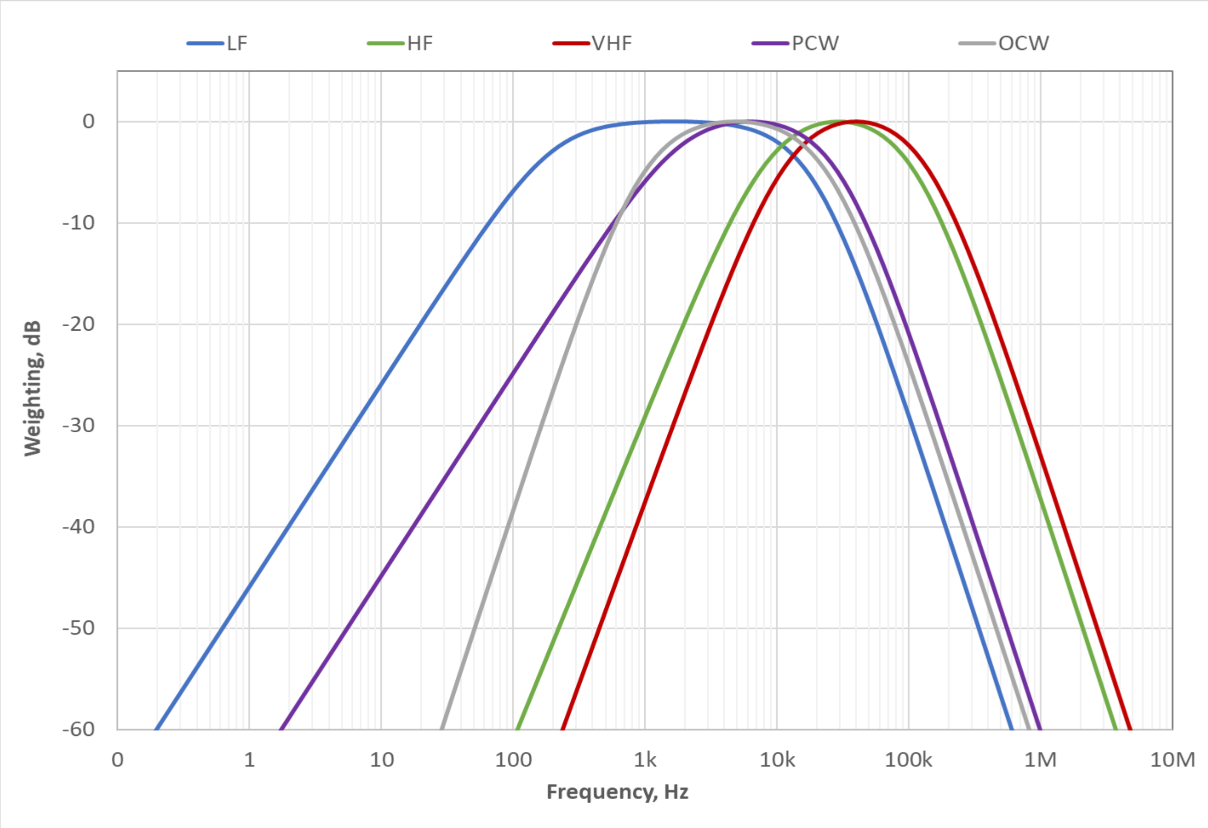

Figure 1.4: Hearing weighting functions for pinnipeds and cetaceans (Southall *et al.*, 2019)

1.4.2.3 Auditory injury criteria proposed in Southall *et al.* (2019) 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 and underwater explosions.
- **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 sonar, and vessels.

1.4.2.4 The criteria for impulsive and non-impulsive sound have been adopted for this study given the nature of the variety of sound sources during the various activities. The relevant criteria proposed by Southall *et al.* (2019) are summarised in **Table 1.2** and **Table 1.3**.

Table 1.2: Summary of PTS onset acoustic thresholds (Southall *et al.*, 2019; tables 6 and 7)

Hearing Group	Parameter	Impulsive	Non-impulsive
LF cetaceans	Peak, dB re 1 µPa (unweighted)	219	-
	SEL, dB re 1 µPa²s (LF weighted)	183	199
HF cetaceans	Peak, dB re 1 µPa (unweighted)	230	-
	SEL, dB re 1 µPa²s (HF weighted)	185	198
VHF cetaceans	Peak, dB re 1 µPa (unweighted)	202	-
	SEL, dB re 1 µPa²s (VHF weighted)	155	173
PCW	Peak, dB re 1 µPa (unweighted)	218	-
	SEL, dB re 1 µPa²s (PCW weighted)	185	201
OCW	Peak, dB re 1 µPa (unweighted)	232	-
	SEL, dB re 1 µPa²s (OCW weighted)	203	219

Table 1.3: Summary of TTS onset acoustic thresholds (Southall *et al.*, 2019; tables 6 and 7)

Hearing Group	Parameter	Impulsive	Non-impulsive
LF cetaceans	Peak, dB re 1 µPa (unweighted)	213	-
	SEL, dB re 1 µPa²s (LF weighted)	168	179
HF cetaceans	Peak, dB re 1 µPa (unweighted)	224	-
	SEL, dB re 1 µPa²s (HF weighted)	170	178
VHF cetaceans	Peak, dB re 1 µPa (unweighted)	196	-
	SEL, dB re 1 µPa²s (VHF weighted)	140	153
PCW	Peak, dB re 1 µPa (unweighted)	212	-
	SEL, dB re 1 µPa²s (PCW weighted)	170	181
OCW	Peak, dB re 1 µPa (unweighted)	226	-
	SEL, dB re 1 µPa²s (OCW weighted)	188	199

1.4.2.5 These updated marine mammal threshold criteria were published in March 2019 (Southall *et al.*, 2019). The paper utilised the same hearing weighting curves and thresholds as presented in the preceding regulations document National Marine Fisheries Service (NMFS) (2018) (and prior to that Southall et al. (2007)) with the main difference being the naming of the hearing groups and introduction of additional thresholds for animals not covered by NMFS (2018). A comparison between the two naming conventions is shown in **Table 1.4**.

1.4.2.6 For avoidance of doubt, the naming convention used in this report is based upon those set out in Southall *et al.* (2019). Consequently, this assessment utilises criteria which are applicable to both NMFS (2018) and Southall *et al.* (2019).

Table 1.4: Comparison of hearing group names between NMFS (2018) and Southall *et al.* (2019)

NMFS (2018) hearing group name	Southall *et al.* (2019) hearing group name
Low-frequency cetaceans (LF)	LF
Mid-frequency cetaceans (MF)	HF
High-frequency cetaceans (HF)	VHF
Phocid pinnipeds in water (PW)	PCW

1.4.3 Disturbance to marine mammals

1.4.3.1 Beyond the area in which auditory injury may occur, effects on marine mammal behaviour are 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.

1.4.3.2 To consider the possibility of disturbance resulting from the Transmission Assets, 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.

1.4.3.3 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 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)

1.4.3.4 Southall *et al.* (2007) recommended that the only feasible way, at the time of the study, to assess whether a specific sound could cause disturbance is to compare the circumstances of the situation with empirical studies. JNCC guidance in the United Kingdom (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.

1.4.3.5 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-pulsed) or impulsive (single or multiple pulsed).

1.4.3.6 Disturbance to marine mammals is discussed in more detail in Volume 2, Chapter 4: Marine mammals of the ES.

1.4.4 Continuous (non-pulsed, non-impulsive) sound

1.4.4.1 For non-pulsed sound (e.g. vessels etc.), the lowest sound pressure level at which a score of five or more on the Southall *et al.* (2007) behavioural response severity scale occurs for low frequency cetaceans is 90 dB to 100 dB re 1 µPa (rms). However, this relates to a study involving only migrating grey whales. A study for minke whale showed a response score of three at a received level of 100 dB to 110 dB re 1 µPa (rms), with no higher severity score encountered for this species. For mid frequency cetaceans, a response score of eight was encountered at a received level 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 Transmission Assets. For Atlantic white-beaked dolphin *Lagenorhynchus albirostris*, 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 high frequency 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).

1.4.4.2 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 1.3** for a discussion of these different metrics).

1.4.4.3 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 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.

1.4.5 Impulsive (pulsed) sound

1.4.5.1 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. Although these datasets contain much relevant data for LF cetaceans, there is less data for MF or HF cetaceans (HF or VHF in Southall *et al.* (2019), see **Table 1.4**) within the document. Low frequency cetaceans, other than bow-head whales, were typically observed to respond significantly at a received level ranging 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 or minor separation of females and dependent offspring. The data available for MF cetaceans (HF in Southall *et al.* (2019), see **Table 1.4**) 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 (HF in Southall *et al.* (2019), see **Table 1.4**) 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).

1.4.5.2 A more recent study is described in Graham et al. (2019). Empirical evidence from piling at the Beatrice Offshore Wind Farm (Moray Firth, Scotland) was used to derive a dose-response curve for harbour porpoise8. 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 (un-weighted) SEL of 180 dB re 1 µPa^{2}s, 50% at 155 dB re 1 µPa^{2}s and dropping to approximately 0% at an SEL of 120 dB re 1 µPa^{2}s. This approach to representing the behavioural effects from piling has been applied at other UK offshore wind farms (for example Seagreen Alpha/Bravo (Seagreen Wind Energy, 2018) and Hornsea Three (Orsted, 2020)). 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. Southall *et al.*, 2017).

1.4.5.3 According to Southall et al. (2007), there has historically been a general paucity of data relating to the effects of sound on pinnipeds in particular. One study using ringed *Pusa hispida*, bearded *Erignathus barbatus* and spotted *Phoca largha* seals (Harris et al., 2001) found onset of a significant response at a received sound pressure level of 160 dB to 170 dB re 1 µPa (rms), although larger numbers of animals showed no response at sound levels of up to 180 dB re 1 µPa (rms). It is only at much higher sound pressure levels

[8] Dose-response relationships describe the magnitude of the response of an organism, as a function of exposure to a stimulus or stressor after a certain exposure time.

in the range of 190 dB to 200 dB re 1 µPa (rms) that significant numbers of seals were found to exhibit a significant response. For non-pulsed sound, one study elicited a significant response on a single harbour seal at a received level of 100 dB to 110 dB re 1 µPa (rms), although other studies found no response or non-significant reactions occurred at much higher received levels of up to 140 dB re 1 µPa (rms). No data are available for higher sound levels and the low number of animals observed in the various studies means that it is difficult to make any firm conclusions from these studies.

1.4.5.4 Southall *et al.* (2007) also notes that, due to the uncertainty over whether HF cetaceans may perceive certain sounds and due to paucity of data, it was not possible to present any data on responses of HF cetaceans. However, Lucke *et al.* (2009) showed a single harbour porpoise consistently showed aversive behavioural reactions to pulsed sound at received SPL above 174 dB re 1 µPa (peak-to-peak) or a SEL of 145 dB re 1 µPa^{2}s, equivalent to an estimated[9] rms sound pressure level of 166 dB re 1 µPa.

1.4.5.5 There is much intra-category and perhaps intra-species variability in behavioural response. As such, a conservative approach should be taken to ensure that the most sensitive marine mammals remain protected.

1.4.5.6 The High Energy Seismic Survey (HESS) workshop on the effects of seismic (i.e. pulsed) sound on marine mammals (HESS, 1997) concluded that mild behavioural disturbance would most likely occur at rms sound levels greater than 140 dB re 1 µPa (rms). This workshop drew on studies by Richardson (1995) but recognised that there was some degree of variability in reactions between different studies and mammal groups. Consequently, for the purposes of this study, a precautionary level of 140 dB re 1 µPa (rms) is used to indicate the onset of low-level marine mammal disturbance effects for all mammal groups for impulsive sound.

1.4.5.7 For impulsive sound sources (e.g. UXO clearance, 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 this assessment.

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[9] Based on an analysis of the time history graph in Lucke et al. (2007), the T90 period is estimated to be approximately 8 ms, resulting in a correction of 21 dB applied to the SEL to derive the rms_{T90} sound pressure level. However, the T90 was not directly reported in the paper.

1.4.5.8 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… 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. However, Southall *et al.* (2021) does not present thresholds for assessing disturbance based on these severity categories, therefore the thresholds discussed above have been adopted for this study. The assessment of disturbance and behavioural response is presented in full in the Marine Mammals chapter (Volume 2, Chapter 4: Marine mammals of the ES).

1.4.5.9 It is important to understand that exposure to sound levels in excess of the behavioural change threshold 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.

Table 1.5: Disturbance criteria for marine mammals used in this study

Effect	Non-Impulsive Threshold	Impulsive Threshold
Mild disturbance (all marine mammals)	-	140 dB re 1 µPa (rms)
Strong disturbance (all marine mammals)	120 dB re 1 µPa (rms)	160 dB re 1 µPa (rms)

1.4.5.10 Another important consideration is that the majority of sound produced by project activities (UXO clearance, geophysical and geotechnical surveys, cable laying etc.) 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.

1.4.6 Injury and disturbance to fish

1.4.6.1 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). 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: fishes 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 sharks, which do not have a swim bladder, also fall into this hearing group.

- Group 2: fishes 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: Fishes 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: Fishes that have special structures mechanically linking the swim bladder to the ear (e.g. clupeids such as herring, sprat and shads). 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 the hearing range has been recorded as between 50 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.

1.4.6.2 The guidelines set out criteria for injury effects due to different sources of sound. Non-impulsive sources were not considered to be a key potential impact and therefore were screened out of the guidance[10]. 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, independent of sound level or duration, 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 significant with respect to determining the potential effect of sound on fish.

[10] Guideline exposure criteria for piling, seismic surveys, continuous sound and naval sonar are also presented though are not applicable to the Transmission Assets.

1.4.6.3 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. 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.

1.4.6.4 The criteria used in this underwater sound assessment for continuous sound sources, such as vessels, are given in **Table 1.6**. The only numerical criteria for these sources are for recoverable injury and TTS for Groups 3 and 4 Fish.

Table 1.6: 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 1 μPa (rms) for 48 hours	158 dB re 1 μPa (rms) for 12 hours
Sea turtles	(Near) Low (Intermediate) Low (Far) Low	(Near) Low (Intermediate) Low (Far) Low	(Near) Moderate (Intermediate) Low (Far) Low

Type of Animal	Mortality and Potential Mortal Injury	Recoverable Injury	TTS
Eggs and larvae	(Near) Low (Intermediate) Low (Far) Low	(Near) Low (Intermediate) Low (Far) Low	(Near) Low (Intermediate) Low (Far) Low

1.4.6.5 The criteria used in this underwater sound assessment for explosives are given in **Table 1.7**.

Table 1.7: Criteria for injury to fish due to 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 1 µPa	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 1 µPa	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 1 µPa	229 - 234	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) High (Far) Low

1.4.6.6 It should be noted that there are no thresholds in Popper *et al.* (2014) in relation to sound from high frequency sonar (>10 kHz). This is because the hearing range of fish species falls well below the frequency range of high frequency sonar systems such as sub-bottom profilers. Consequently, the effects of sound from high frequency sonar 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 also due to the lack of any suitable thresholds.

1.4.6.7 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 1.9** 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[11].

1.4.6.8 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.

1.4.6.9 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

1.4.6.10 **Table** 1.8.

Table 1.8: 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 Sound	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
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

[11] 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 Sound	**Explosives**	**Non-Impulsive Sound**
Eggs and larvae	(Near) Moderate (Intermediate) Low (Far) Low	(Near) High (Intermediate) Low (Far) Low	(Near) Moderate (Intermediate) Moderate (Far) Low

1.4.6.11 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. UXO clearance) would be predicted to result in the same potential impact, no matter the level of sound produced or the propagation characteristics.

Use of impulsive sound thresholds at large ranges

1.4.6.12 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 (B. L. Southall *et al.,* 2007; 2019; NMFS, 2018; Benda-Beckmann *et al.,* 2022). For highly impulsive sounds such as those generated by 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 high frequency 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; B. L. 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.

1.4.6.13 This acoustic wave elongation effect is particularly pronounced at 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 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.

1.4.6.14 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 high frequency 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).

1.4.6.15 Because disturbance ranges are likely to extend beyond the range at which injury (PTS or TTS) 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 rms (T90), 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.

1.5 Baseline

1.5.1.1 Background or ‘ambient’ underwater sound is created by several natural sources (such as rain, breaking waves, wind at the surface), seismic sound, biological sound (marine mammals using sound to communicate, build up an image of their environment and detect prey and predators, as well as certain fish and shrimp) and thermal sound. Anthropogenic sounds related to the proposed project activities can be either impulsive (pulsed) such as UXO clearance, or non-impulsive (continuous) such as ship engines, and the magnitude of the impact on marine life will depend heavily on these characteristics. Anthropogenic sources of sound in the marine environment include fishing boats, ships (non-impulsive), marine construction, seismic surveys and leisure activities (all could be either impulsive or non-impulsive), all of which add to ambient background sound. Other anthropogenic sound within the vicinity of the Transmission Assets will arise primarily from shipping, the offshore oil and gas industry, subsea geophysical and geotechnical surveys, and the offshore renewables industry. Underwater acoustic measurements of operational sound were undertaken in and around the Ormonde Wind Farm in June 2012 (Nedwell *et al.*, 2012). The results reported that there was an increase in sound levels between 0 and 50 kHz at a water depth of 30 m around individual wind turbines. The sound was continuous in nature, and the increase was detectable to a maximum range of approximately 1 km. Beyond this range, the underwater sound level was consistent with the ambient underwater sound in the region (Nedwell *et al.*, 2012).

1.5.1.2 Historically, research relating to both physiological effects and behavioural disturbance of sound on marine receptors has typically been based on determining the absolute sound level for the onset of that effect (whether presented as a single onset threshold or a dose-response/probabilistic function).

Consequently, the available numerical criteria for assessing the effects of sound on marine mammals, fish and shellfish, tend to be based on the absolute sound level criteria, rather than the difference between the baseline sound level and the sound being assessed (Southall *et al.*, 2019).

1.5.1.3 Baseline or background sound levels vary significantly depending on multiple factors, such as seasonal variations and different sea states.

Lack of long term measurements/sound data is a widely recognised gap in knowledge in relation to general soundscape and potential effects of human activities on marine life. Understanding the baseline sound level could therefore be valuable in enabling future studies to assess long term effects related to continuous sound levels over time in addition to activity specific effects such as masking impacts. However, the value of establishing the precise baseline sound level is limited in relation to the current assessment methods due to the lack of available evidence-based studies on the effects of sound relative to background levels on marine receptors.

1.6 Source sound levels

1.6.1 General

1.6.1.1 Underwater sound source level is usually quantified using a decibel (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). 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 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 sound pressure level 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.

1.6.1.2 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 1.6.2** to **1.6.7** detail the types of sound sources present during different activities, their potential signatures in different frequency bands, and acoustic levels.

1.6.2 Types of sound sources

1.6.2.1 The sound sources and activities which were investigated during the underwater sound technical report are summarised in **Table 1.9**.

Table 1.9: Summary of sound sources and activities included in the underwater sound assessment

Phase	Source/Activity
Pre-Construction	Geophysical and geotechnical site investigation activities including: • Multi-Beam Echo-Sounder (MBES); • Sidescan Sonar (SSS); • Single Beam Echosounder (SBES); • Sub-Bottom Profilers (SBP); • Ultra-High Resolution Seismic (UHRS) (sparker); • Cone Penetration Testing (CPT); and • Vibro-coring. Use of geophysical survey vessels. Clearance of UXOs including potential use of low-order and low-yield techniques as well as possible high order detonation.
Construction	Vessels used for a range of construction activities including e.g. boulder clearance, sand wave clearance, cable laying and trenching. Range of construction vessels including: • tug/anchor handlers; • cable lay installation and support vessels; • jack-up vessels; • guard vessels; • survey vessels (e.g. for geophysical surveys); • seabed preparation vessels for boulder removal, grapnel, pre-sweep/levelling; • crew transfer vessels; and • cable protection installation vessels.
Operation and maintenance	Operations and maintenance vessels, including: • crew transfer vessels/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.

1.6.2.2 The maximum design scenario for the above sources for each phase of the Transmission Assets are considered in more detail in the following sections.

1.6.3 Pre-construction phase

Geophysical surveys

1.6.3.1 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.

1.6.3.2 The characteristics assumed for each device modelled in this assessment are summarised in **Table 1.10**. For the purpose of potential impacts, these sources are considered to be continuous (non-impulsive).

Table 1.10: Typical Sonar based survey equipment parameters used in assessment

Survey Type	Frequency (kHz)	Source Level, (dB re 1 µPa re 1 m) (rms)	Pulse Rate, s^{-1}	Pulse Width (ms)	Beam Width
MBES	200 - 500	180 - 240	10	0.3 - 1.5	1 - 10°
SSS	200 - 700	216 - 228	3 - 15	0.1	Horizontal 0.2 - 1.5° Vertical 40 - 55°
SBES	20 - 400	180 - 240	10	0.3 - 1.5	1 - 10°
SBP (pinger and chirp)	0.2 - 14 (chirp) 2 - 7 (pinger)	200 - 240 chirp 200 - 235 pinger	4	1.5	2°

1.6.3.3 The assumed pulse rate has been used to calculate the SEL, which is normalised to one second, from the rms sound pressure level. 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.

1.6.3.4 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 are summarised in **Table 1.11**.

Table 1.11: Typical UHRS survey equipment parameters used in assessment

Source	Peak Frequency (kHz)	Source Level (dB re 1 µPa re 1 m) (peak)	Source SEL (dB re 1 µPa^{2}s re 1m)	Source Level (dB re 1 µPa re 1m) (rms)	T90 (ms)
UHRS (sparker)	0.05 - 4	219	182	170-200	0.7

Geotechnical surveys

1.6.3.5 Source sound data for the proposed CPTs was reported by Erbe and McPherson (2017). In this report, the SEL measurements at two different sites in Western Australia at a measured distance of 10 m were presented. The signature is generally broadband in nature with levels measured generally 20 dB above the baseline sound levels. The report also mentions other paths for acoustic energy including direct air to water transmission and other multipath directions, which implied that measured sound level is strongly dependant on depth and range from the source. The third octave band SEL levels from the CPT extracted are presented in **Table 1.12**.

Table 1.12: CPT source levels in different third octave band frequencies (SEL metric) used for the assessment (Erbe and McPherson, 2017).

SEL (dB re 1µPa^{2}s)	Third octave band centre frequency (kHz)									
	0.016	0.0315	0.063	0.125	0.25	0.5	1	2	4	8
189	173	173	164	163	172	177	180	182	184	182

1.6.3.6 Seismic CPT sound is classified as impulsive at source since it has a rapid rise time and a high peak sound pressure level of 220 dB re 1 µPa (pk), compared to a SEL of 189 dB re 1 µPa^{2}s.

1.6.3.7 The seismic CPT test is typically conducted at various depths for each location every three to five minutes with between 10 and 20 strikes per depth.

1.6.3.8 It should be noted that if non-seismic CPT were to be used, the sound would be considered non-impulsive if it produced any sound at all, and therefore the assessment of seismic CPT is considered precautionary.

1.6.3.9 Measurements of a vibro-core test (Reiser *et al*., 2011) show underwater source sound pressure levels 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).

Table 1.13: 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 1m
RMS$_{(T90)}$	187	dB re 1 µPa re 1m
Peak	190	dB re 1 µPa re 1m

1.6.3.10 The frequency spectral shape for vibro-coring is presented in **Figure 1.5**.

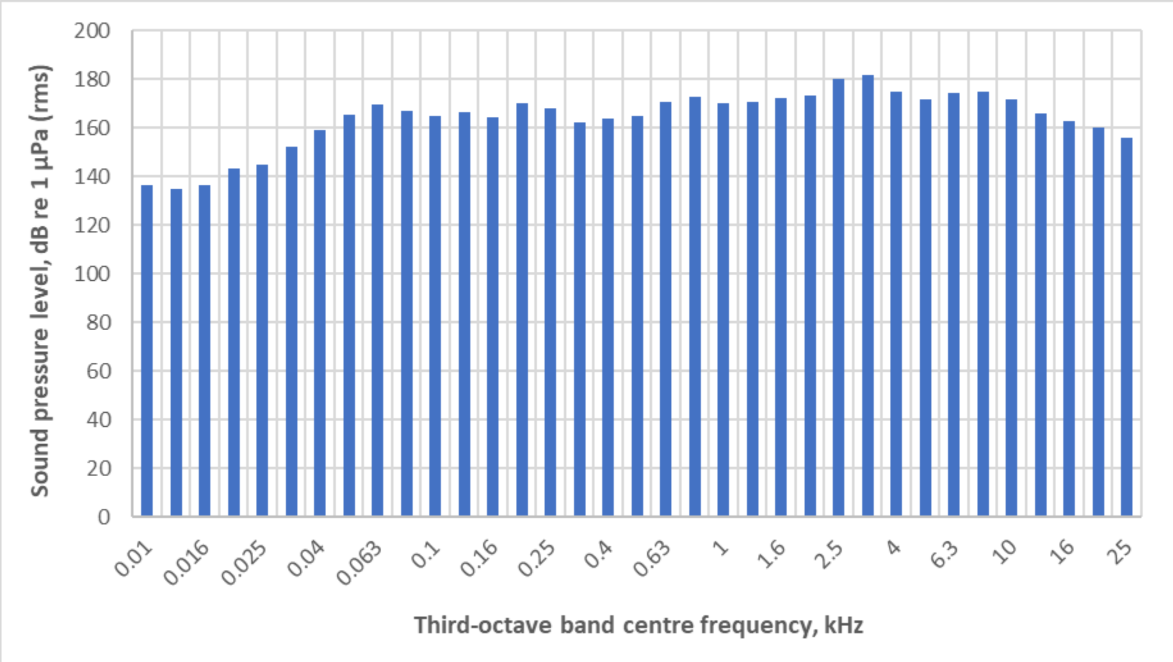

Figure 1.5: Frequency spectral shape used for vibro-coring.

UXO clearance

1.6.3.11 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 907 kg cleared by either low order or high order techniques. Low order techniques are not always possible and are dependent upon the individual situations surrounding each UXO.

1.6.3.12 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 Net Explosive Quantity (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.

1.6.3.13 Recent controlled experiments showed low-order deflagration to result in a substantial reduction in acoustic output over traditional high order methods, with SPL_{pk} 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.

1.6.3.14 It is possible that there will be residual explosive material remaining on the seabed following the use of low order techniques for unexploded ordnance 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'.

1.6.3.15 Alternatively, a low-yield clearance technique could be utilised for UXOs utilising two 750 g donor charges, or four 750 g donor charges in the case of German ground mines.

1.6.3.16 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. These are likely to range between 25 kg to 907 kg, with the most common UXO size likely to be in the order of 130 kg.

1.6.3.17 The underwater sound modelling has been undertaken for a range of charge configurations as set out in **Table 1.14**.

Table 1.14: 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
2 x 0.75 kg	Charge configuration for low-yield technique for most UXO
4 x 0.75 kg	Maximum charge configuration for low-yield technique (for German ground mines)
High-order donor charge options	
1.2 kg	Most common donor charge for high-order UXO disposal
3.5 kg	Single barracuda blast-fragmentation charge for high-order disposal
Potential UXOs (high-order disposal)	
25 kg	Smallest potential UXO size
130 kg	Most common/likely (based on estimated number of devices) UXO size
907 kg	Maximum UXO size

1.6.3.18 The source levels for UXO are included within the terms for propagation modelling and are described in **section 1.7.6**.

1.6.4 Construction phase

1.6.4.1 The sound source 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 vessels. The SEL based source levels are presented in **Table 1.15**.

Table 1.15: SEL based source levels for construction phase sources

Source	Data Source	rms (dB re 1 µPa)	Frequency (Hz)											
			16	31.5	63	125	250	500	1k	2k	4k	8k	16k	31.5 k
Cable laying	Wyatt (2008)	180	168	166	166	165	162	157	153	155	138	131	125	161
Cable trenching/ cutting	Nedwell *et al.* (2003)	178	135	135	148	161	167	169	167	162	157	148	142	141
Jack up barge	Evans (1996)	163	120	132	141	148	148	152	149	143	148	152	145	139

1.6.4.2 The potential impact of vessels sound emissions is addressed in **section 1.6.7** for all phases of the Transmission Assets.

1.6.5 Operation and maintenance phase

Geophysical surveys

1.6.5.1 Routine geophysical surveys will be similar to the geophysical surveys already discussed for the pre-construction phase (see **section 1.6.3**).

1.6.6 Decommissioning phase

1.6.6.1 As agreed with stakeholders during the pre-Application consultation phase as part of an Expert Working Groups (EWG) meeting, only the potential impact of sound from vessel activity has been scoped into the underwater sound assessment for the decommissioning phase of the Transmission Assets. It should be noted that cavitation from the vessels themselves is likely to dominate the soundscape for other decommissioning activities (e.g. removal of subsea structures). The potential impact of vessels sound emissions is addressed in **section 1.6.7** for all phases of the Transmission Assets.

1.6.7 Vessels (all phases)

1.6.7.1 The sound emissions from the types of vessels that may be used for the Transmission Assets are quantified in **Table 1.16**, 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.

1.6.7.2 In **Table 1.16**, 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). Modelling has been undertaken using the rms sound source level for the relevant assessment time, noting that for fish the relevant time periods are 12 and 48 hours of exposure. Source sound levels for vessels depend on the vessel size and speed as well as propeller design and other factors. There can be considerable variation in sound magnitude and character between vessels even within the same class. Therefore, source data for the Transmission Assets has been based on maximum design assumptions (i.e. using sound 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 dynamic positioning and therefore likely to have a similar acoustic footprint.

Table 1.16: Source sound data for construction, installation and operation vessels

Item	Description/ Assumptions	Data Source	Source SPL at 1 m	
			rms (dB re 1 μPa)	SEL(24h) (dB re 1 μPa^{2}s)
Sandwave clearance	'Gerardus Mercator' trailer hopper suction dredger using dynamic positioning (DP) as proxy	Wyatt *et al.* (2020)	180	229
Boulder clearance, floating crane vessel	Back-hoe dredger used as proxy	Nedwell *et al.* (2008)	163	212
Jack up barge	Jack up barge	Evans (1996)	163	212
Tug/Anchor Handlers	Tug used as proxy	Richardson (1995)	172	221
Cable 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
Guard Vessels	Tug used as proxy	Richardson (1995)	172	221

Item	Description/ Assumptions	Data Source	Source SPL at 1 m	
			rms (dB re 1 µPa)	SEL(24h) (dB re 1 µPa^{2}s)
Survey Vessels	Offshore support vessel used as proxy	McCauley (1998)	179	228
Crew Transfer Vessels, Service Operation Vessels	Offshore support vessel used as proxy	McCauley (1998)	179	228
Cable Protection/Seabed Preparation/Installation Vessels	Offshore support vessel used as proxy	McCauley (1998)	179	228

1.7 Propagation modelling

1.7.1 Propagation of sound underwater

1.7.1.1 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.

1.7.1.2 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[12].

1.7.1.3 In acoustically shallow waters[13] in particular, the propagation mechanism is influenced by multiple interactions with the seabed and the water surface (Lurton, 2002; Etter, 2013; Urick, 1983; Brekhovskikh and Lysanov, 2014; Kinsler *et al.*, 1999). Whereas in deeper waters, the sound will propagate further without encountering the surface or bottom of the sea (seabed).

1.7.1.4 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

[12] 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.

[13] 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.

sound energy is scattered (e.g. Eckart, 1953; Fortuin, 1970; Marsh, Schulkin, and Kneale, 1961; Urick and Hoover, 1956). Scattering can also occur due to bubbles near the surface such as those generated by wind or 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.

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

1.7.1.6 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, seabed 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).

1.7.1.7 The waveguide effect should also be considered, which defines the shallow water columns that do not allow the propagation of low frequency 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 1.6** for a range of seabed types. Any sound below this frequency will not propagate far due to energy losses through multiple reflections.

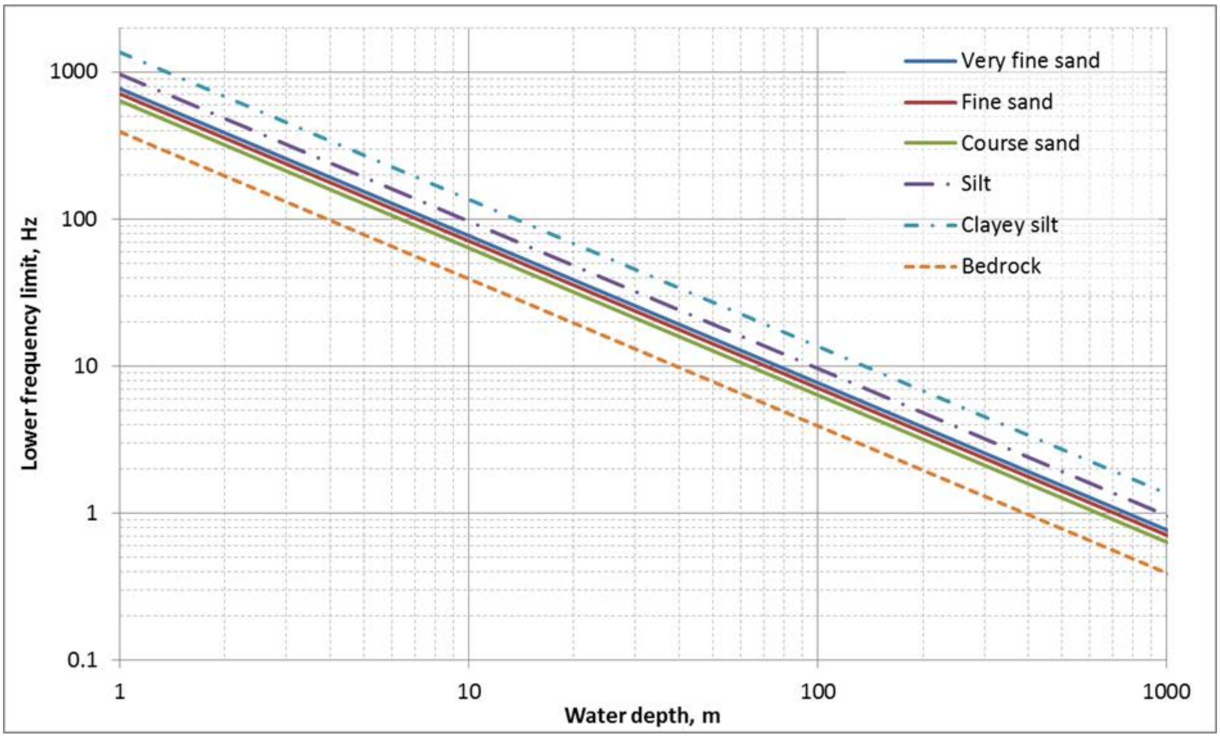

Figure 1.6: Lower cut-off frequency as a function of depth for a range of seabed types

1.7.1.8 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 high-frequency sound. 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 but, for example, a 25 m thick layer would not act as a duct for frequencies below 1.5 kHz. The temperature gradient can vary throughout the year and thus there will be potential variation in sound propagation depending on the season.

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

1.7.2 Modelling approach

1.7.2.1 There are several methods available for modelling the propagation of sound between a source and receiver ranging from very simple models which simply assume 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, whose complexity and accuracy are somewhere in between these two extremes.

1.7.2.2 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", NPL 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.

1.7.2.3 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.

1.7.2.4 For the sound field model, relevant survey parameters were chosen based on a combination of data provided by the Applicants 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 (for more information see volume 3, appendix 10.1, annex C; Weston, 1971; 1980a; 1980b), suited to the region and the frequencies of interest. 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 1,000 kHz (1 MHz), with different sound sources operating in different frequency bands. These frequencies overlap with the hearing sensitivities (as per **Figure 1.4**) of some of the marine mammals that are likely to be present in the Transmission Assets area.

Table 1.17: Regions of transmission loss derived by Weston (1971)

Region	Transmission Loss	Range of validity
Spherical	$TL = 10\log_{10}[R^2]$	$R < \frac{H_a}{2\theta_c}$
Channelling	$TL = 10\log_{10}\left[\frac{RH_aH_b}{2H_c\theta_c}\right]$	$\frac{H_a}{2\theta_c} < R < \frac{6.8H_a}{\alpha{\theta_c}^2}$
Mode stripping	$TL = 10\log_{10}\left[\frac{RH_aH_b}{5.22}\left(\alpha\int_0^R \frac{dR}{H^3}\right)^{1/2}\right]$	$\frac{6.8H_a}{\alpha{\theta_c}^2} < R < \frac{27k^2{H_a}^3}{(2\pi)^2\alpha}$
Single mode	$TL = 10\log_{10}\left[\frac{RH_aH_b}{\lambda}\right] + \frac{\lambda^2\alpha}{8}\int_0^R \frac{dR}{H^3}$	$R > \frac{27k^2{H_a}^3}{(2\pi)^2\alpha}$

1.7.2.5 The propagation loss is calculated using one for the four formulae detailed in the table above, 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.

1.7.2.6 In **Table 1.17**, H_a is the depth at the source, H_b is the depth at the receiver, H_c is the minimum depth along the bathymetry profile (between the source and the receiver), θ_c is the critical grazing angle (related to the speed of sound in both seawater and the seafloor material), λ and k are the wavelength and wavenumber as usual, and α is the seabed reflection loss gradient, empirically derived to be 12.4 dB/rad in Weston (1971).

1.7.2.7 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 θ_c. 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.

1.7.2.8 For estimation of propagation loss of acoustic energy at different distances away from the sound source location (in different directions, see **Figure 1.7**), the following steps were considered.

- The bathymetry information around this chosen source points were extracted from the GEBCO database up to 120 km (where possible, for example where not interrupted by land) in 72 different transects.
- A calibrated Weston Energy model was employed to estimate the TL matrices for different frequencies of interest (from 25 Hz to 80 kHz) along the 72 different transects.
- The calculated source level values were combined with the TL results to achieve a frequency and range dependant RL of acoustic energy around the chosen source position.
- The TTS and PTS potential impact distances for different marine mammal groups were calculated using relevant metrics and weighting functions (from Southall *et al.,* 2019) and by employing a simplistic animal movement model (directly away from the sound source) where appropriate.

1.7.2.9 The propagation and sound exposure calculations were conducted over a range of locations representing different geoacoustic conditions, water column depths and proximities to receptors to determine the likely range for injury and disturbance.

1.7.2.10 It should be noted that sound levels (and associated range of effects) will vary depending on actual conditions at the time (day-to-day and season-to-season) and that the model predicts a typical maximum design scenario. Considering factors such as animal behaviour and habituation, any injury and disturbance ranges should be viewed as indicative and probabilistic ranges to assist in understanding potential impacts on marine life rather than lines either side of which a potential impact will or will not occur.

1.7.2.11 The Weston energy flux propagation model used for this assessment has been calibrated against a range of other propagation models showing good agreement (typically within +/- 1 dB to a range of 2.5 km). The acoustical properties of different layers employed in the propagation calibration are presented in **Table 1.18**. This data is evaluated using recommendations by Hamilton (1980; 1978) based on the geological layers present in the survey region and the acoustic properties of the water column. Due to the relatively shallow nature of the area, only a single speed of sound in the water column was considered.

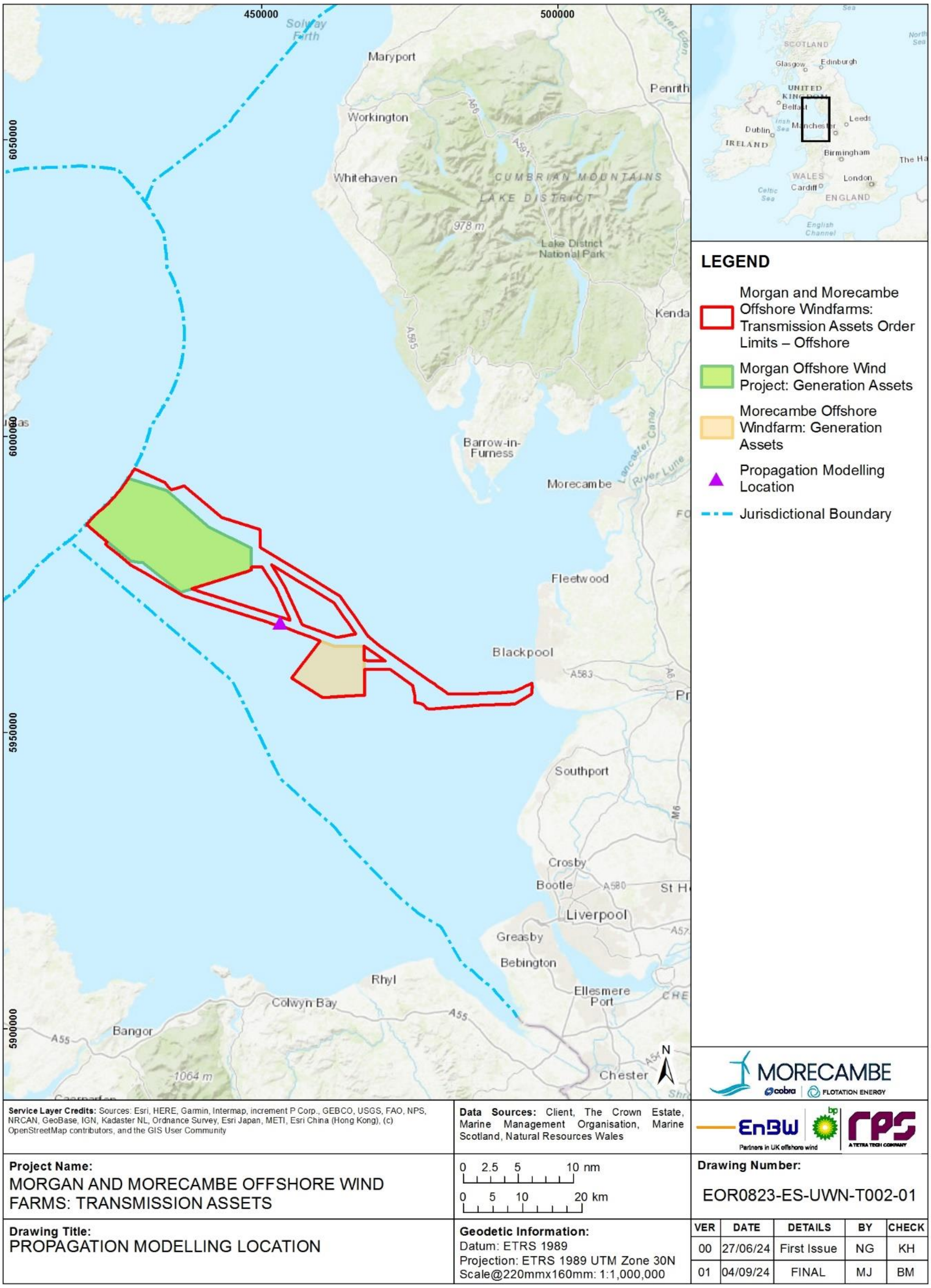

Figure 1.7: Propagation modelling location for the Transmission Assets

Table 1.18: Acoustical properties of the water layer and sediment used for propagation modelling calibration

Depth below sea floor [m]	Soil/Rock	Soil unit weight [kN/m³]	Wave velocity		Attenuation coeff		Density [kg/m³]
			V_p [m/s]	V_s [m/s]	α_p [dB/λ_p]	α_s [dB/λ_s]	
0	Water		1,493				1,000
0 - 1	Sand	20.5	1,806	124	0.8	2.5	2,090
1 - 2	Sand	20.5	1,825	154	0.8	2.5	2,090
2 - 3	Sand	20.5	1,836	174	0.8	2.5	2,090
3 - 4	Sand	20.5	1,843	190	0.8	2.5	2,090
4 - 5	Sand	20.5	1,850	202	0.8	2.5	2,090
5 - 6	Sand	20.5	1,855	213	0.8	2.5	2,090
6 - 7	Sand	20.5	1,859	222	0.8	2.5	2,090
7 - 8	Sand	20.5	1,863	230	0.8	2.5	2,090
8 - 9	Sand	20.5	1,866	238	0.8	2.5	2,090
9 - 10	Sand	20.5	1,869	245	0.8	2.5	2,090
10 - 15	Clay	22.9	1,515	127	0.2	1	2,334
15 - 75	Carboniferous Sandstone	22	3,933	2,105	0.1	0.2	2,243
75-200	Carboniferous Sandstone	22	4,020	3,134	0.1	0.2	2,265
200-300	Carboniferous Sandstone	22	4,123	3,215	0.1	0.2	2,288
300-400	Carboniferous Sandstone	22	4,217	3,288	0.1	0.2	2,308
400-500	Carboniferous Sandstone	22	4,300	3,353	0.1	0.2	2,326
500-600	Carboniferous Sandstone	22	4,375	3,412	0.1	0.2	2,341
600-700	Carboniferous Sandstone	22	4,445	3,466	0.1	0.2	2,356
700-800	Carboniferous Sandstone	22	4,510	3,516	0.1	0.2	2,370
800-900	Carboniferous Sandstone	22	4,571	3,564	0.1	0.2	2,382
900-1000	Carboniferous Sandstone	22	4,630	3,611	0.1	0.2	2,394
1000+	Halfspace (Sandstone)	22	4,660	3,634	0.1	0.2	2,400

1.7.2.12 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 hard and fast distance beyond which no effect can occur, and it would be equally misleading to present any sound modelling results in such a way.

1.7.3 Batch processing

1.7.3.1 To improve the performance and reduce the time taken to process and evaluate multiple TL calculations required for this study, Seiche Ltd's proprietary software was employed. This software iteratively evaluates the propagation modelling routine for the specified number of azimuthal bearings radiating from a source point, providing a fan of range-dependent TL curves departing from the sound source for each given frequency and receiver depth. In-house routines are then employed to interpolate the TL values across transects, to give an estimate of the sound field for the whole area around the source point.

1.7.3.2 Once the TL values were evaluated at the source points, in all azimuthal directions, and at all frequencies of interest for various sources, the results were then coupled with the corresponding SL values in third octave frequency bands. The combination of SL with TL data provided us with the third octave band RL at each point in the receiver grid (i.e. at each modelled range, depth, and azimuth of the receiver).

1.7.3.3 The received levels were evaluated for the SPL_{pk}, SPL_{rms} or SEL metric, for each source type, source location, and azimuthal transect to produce the associated 2-D maps. The broadband RL were then calculated for these metrics and from the third octave band results. The set of simulated RL transects were circularly interpolated to generate the broadband 2-D RL maps centred around each source point.

1.7.4 Exposure calculations

1.7.4.1 As well as calculating the un-weighted sound levels at various distances from different source, it is also necessary to calculate the received acoustic signal in terms of the SEL metric (where necessary and possible) for a marine mammal using the relevant hearing weighting functions. For different operations related 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 cSEL (cumulative SEL) metric for different marine mammal groups to assess potential impact ranges.

1.7.4.2 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 for mobile animals, as the 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.

1.7.4.3 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. The real world situation is more complex. The SEL calculations presented in this study do not take any breaks in activity into account, such as repositioning of vessels.

1.7.4.4 Furthermore, the sound criteria described in the Southall *et al.* (2019) 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 (Benda-Beckmann *et al*. 2022) and, therefore, the assessment of sound exposure level is conservative.

1.7.4.5 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.

1.7.4.6 As an animal swims away from the sound source, the sound it experiences will become progressively lower (more attenuated); the cumulative SEL 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.

1.7.4.7 The assumed swim speeds for animals likely to be present across the Transmission Assets are set out in **Table 1.19**.

Table 1.19: Assessment swim speeds of marine mammals and fish that are likely to occur within the Irish Sea for the purpose of exposure modelling.

[a] As a sensitivity check, exposure modelling has also been performed for stationary fish.

Species	Hearing group	Swim speed (m/s)	Source reference
Harbour seal *Phoca vitulina*	PCW	1.8	Thompson *et al.* (2015)
Grey seal *Halichoerus grypus*	PCW	1.8	Thompson *et al.* (2015)
Harbour porpoise *Phocoena phocoena*	VHF	1.5	Otani *et al.* (2000)
Minke whale *Balaenoptera acutorostrata*	LF	2.3	Boisseau *et al.* (2021)
Bottlenose dolphin *Tursiops truncatus*	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 *Cetorhinus maximus*	Group 1 fish	1.0	Sims *et al.* (2000)
All fish hearing groups[a] (excluding basking sharks)	Group 1 to 4 fish	0 and 0.5[a]	Popper *et al.* (2014)

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

1.7.4.9 To perform the cumulative exposure calculation, the first step is to parameterise the m-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.

1.7.5 Sonar Like Sources Directivity

1.7.5.1 An important factor affecting the received sound level from sonar like sources (SSS, SBP, MBES and SBES) is the source directivity characteristics, i.e. the directionality of the source. Sonar like sources are designed so that the majority of acoustic energy is directed downwards towards the ocean bottom (or within the swathe). Therefore, the amount of energy emitted outside the beam or swathe will be significantly less than that inside the beam.

1.7.5.2 Directivity is a frequency dependent effect and is more pronounced at higher frequencies than at lower frequencies. Directivity functions have been applied to the source sound level data based on based on the calculation methodologies set out in Ainslie (2010). Directivity factors were derived based on source take-off angle for an animal near the bottom of the water column. This results in a greater correction (reduction in level) due to directivity at distances further from the source than for receivers close to the source.

1.7.5.3 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 array. The cumulative SEL is then calculated based on the method described in **section 1.7.4**, taking into account the pulse rate and pulse width.

1.7.6 UXO sound modelling

High order detonation

1.7.6.1 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.

1.7.6.2 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.

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

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

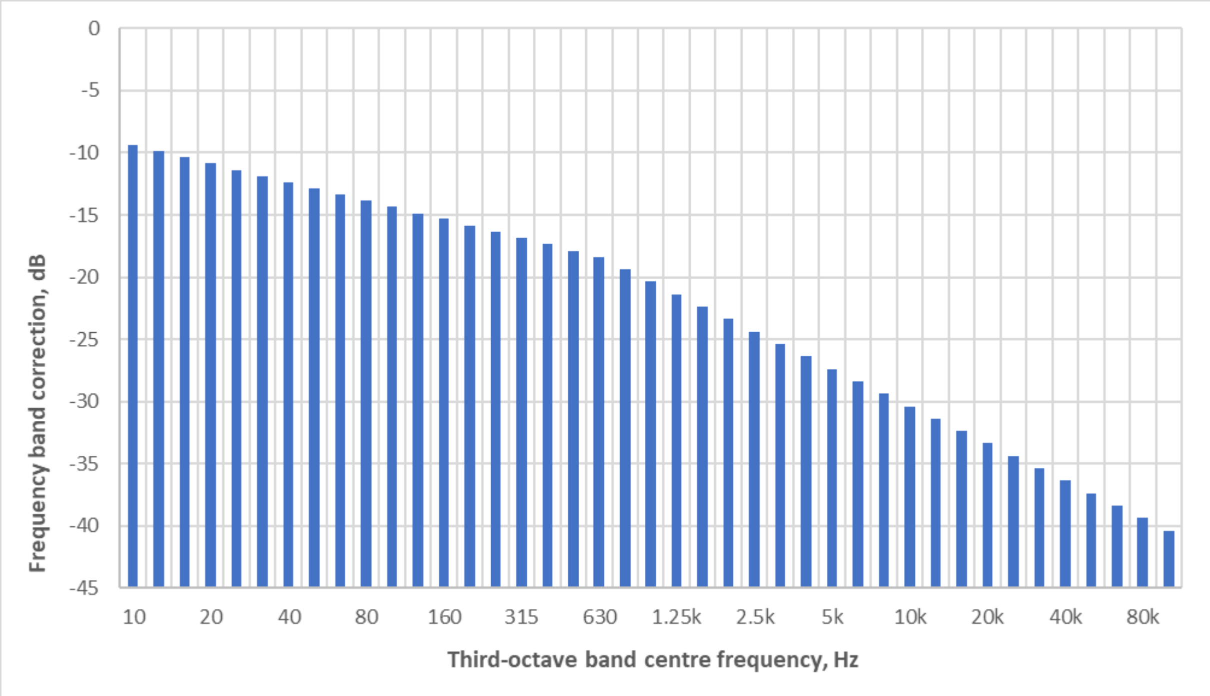

Figure 1.8: Assumed explosive spectrum shape used to estimate hearing weighting corrections to SEL

1.7.6.4 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 1.8**) 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.

Low order techniques

1.7.6.5 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.

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

1.8 Sound modelling results

1.8.1 Pre-construction phase

1.8.1.1 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 activities, UXO clearance and supported vessel activities.

1.8.1.2 The potential ranges presented for injury and disturbance 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 PTS 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 understandable way in which a wider audience can appreciate the potential spatial extent of the impact.

Geophysical and geotechnical surveys

1.8.1.3 Geophysical surveying includes many sonar like sound sources and the resulting injury and disturbance ranges for marine mammals are presented in

1.8.1.4 **Table 1.20**, based on a comparison to the non-impulsive thresholds set out in Southall *et al.* (2019).

1.8.1.5 **Table** 1.21 presents the results for geotechnical investigations. CPT distances are based on a comparison to the Southall *et al*. (2019) thresholds for impulsive sound (with the distances presented in brackets for peak SPL thresholds) whereas vibro-core results are compared against the non-impulsive thresholds.

1.8.1.6 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. It should be noted that, for the sonar-like survey sources, many of the injury ranges are limited to approximately 65 m as this is the approximate water depth in the area. 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 ranges are similar (i.e. limited by the depth of the water). Disturbance thresholds are, as shown in **Table 1.5**, for impulsive and non-impulsive sources respectively, noting that impulsive sources have both a strong and a mild disturbance threshold.

1.8.1.7 It should be noted that results are presented for the most precautionary case for sonar like sources (MBES, SSS, SBES and SBP) where a range of potential settings have been provided. For example, the SSS could operate at a frequency of 200 to 700 kHz, with a source level of 216 to 228 dB re 1 µPa re 1 m. For this source, the 200 kHz frequency setting results in the highest marine mammal weighted SEL and the 700 kHz frequency results in a significantly lower weighted SEL. Ruppel *et al.* (2022) propose four tiers of controlled active marine acoustic sources based on their impact on marine mammals. Tier four are classed as "*de minimis*" sources which are not likely to result in incidental take of marine mammals. Tier four includes, but is not limited to, all acoustic sources operating at source level of less than 160 dB re 1 µPa re 1 m or transmitting at frequencies higher than 180 kHz. MBES, SSS, SBES would likely be classed under Tier four which is consistent with the results of the acoustic modelling shown in

1.8.1.8 **Table 1.20** where the predicted injury ranges are small even for the worst case settings likely to be used in the survey. It should also be noted that the calculation assumes the sources will be operating continuously for a 24 hour period, which particularly in the case of the geotechnical surveys is highly unlikely to occur in reality.

Table 1.20: Potential Impact Ranges (m) for Marine Mammals During the Various Geophysical Site Investigation Activities Based on Comparison to Southall *et al.* (2019) SEL Thresholds

N/E- Not Exceeded

*Non-impulsive threshold

**Impulsive threshold

Source	Potential Impact Range (m)										
	LF		HF		VHF		PCW		OCW		All
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
MBES*	40	12	45	41	175	68	40	25	3	2	830
SSS*	29	2	29	2	46	41	37	6	5	N/E	310
SBES*	40	12	40	12	175	68	40	25	3	2	830
SBP (chirp/ pinger) *	76	40	76	40	2,300	254	81	40	40	38	17,300
UHRS (sparker) **	30	N/E	N/E	N/E	48	11	6	N/E	N/E	N/E	637 (mild) 95 (strong)

Table 1.21: Potential Impact Ranges (m) for Marine Mammals During the Various Geotechnical Site Investigation Activities Based on Comparison to Southall *et al.* (2019) SEL Thresholds (comparison to ranges for peak SPL where threshold was exceeded shown in brackets)

N/E- Not Exceeded

*Non-impulsive threshold

**Impulsive threshold

Source	Potential Impact Range (m)										
	LF		HF		VHF		PCW		OCW		All
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
Cone penetration testing**	117	4	9	N/E	950 (30)	55 (14)	39	N/E	N/E	N/E	1,350 (mild) 158 (strong)
Vibro-coring*	N/E	N/E	N/E	N/E	396	N/E	N/E	N/E	N/E	N/E	10,603

UXO clearance

1.8.1.9 The predicted injury ranges for low order disposal are presented in **Table 1.22**, for high order donor charges in

1.8.1.10 Table 1.23 and for high order detonation of UXOs in **Table 1.24**. All UXO injury and disturbance ranges are based on a comparison to the relevant impulsive sound thresholds as set out in **section 1.4.5**.

1.8.1.11 It should be noted that, due to a combination of dispersion (i.e. where the waveform elongates), multiple reflections from the sea surface and bottom and molecular absorption of high frequency 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 derived using the threshold criteria for impulsive sources 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 1.22: Potential Impact Ranges for Low Order and Low Yield UXO Clearance Activities

N/E- Not Exceeded

	PTS range, m		TTS range, m	
	SPL_{pk}	SEL	SPL_{pk}	SEL
0.08 kg low-order donor charge				
LF	122	47	224	655
HF	40	2	73	23
VHF	685	190	1,265	1,500
PCW	135	9	247	124
OCW	32	N/E	60	5
Fish (lower range)	44			
Fish (upper range)	27			
0.5 kg clearing shot				
LF	223	115	411	1,585
HF	73	4	134	56
VHF	1,265	421	2,325	2,435
PCW	247	22	455	301
OCW	60	N/E	110	13
Fish (lower range)	81			
Fish (upper range)	49			
2 x 0.75 kg low-yield charge				
LF	322	196	593	2,665

	PTS range, m		TTS range, m	
HF	105	7	194	95
VHF	1,820	650	3,350	3,120
PCW	357	38	660	504
OCW	86	2	158	23
Fish (lower range)	117			
Fish (upper range)	70			
4 x 0.75 kg low-yield charge				
LF	406	275	750	3,670
HF	133	10	244	131
VHF	2,290	840	4,220	3,600
PCW	449	53	830	695
OCW	108	2	199	32
Fish (lower range)	147			
Fish (upper range)	88			

Table 1.23: Potential Impact Ranges for Donor Charges used in High Order UXO Clearance Activities

	PTS range, m		TTS range, m	
	SPL_{pk}	SEL	SPL_{pk}	SEL
1.2 kg donor charge for high-order UXO disposal				
LF	299	176	551	2,400
HF	98	6	180	85
VHF	1,690	596	3,110	2,975
PCW	331	34	610	454
OCW	80	1	147	21
Fish (lower range)	108			
Fish (upper range)	65			
3.5 kg donor blast-fragmentation charge for high-order UXO disposal				
LF	427	297	790	3,940
HF	140	10	257	141
VHF	2,415	885	4,445	3,715
PCW	473	57	875	745
OCW	114	2	209	35
Fish (lower range)	154			
Fish (upper range)	93			

Table 1.24: Potential Impact Ranges for High Order Clearance of UXOs

	PTS range, m		TTS range, m	
	SPL_{pk}	SEL	SPL_{pk}	SEL
25 kg UXO – high order explosion				
LF	825	775	1,515	9,325
HF	268	27	494	343
VHF	4,645	1,645	8,555	5,290
PCW	910	147	1,680	1,760
OCW	219	6	403	90
Fish (lower range)	297			
Fish (upper range)	179			
130 kg UXO – high order explosion				
LF	1,425	1,705	2,625	17,755
HF	464	61	855	680
VHF	8,045	2,520	14,825	6,830
PCW	1,580	323	2,905	3,360
OCW	379	15	700	200
Fish (lower range)	514			
Fish (upper range)	309			
907 kg UXO – high order explosion				
LF	2,720	4,215	5,015	34,365
HF	890	151	1,635	1,380
VHF	15,370	3,820	28,320	8,925
PCW	3,015	800	5,550	6,470
OCW	725	37	1,335	501
Fish (lower range)	985			
Fish (upper range)	590			

1.8.2 Construction phase

1.8.2.1 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 1.25**. The potential impact ranges for fish are presented in **Table 1.26**.

Table 1.25: Potential Impact Ranges (m) for Marine Mammals During Construction Related Operations

N/E- Not Exceeded

Source	Potential Impact Ranges (m)										
	LF		HF		VHF		PCW		OCW		All
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
Cable trenching	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	3,430
Cable laying	N/E	N/E	N/E	N/E	< 60	N/E	N/E	N/E	N/E	N/E	2,335
Jack-up rig	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	<10

Table 1.26: Median Potential Impact Ranges (m) for Group 3 and 4 Fish Exposed to Other Construction Related Operations

N/E- Not Exceeded

Source	Injury Zone Radius (m)	
	Recoverable Injury	TTS
	170 dB rms for 48 hrs	158 dB rms for 12 hrs
Cable trenching	< 10	27
Cable laying	< 10	15
Jack-up rig	N/E	N/E

1.8.3 Vessels and other continuous sounds (all phases)

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

1.8.3.2 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.

1.8.3.3 The estimated median ranges for onset of TTS or PTS for different marine mammal groups exposure to different sound characteristics of different vessel traffic are shown in **Table 1.27**. The exposure metrics for different marine mammal and swim speeds (as detailed in **section 1.7.4**) were employed.

Table 1.27: Estimated PTS and TTS Ranges from Different Vessels for Marine Mammals

N/E- Not Exceeded

Source/Vessel	Range (m)										
	LF		HF		VHF		PCW		OCW		All
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
Boulder clearance	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	373
Jack up barge	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	<10
Tug/anchor handlers	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	1,442
Rock placement vessel, cable installation and sandwave clearance vessels	N/E	N/E	N/E	N/E	59	N/E	N/E	N/E	N/E	N/E	2,335
Guard vessels	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	1,442
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	4,021
Crew transfer vessel	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	4,021
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	4,021

1.8.3.4 The ranges for recoverable injury and TTS for Groups 3 and 4 Fish are presented in **Table 1.28** based on the thresholds contained in Popper *et al*. (2014). It should be noted that fish would need to be exposed within these potential impact ranges for a period of 48 hours continuously in the case of recoverable injury and 12 hours continuously in the case of TTS for the effect to occur. It is therefore considered that these ranges are highly precautionary, and injury is unlikely to occur in reality, as the fish is unlikely to stay in the vicinity of the vessel for the entire time period.

Table 1.28: Estimated Recoverable Injury and TTS Ranges from Vessels for Groups 3 and 4 Fish

N/E- Not Exceeded

Source/Vessel	Injury Zone Radius (m)	
	Recoverable Injury	TTS
	170 dB rms for 48 hrs	158 dB rms for 12 hrs
Boulder clearance	N/E	< 10
Jack up rig	N/E	N/E
Tug/anchor handlers	N/E	< 10
Rock placement vessel, cable installation and sandwave clearance vessels	< 10	27
Guard vessels	N/E	< 10
Survey vessel and support vessels	N/E	< 20
Crew transfer vessel	N/E	< 20
Cable Protection/Seabed Preparation/Installation Vessels	N/E	< 20

1.9 Particle motion

1.9.1 Introduction

1.9.1.1 This Underwater Sound Technical Report provides an analysis of the effects of sound on marine life. However, there are uncertainties in relation to the presence of compression and interface waves at the water/ground substrate boundary during activities, 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 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 UXO clearance. However, the Popper *et al.* (2014) paper primarily addresses high amplitude sounds and high dynamic pressure, rather than particle motion.

1.9.1.2 The majority of measurements are undertaken using hydrophones in the water column which includes contributions from both direct radiated sound, 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 source could be under-estimated, particularly for species primarily sensitive to vibration of the seafloor sediment.

1.9.1.3 To put this issue into perspective, under section 5.1 entitled “Death or Injury”, Popper *et al.* (2014) states 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 for this issue to be currently assessed. Thus, in terms of potential damage to fish, Volume 2, Chapter 3: Fish and shellfish of the ES has addressed the impact as far as is practicable with the existing state of knowledge, based primarily on exposure to sound pressure.

1.9.1.4 The purpose of this chapter is to provide an overview of the acoustic aspects of particle motion. Potential effects on marine life are dealt with in the marine ecology topic chapters of the ES.

1.9.2 Overview of particle motion

1.9.2.1 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 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 (ms^{-2}), u = particle velocity (ms^{-1}), $2\pi f$ = angular frequency, and ξ = displacement (m).

1.9.2.2 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.

1.9.2.3 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.

1.9.2.4 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).

1.9.2.5 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.

1.9.2.6 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 a Sound Pressure Level (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).

1.9.3 Hearing in fish and invertebrates

1.9.3.1 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).

1.9.3.2 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).

1.9.3.3 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 focussed on particle motion specifically (Popper and Hawkins, 2019).

1.9.3.4 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).

1.9.4 Effects of sound and particle motion

1.9.4.1 Potential effects of sound 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 life. 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.
  - 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 fishes.
  - While experiencing TTS, fish may have a decrease in fitness in terms of communication, detecting predators or prey, and/or assessing their environment.
  - 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 and sea turtles. 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.
  - 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.

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

- Fishes 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.
- Sea turtles.
- Fish eggs and larvae.

1.9.4.3 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; Discovery of Sound in the Sea). 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 processes like UXO clearance that generate sound deep into the substrate. The repercussion of this is that offshore 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).

1.9.4.4 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, for example, 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.

1.9.5 Potential range of effects due to particle motion at the Transmission Assets

1.9.5.1 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 life for the Transmission Assets.

1.9.5.2 An added complication in predicting particle motion is the propagation of sound through the substrate. This is particularly prominent in UXO clearance activities where the UXO is partially or completely buried in the substrate, the detonation could cause a considerable wave through the substrate. This particle motion can impact the benthic species in the area with potential for injury or due to behavioural reactions. 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).

1.9.5.3 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 UXO clearance at the Transmission Assets, 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 and effects on marine life, 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.

1.10 Conclusions

1.10.1.1 Acoustic modelling has been undertaken to determine distances at which potential effects on marine mammals, fish, and sea turtles may occur due to underwater sound associated with construction of the Transmission Assets. Injury ranges have been derived based on the thresholds set out in Southall *et al.* (2019) for marine mammals and Popper *et al.* (2014) for fish.

1.10.1.2 The maximum PTS injury ranges for the various sources are as follows.

- The maximum ranges for geophysical sources is for the SBP "chirp/pinger", which resulted in injury ranges for LF cetaceans of 40 m and VHF of 254 m, and which also resulted in the maximum disturbance range of 17 km.
- The were no exceedances of the PTS thresholds for any construction sources, the greatest disturbance range was found to be 3.4 km for the cable trenching activities.

- There were no exceedances of the PTS thresholds for any vessel sources, the maximum disturbance range was found to be 4 km.
- There were no exceedances of the recoverable injury thresholds for groups 3 and 4 fish of more than 10 m for any sources.

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