Environmental Impact Assessment Report - Volume 2B

Appendix 10-2:
Subsea Noise Technical Report

C1 - Public

ORIEL WIND FARM PROJECT

Environmental Impact Assessment Report
Appendix 10-2: Subsea Noise Technical Report

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Glossary

Term	Meaning
Decibel	A customary scale most commonly used (in various ways) for reporting levels of sound. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be 10 log10(actual/reference), where (actual/reference) is a power ratio. The standard reference for underwater sound pressure is 1 micro-Pascal (μPa), and 20 micro-Pascals is the standard for airborne sound. The dB symbol is followed by a second symbol identifying the specific reference value (i.e. re 1 μPa).
Grazing angle	A glancing angle of incidence (the angle between a ray incident on a surface and the line perpendicular to the surface).
Peak pressure	The highest pressure above or below ambient that is associated with a sound wave.
Permanent Threshold Shift (PTS)	A total or partial permanent loss of hearing caused by some kind of acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the ear, and thus a permanent reduction of hearing acuity.
Sound Exposure Level (SEL)	The representation of a noise event if all the energy were compressed into a 1 second period. This provides a uniform way to make comparisons between noise events of different durations.
Temporary Threshold Shift (TTS)	Temporary loss of hearing as a result of exposure to sound over time. Exposure to high levels of sound over relatively short time periods will cause the same amount of TTS as exposure to lower levels of sound over longer time periods. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory cells. The duration of TTS varies depending on the nature of the stimulus, but there is generally recovery of full hearing over time.

Acronyms

Term	Meaning
ADD	Acoustic Deterrent Device
ANSI	American National Standards Institute
Cefas	Centre for Environment, Fisheries and Aquaculture Science
cSEL	Cumulative SEL
CTV	Crew Transfer Vessel
DP	Dynamic Positioning
EIAR	Environmental Impact Assessment Report
HESS	High Energy Seismic Survey
HF	High Frequency (Cetaceans)
LCRI	Low Carbon Research Institute
LF	Low Frequency (Cetaceans)
MF	Mid Frequency (Cetaceans)
NIOSH	National Institute for Occupational Safety and Health
NMFS	National Marine Fisheries Service
OCA	Other Marine Carnivores in Air
OCW	Other Marine Carnivores in Water
OSS	Offshore Substation
OW	Otariid pinnipeds
PCW	Phocid Carnivores in Water
PE	Parabolic Equation
PTS	Permanent Threshold Shift
PW	Phocid pinnipeds
RAM	Range-dependent Acoustic Model
RMS or rms	Root Mean Square
SEL	Sound Exposure Level
SL	Source Level
SPL	Sound Pressure Level
TTS	Temporary Threshold Shift
VHF	Very High Frequency
WTGs	Wind Turbine Generators

Units

Unit	Description
dB	Decibel (Sound)
Hz	Hertz (Frequency)
kHz	Kilohertz (Frequency)
kJ	Kilojoule (Energy)
km	Kilometre (Distance)
km^2	Kilometre squared (Area)
m	Metre
ms	Millisecond (10^{-3} seconds) (Time)
ms^{-1} or m/s	Metres per second (Velocity)
MW	Megawatt
µPa	Micro Pascal
Pa	Pascal (Pressure)
pH	Power of hydrogen

1 SUBSEA NOISE TECHNICAL REPORT

1.1 Introduction

This Subsea Noise Technical Report presents the results of a desktop study considering the potential effects of underwater noise on the marine environment from the Oriel Wind Farm Project (hereafter referred to as “the Project”).

Sound is readily transmitted into the underwater environment and there is potential for the sound emissions from the survey to adversely affect marine mammals and fish. At close ranges from the noise source with high noise levels, permanent or temporary hearing damage may occur to marine species, while at a very close range gross physical trauma is possible. At long ranges the introduction of any additional noise could potentially cause short-term behavioural changes, for example to the ability of species to communicate and to determine the presence of predators, food, underwater features, and obstructions.

This report provides an overview of the potential effects due to underwater noise from the Project on the surrounding marine environment. The results from this underwater noise appraisal have been used to inform chapter 9: Fish and Shellfish Ecology and chapter 10: Marine Mammals and Megafauna of the Project Environmental Impact Assessment Report (EIAR) (see volume 2B) in order to determine the potential impact of underwater noise on marine life.

Consequently, the primary purpose of the underwater noise appraisal is to predict the likely range of onset for potential physiological and behavioural effects due to increased anthropogenic noise due to the construction of the Project. The sensitivity of species, magnitude of impact and significance of impact from underwater noise associated with the Project are addressed within chapter 9: Fish and Shellfish Ecology and chapter 10: Marine Mammals and Megafauna.

1.2 Acoustic concepts and terminology

Sound travels through water as vibrations of the fluid particles in a series of pressure waves. The waves comprise a series of alternating compressions (positive pressure variations) and rarefactions (negative pressure fluctuations). Because sound consists of variations in pressure, the unit for measuring sound is usually referenced to a unit of pressure, the Pascal (Pa). The unit usually used to describe sound is the decibel (dB) and, in the case of underwater sound, the reference unit is taken as 1 µPa, whereas airborne sound is usually referenced to a pressure of 20 µPa. To convert from a sound pressure level referenced to 20 µPa to one referenced to 1 µPa, a factor of 20 log (20/1) i.e. 26 dB has to be added to the former quantity. Thus, a sound pressure of 60 dB re 20 µPa is the same as 86 dB re 1 µPa, although care also needs to be taken when converting from in air noise to in water noise levels due to the different sound speeds and densities of the two mediums resulting in a conversion factor of 62 dB. All underwater sound pressure levels in this report are described in dB re 1 µPa. In water, the sound source strength is defined by its sound pressure level in dB re 1 µPa, referenced back to a representative distance of 1 m from an assumed (infinitesimally small) point source. This allows calculation of sound levels in the far-field. For large distributed sources, the actual sound pressure level in the near-field will be lower than predicted.

There are several descriptors used to characterise a sound wave. The difference between the lowest pressure variation (rarefaction) and the highest pressure variation (compression) is the peak to peak (or pk-pk) sound pressure level. The difference between the highest variation (either positive or negative) and the ambient 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. These descriptions are shown graphically in Figure 1-1.

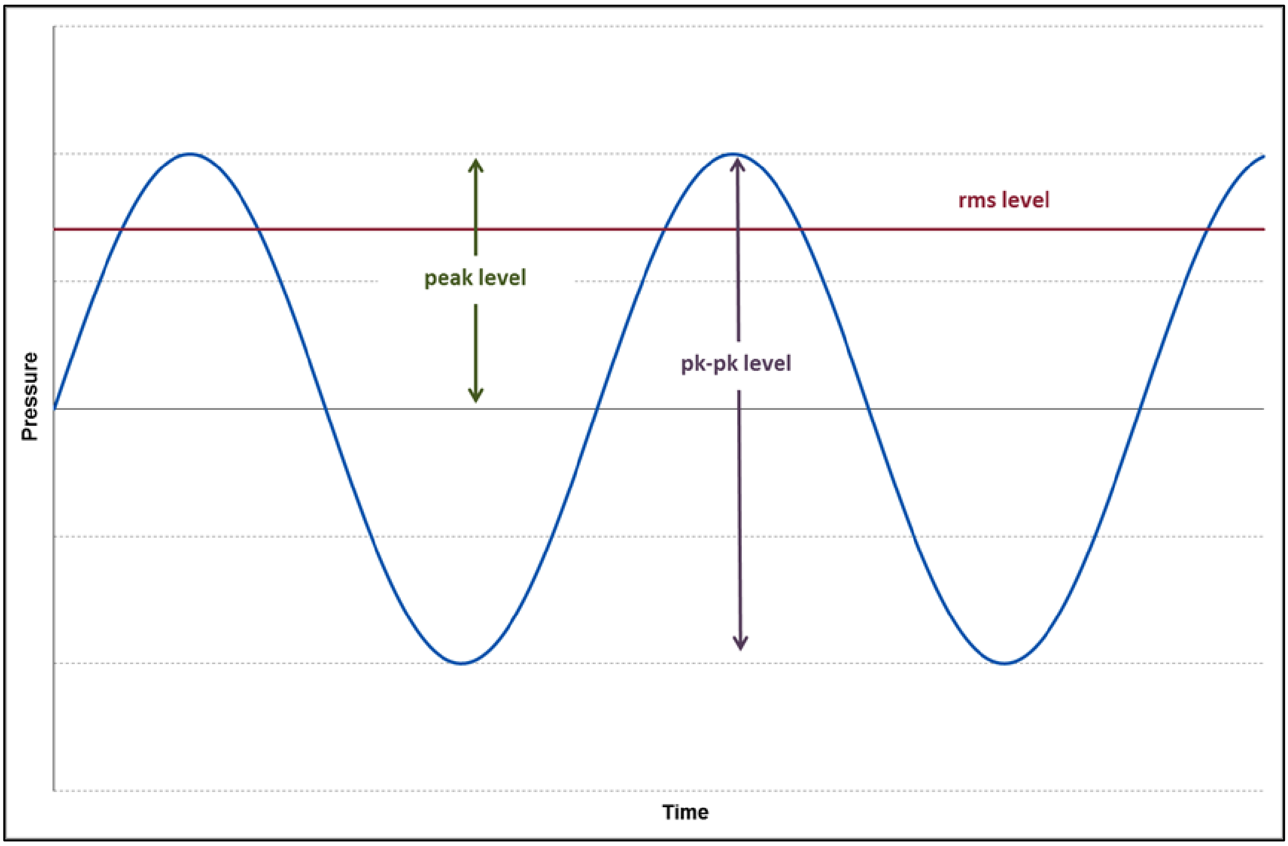


Figure 1-1: Graphical representation of acoustic wave descriptors.

The rms sound pressure level (SPL) is defined as follows:

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

Another useful measure of sound used in underwater acoustics is the Sound Exposure Level, or 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. Historically, use was primarily made of rms and peak sound pressure level metrics for assessing the potential effects of sound on marine life. However, the SEL is increasingly being used as it allows exposure duration and the effect of exposure to multiple events over a 24 hour period to be taken into account. The SEL is defined as follows:

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

The frequency, or pitch, of the sound is the rate at which these oscillations occur 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 faculties of marine mammals and fish are not the same as humans, with marine mammals hearing over a wider range of frequencies, fish over a typically smaller range of frequencies and both with different sensitivities. It is therefore important to understand how an animal's hearing varies over the entire frequency range in order to assess the effects of sound on marine life. Consequently, use can be made of frequency weighting scales to determine the level of the sound in comparison with the auditory response of the animal concerned. A comparison between the typical hearing response curves for fish, humans and marine mammals is shown in Figure 1-2. 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. It is also worth noting that some fish are sensitive to particle velocity rather than pressure, although paucity of data relating to particle velocity levels for anthropogenic noise sources means that it is often not possible to quantify this effect.

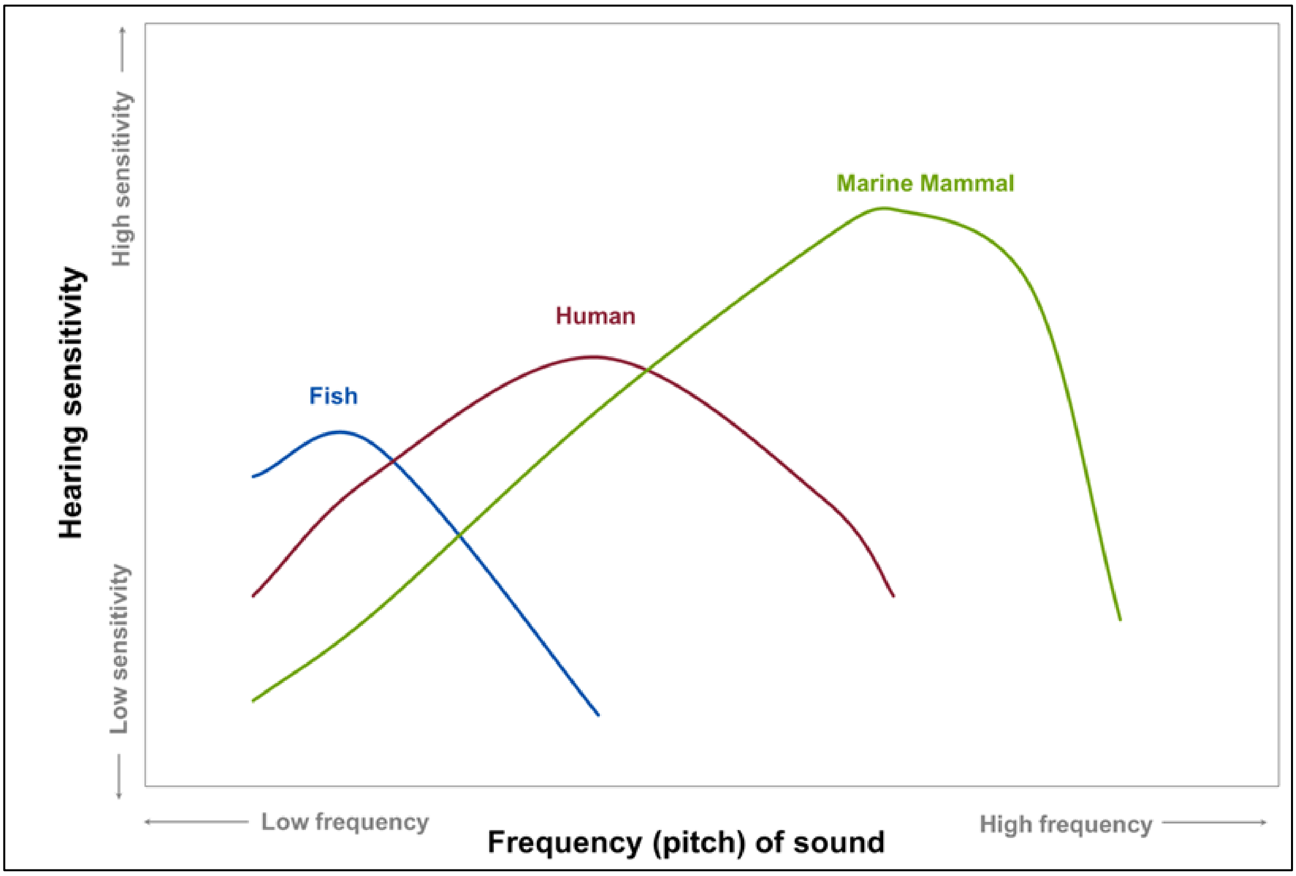


Figure 1-2: Comparison between hearing thresholds of different marine animals and humans.

1.3 Review of sound propagation concepts

Increasing the distance from the noise source usually results in the level of noise getting lower, due primarily to the spreading of the sound energy with distance, analogous to the way in which the ripples in a pond spread after a stone has been thrown in.

The way that the noise spreads will depend upon several factors such as water column depth, pressure, temperature gradients, salinity, as well as water surface and 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.

In acoustically shallow waters[1] in particular, the propagation mechanism is coloured by multiple interactions with the seabed and the water surface (Lurton, 2002; Etter, 2013; Urick, 1983; Brekhovskikh and Lysanov 2003, Kinsler *et al*., 1999). Whereas in deeper waters, the sound will propagate further without encountering the surface or bottom of the sea, in shallower waters the sound may be reflected from either or both boundaries (potentially more than once).

[1] Acoustically, shallow water conditions exist whenever the propagation is characterised by multiple reflections with both the sea surface and seabed (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.

At the sea surface, the majority of sound is reflected back into the water due to the difference in acoustic impedance (i.e. sound speed and density) between air and water. However, scattering of sound at the surface of the sea is an important factor with respect to the propagation of sound from a source. In an ideal case (i.e. for a perfectly smooth sea surface), the majority of sound wave energy will be reflected back into the sea. However, for rough waters, much of the sound energy is scattered (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.

Because surface scattering results in differences in reflected sound, its effect will be more important at longer ranges from the source sound 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 water surface smoothness/wind speed, water depth, frequency of the sound, temperature gradient, grazing angle and range from source. Depending upon variations in the aforementioned factors, significant scattering could occur at sea state 3 or more for higher frequencies (e.g. 15 kHz or more). It should be noted that variations in propagation due to scattering will vary temporally (primarily due to different sea-states/wind speeds at different times) and that more sheltered areas (which are more likely to experience calmer waters) could experience surface scattering to a lesser extent, and less frequently, than less sheltered areas which are likely to encounter rougher waters. However, over shorter ranges (e.g. a few hundred meters or less) the sound will experience fewer reflections and so the effect of scattering should not be significant. Consequently, taking into account the sheltered location of the Offshore Wind Farm Area (i.e. to the east of Dundalk Bay) and likely distances over which injury will occur, this effect is unlikely to significantly affect the injury ranges presented in this report, although it is possible that disturbance ranges could vary depending on local and seasonal conditions.

When sound waves encounter the seabed, the amount of sound reflected will depend on the geoacoustic properties of the seabed (e.g. grain size, porosity, density, sound speed, absorption coefficient and roughness) as well as the grazing angle and frequency of the sound (Cole, 1965; Hamilton, 1970; Mackenzie, 1960; McKinney and Anderson, 1964; Etter, 2013; Lurton, 2002; Urick, 1983). Thus, seabeds comprising primarily of mud or other acoustically soft sediment will reflect less sound than acoustically harder seabeds such as rock or sand. This will also depend on the profile of the seabed (e.g. the depth of the sediment layer and how the geoacoustic properties vary with depth below the sea floor). The effect is less pronounced at low frequencies (a few kHz and below) and so might not be a significant factor to take into account with respect to piling noise (where most of the acoustic energy is at frequencies of a few hundred Hz). 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).

Another phenomenon is the waveguide effect which means that shallow water columns 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. Any sound below this frequency will not propagate far due to energy losses through multiple reflections. The cut-off frequency as a function of water depth is shown in Figure 1-3 for a range of seabed types. Thus, for a water depth of 10 m (i.e. shallow waters typical of coastal areas and estuaries) the cut-off frequency would be approximately 70 Hz for sand, 100 Hz for silt, 140 Hz for clayey silt and 40 Hz for bedrock.

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.

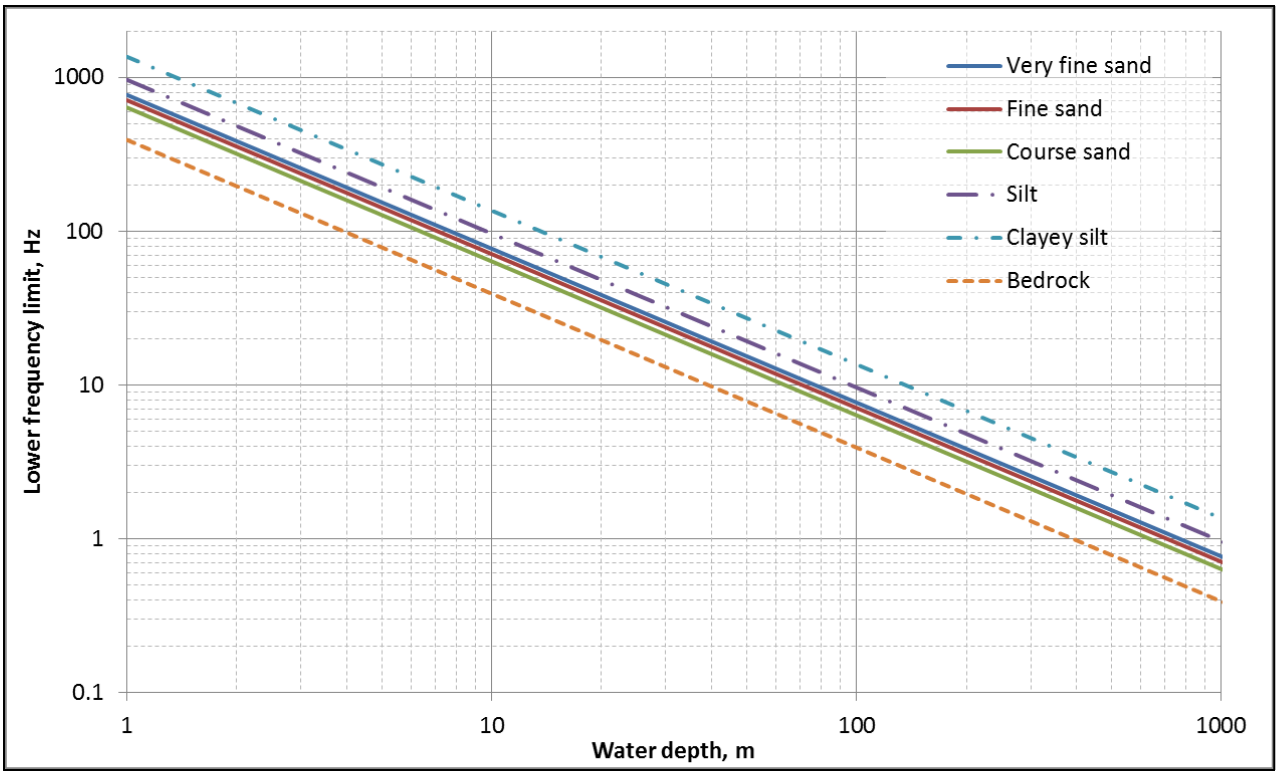


Figure 1-3: Lower cut-off frequency as a function of depth for a range of seabed types.

Sound energy can also be 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. This is shown in Figure 1-4. Although the effect of this absorption will be higher in cold water and with higher levels of magnesium sulphate, $MgSO^4$, these variations are relatively insignificant.

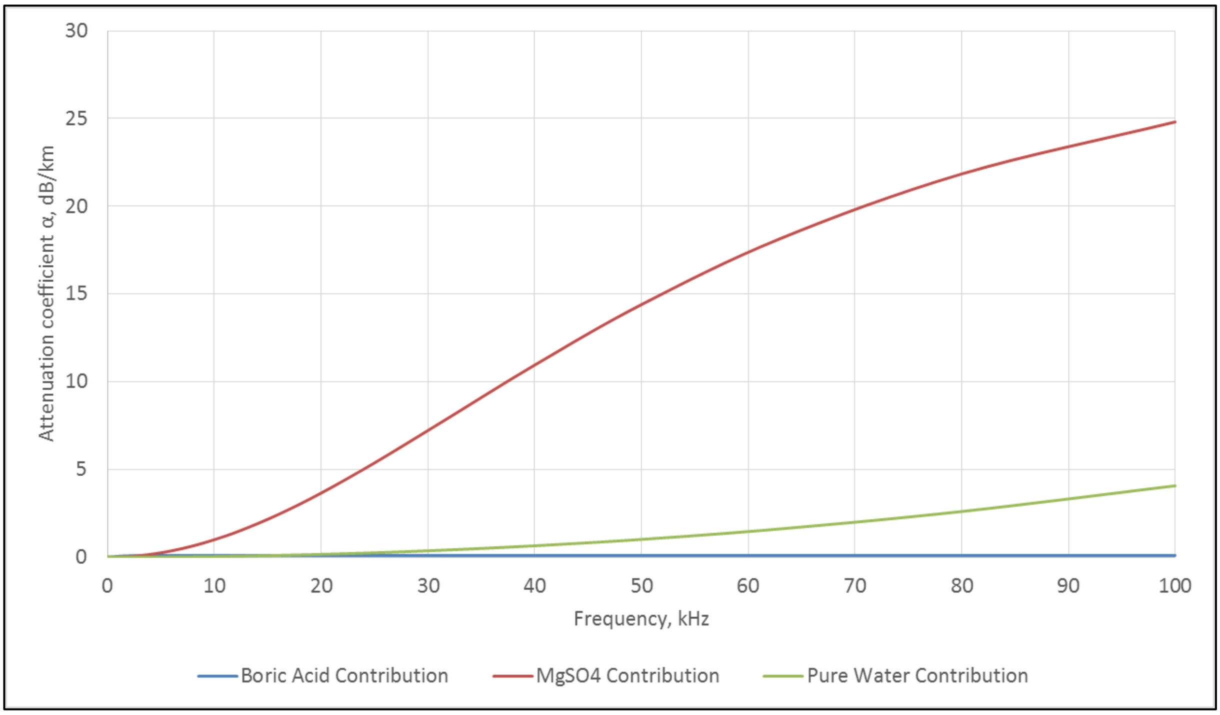


Figure 1-4: Absorption loss coefficient (α), dB/km (pH 8, 5 ºC, salinity 35 ppt).

1.4 Assessment criteria

1.4.1 General

In order to determine the potential spatial range of injury and disturbance, assessment criteria have been developed based on a review of available evidence including national and international guidance and scientific literature. The following sections summarise the relevant criteria and describe the evidence base used to derive them.

Underwater noise has the potential to affect marine life in different ways depending on its noise level and characteristics. Assessment criteria generally separate sound into two distinct types, 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; NIOSH 1998; ANSI 2005). This category includes sound sources such as seismic surveys, impact piling and underwater explosions; and
- **Non-impulsive (continuous) sounds** which can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent and typically do not have a high peak sound pressure with rapid rise/decay time that impulsive sounds do (ANSI 1995; NIOSH 1998). This category includes sound sources such as continuous vibro-piling, running machinery, sonar and vessels.

The acoustic assessment criteria for marine mammals and fish in this report has followed the latest international guidance (based on the best available scientific information), that are widely accepted for assessments in the UK, Europe and worldwide.

1.4.2 Injury to marine mammals

Underwater noise has the potential to affect marine life in different ways depending on its noise level and characteristics. Richardson *et al.* (1995) defined four zones of noise 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 noise 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 (for example, humans can hear tones well below the numeric value of the overall noise level).

- **The zone of responsiveness**: this is defined as the area within which the animal responds either behaviourally or physiologically. The zone of responsiveness is usually smaller than the zone of audibility because, as stated previously, audibility does not necessarily evoke a reaction.

- **The zone of injury / hearing loss**: this is the area where the sound level is high enough to cause tissue damage in the ear. This can be classified as either Temporary Threshold Shift (TTS) or Permanent Threshold Shift (PTS). At even closer ranges, and for very high intensity sound sources (e.g. underwater explosions), physical trauma or even death are possible.

For this study, 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.

The zone of injury in this study is classified as the distance over which a marine mammal can suffer a PTS leading to non-reversible auditory injury. Injury thresholds are based on a dual criteria approach using both linear (i.e. un-weighted) peak SPL and marine mammal hearing-weighted SELs. The hearing weighting function is designed to represent the bandwidth for each group within which acoustic exposures can have auditory effects. The categories include:

- **Low Frequency (LF) cetaceans**: i.e. marine mammal species such as baleen whales (e.g. minke whale *Balaenoptera acutorostrata*);

- **High Frequency (HF) cetaceans**: i.e. marine mammal species such as dolphins, toothed whales, beaked whales and bottlenose whales (e.g. bottlenose dolphin *Tursiops truncates* and white-beaked dolphin *Lagenorhynchus albirostris*);

- **Very High Frequency (VHF) cetaceans**: i.e. 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)/ Phocid pinnipeds in water (PW)**: i.e. true seals (e.g. harbour seal *Phoca vitulina* and grey seal *Halichoreus grypus*); hearing in air is considered separately in the group 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).

These weightings have therefore been used in this study and are shown in Figure 1-5. It should be noted that not all of the above categories of marine mammal will be present in the Marine Megafauna Study Area (as defined in chapter 10: Marine Mammals and Megafauna) but criteria are presented in this report for completeness.

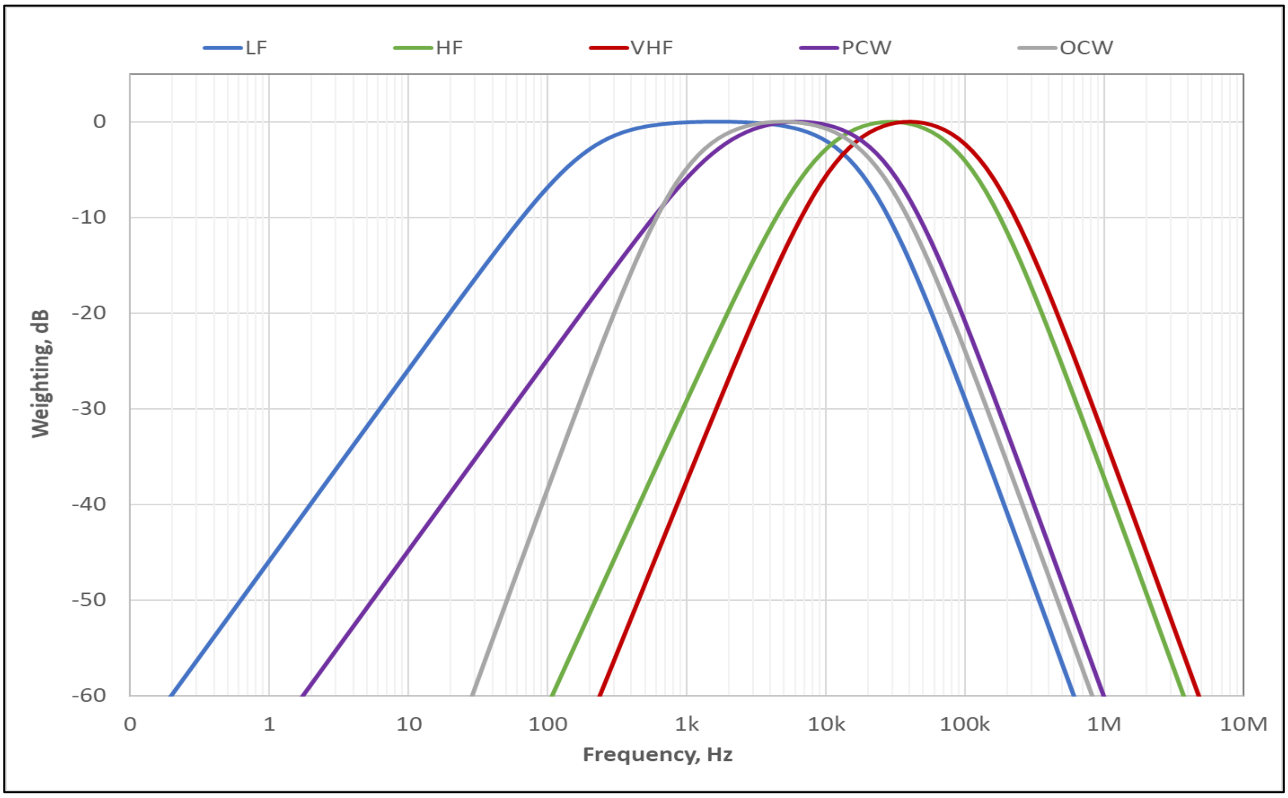


Figure 1-5: Hearing weighting functions for pinnipeds and cetaceans (NMFS, 2018).

The criteria for impulsive and non-impulsive sound have been adopted for this study given the nature of the sound source used during construction activities. The relevant criteria proposed by Southall *et al*. (2019) are as summarised in Table 1-1.

These updated marine mammal injury 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 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 1-2.

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 1-1: Summary of PTS and TTS onset acoustic thresholds (Southall *et al., 2019*; Tables 6 and 7).

Hearing Group	Parameter	Impulsive		Non-impulsive	
		PTS	TTS	PTS	TTS
Low frequency (LF) cetaceans	Peak, dB re 1 µPa (unweighted)	219	213	-	-
	SEL, dB re 1 µPa²s (LF weighted)	183	168	199	179
High frequency (HF) cetaceans	Peak, dB re 1 µPa (unweighted)	230	224	-	-
	SEL, dB re 1 µPa²s (MF weighted)	185	170	198	178
Very high frequency (VHF) cetaceans	Peak, dB re 1 µPa (unweighted)	202	196	-	-
	SEL, dB re 1 µPa²s (HF weighted)	155	140	173	153
Phocid carnivores in water (PCW)	Peak, dB re 1 µPa (unweighted)	218	212	-	-
	SEL, dB re 1 µPa²s (PW weighted)	185	170	201	181

Other marine carnivores in water (OCW)	Peak, dB re 1 µPa (unweighted)	232	226	-	-
	SEL, dB re 1 μPa^2s (OW weighted)	203	188	219	199

Table 1-2: 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

Under current legislation in Ireland[2], it is an offence to disturb or injure a marine mammal whether this occurs via introduced sound or another anthropogenic source. The induction of temporary or permanent tissue damage and a Temporary Threshold Shift (TTS) in hearing sensitivity, which can have negative effects on the ability to use natural sounds (e.g. to communicate, navigate, locate prey) for a period of minutes, hours or days may constitute such an injury. It is therefore considered that anthropogenic sound sources with the potential to induce TTS in a receiving marine mammal contain the potential for both disturbance and injury to the animal.

UK industry guidelines on the prevention of injury to marine mammals recommend that only PTS is considered to result in injury for which appropriate mitigation should be followed (JNCC, 2010). The equivalent guidance in Ireland on managing the risk to marine mammals from subsea noise, suggests that risks to protected species should also be assessed with respect to the potential for TTS to occur (NPWS, 2014). The NMFS (2018) and Southall *et al*. (2019) guidelines define TTS as a 6 dB shift in the hearing threshold. Although animals are able to recover fully from TTS, particularly as they move away from a source, hearing loss may become permanent if TTS occurs over a sustained period of time, and if hearing does not return to pre-impact levels. Thus, the distinction between TTS and PTS depends on whether there is complete recovery of the individual's hearing or not.

This assessment considers the potential for a permanent injury to occur by considering two different noise thresholds that could lead to PTS. First, the peak injury thresholds are used to determine potential ranges for instantaneous injury to each species from a single hammer strike. Second, the marine mammal hearing-weighted cumulative SELs were modelled and as described previously, these assume that a marine mammal exposed to noise levels over a prolonged period could experience permanent hearing loss. Thus, as per the NPWS guidance (2014), this assessment considers whether there is the potential for injury to occur.

For completeness, and in line with NPWS (2014), this assessment also considers the range at which the onset of TTS could occur (leading to a reversible hearing loss) using the most recent thresholds (Southall *et al.,* 2019). The most likely response of a marine mammal to noise levels that could induce TTS is to flee from the ensonified area (Southall *et al*., 2019) and subsequently the onset of TTS can be referred to as the fleeing response. This is therefore a behavioural response that overlaps with disturbance ranges and animals exposed to these noise levels are likely to actively avoid hearing damage by moving away from the area.

1.4.3 Disturbance to marine mammals

Beyond the area in which injury may occur, the effect on marine mammal behaviour is the most important measure of potential impact. Significant (i.e. non-trivial) disturbance may occur when there is a risk of

[2] The EC Directive on the conservation of natural habitats and of wild flora and fauna (the Habitats Directive, Council Directive 92/43/EEC) transposed into national law by the European Communities (Birds and Natural Habitats) Regulations 2011 (S.I. No. 477 of 2011).

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.

To consider the possibility of significant disturbance resulting from the Project, it is therefore necessary to consider 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. 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.

Southall *et al.* (2007) recommended that the only currently feasible way to assess whether a specific sound could cause disturbance is to compare the circumstances of the situation with empirical studies. Joint Nature Conservation Committee (JNCC) guidance in the UK (JNCC, 2010) indicates that a score of five or more on the Southall *et al*. (2007) behavioural response severity scale could be significant. The more severe the response on the scale, the lower the amount of time that the animals will tolerate it before there could be significant adverse effects on life functions, which would constitute a disturbance.

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

Continuous (non-pulsed, non-impulsive) sound

For non-pulsed sound (e.g. drilled piles, vessels etc.), the lowest sound pressure level at which a score of five or more occurs for low frequency cetaceans is 90 dB to 100 dB re 1 µPa (rms). However, this relates to a study involving migrating grey whales. A study for minke whales 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 Project. 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 *Tursiops truncatus*, 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).

The NMFS (2005) guidance sets the marine mammal level B harassment threshold for continuous noise 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 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, it is recommended that any ranges predicted using this number are viewed as probabilistic and potentially over precautionary.

Impulsive (pulsed) sound

Southall *et al*. (2007) presents a summary of observed behavioural responses due to multiple pulsed sound, although the data are primarily based on responses to seismic exploration activities (rather than for piling). Although these datasets contain much relevant data for LF cetaceans, there are no strong data for MF or HF cetaceans. Low frequency cetaceans, other than bow-head whales, were typically observed to respond significantly at a received level of 140 dB to 160 dB re 1 µPa (rms). Behavioural changes at these levels during multiple pulses may have included visible startle response, extended cessation or modification of vocal behaviour, brief cessation of reproductive behaviour or brief/minor separation of females and dependent offspring. The data available for MF cetaceans indicate that some significant response was observed at a SPL of 120 dB to 130 dB re 1µPa (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 1µPa (rms). Furthermore, other MF cetaceans within the same study were observed to have no behavioural response even when exposed to a level of 170 dB to 180 dB re 1µPa (rms).

A more recent study is described in Graham *et al*. (2017). Empirical evidence from piling at the Beatrice Offshore Wind Farm (Moray Firth, Scotland) was used to derive a dose-response curve for harbour porpoise. The unweighted single pulse SEL contours were plotted in 5 dB increments and applied the dose-response curve to estimate the number of animals that would be disturbed by piling within each stepped contour. The study shows a 100% probability of disturbance at an (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 is an accepted approach to understanding the behavioural effects from piling and has been applied at other UK offshore wind farms (for example Seagreen and Hornsea Three).

According to Southall *et al.* (2007) there is 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 noise levels of up to 180 dB re 1 μPa (rms). It is only at much higher sound pressure levels 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 noise 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.

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[3] rms sound pressure level of 166 dB re 1 μPa.

Clearly, 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.

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.

This assessment adopts a conservative approach and uses the NMFS (2005) Level B harassment threshold of 160 dB re 1 μPa (rms) for impulsive sound, excluding piling which is assessed based on SEL in volume 2 chapter 10 as presented in Table 1-3. 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.

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.

[3] Based on an analysis of the time history graph in Lucke et al. (2008), 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.

Table 1-3: Disturbance criteria for marine mammals used in this study.

Effect	Non-Impulsive Threshold	Impulsive Threshold (Other than Piling)	Impulsive Threshold (Piling)
Mild disturbance (all marine mammals)	-	140 dB re 1µ Pa (rms)	Based on SEL 5 dB contours
Strong disturbance (all marine mammals)	120 dB re 1µ Pa (rms)	160 dB re 1µ Pa (rms)	Based on SEL 5 dB contours
Disturbance (harbour porpoise)		Based on SEL 5 dB contours	Based on SEL 5 dB contours

1.4.4 Injury and disturbance to fish and sea turtles

Adult fish not in the immediate vicinity of the noise generating activity are generally able to vacate the area and avoid physical injury. However, larvae and eggs are not highly mobile and are therefore more likely to incur injuries from the sound energy in the immediate vicinity of the sound source, including damage to their hearing, kidneys, hearts and swim bladders. Such effects are unlikely to happen outside of the immediate vicinity of even the highest energy sound sources.

For fish, the most relevant criteria for injury are considered to be those contained in the recent Sound Exposure Guidelines for Fishes and Sea Turtles (Popper *et al*., 2014). Popper *et al*. (2014) guidelines do not group by species but instead 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 shark *Cetorhinus maximus*, which does not have a swim bladder, falls 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 *Clupea harengus*, sprat *Sprattus spp.* and shads (*Alosinae*)). 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 noise is therefore inferred from documented effects to other vertebrates. Bone conducted hearing is the most likely mechanism for auditory reception in sea turtles and, since high frequencies are attenuated by bone, the range of hearing are limited to low frequencies only. For leatherback turtle *Dermochelys coracea* the hearing range has been recorded as between 50 Hz and 1,200 Hz with maximum sensitivity between 100 Hz and 400 Hz; and

- **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.

The guidelines set out criteria for injury due to different sources of noise. Those relevant to the Project are considered to be those for injury due to impulsive piling sources only, as non-impulsive sources were not considered to be a key potential impact and therefore were screened out of the guidance[4]. 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 noise levels and therefore all sources of noise, no matter how noisy, 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 animal and impairment effects, this is not considered to be a significant issue with respect to determining the potential effect of noise on fish.

The injury criteria used in this noise assessment for impulsive piling are given in Table 1-4. In the table, both peak and SEL criteria are unweighted. Physiological effects relating to injury criteria are described below (Popper *et al*., 2014; Popper and Hawkins, 2016):

- **Mortality and potential mortal injury**: either immediate mortality or tissue and/or physiological damage that is sufficiently severe (e.g. a barotrauma) that death occurs sometime later due to decreased fitness. Mortality has a direct effect upon animal populations, especially if it affects individuals close to maturity.

- **Recoverable injury**: Tissue and other physical damage or physiological effects, that are recoverable but which may place animals at lower levels of fitness, may render them more open to predation, impaired feeding and growth, or lack of breeding success, until recovery takes place.

- **TTS**: Short term changes in hearing sensitivity may, or may not, reduce fitness and survival. 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.

[4] Guideline exposure criteria for seismic surveys, continuous sound and naval sonar are also presented though are not applicable to the Project.

Table 1-4: Criteria for onset of injury to fish and sea turtles due to impulsive piling (Popper *et al*., 2014).

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

The criteria used in this noise assessment for non-impulsive piling are given in **Table 1-5**.

Table 1-5: Criteria for onset of injury to fish due to non-impulsive sound (Popper *et al*., 2014).

Type of animal	Mortality and potential mortal injury	Recoverable injury
Fish: no swim bladder (particle motion detection)	(*Near*) Low (*Intermediate*) Low (*Far*) Low	(*Near*) Low (*Intermediate*) Low (*Far*) Low
Fish: where swim bladder is not involved in hearing (particle motion detection)	(*Near*) Low (*Intermediate*) Low (*Far*) Low	(*Near*) Low (*Intermediate*) Low (*Far*) Low
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
Sea turtles	(*Near*) Low (*Intermediate*) Low (*Far*) Low	(*Near*) Low (*Intermediate*) Low (*Far*) Low
Eggs and larvae	(*Near*) Low (*Intermediate*) Low (*Far*) Low	(*Near*) Low (*Intermediate*) Low (*Far*) Low

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. 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[5].

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 noise. Flat fish and elasmobranchs have no swim bladders and as such are considered to be relatively less sensitive to sound pressure.

The most recent criteria for disturbance are considered to be those contained in Popper *et al*. (2014) which set out criteria for disturbance due to different sources of noise. The risk of behavioural effects is categorised in relative terms as "high", "moderate" or "low" at three distances from the source: "near" (i.e. in the tens of metres), "intermediate" (i.e. in the hundreds of metres) or "far" (i.e. in the thousands of metres), as shown in Table 1-6.

Table 1-6: 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	Non-impulsive sound
Fish: no swim bladder (particle motion detection)	(*Near*) High (*Intermediate*) Moderate (*Far*) Low	(*Near*) Moderate (*Intermediate*) Moderate (*Far*) Low
Fish: where swim bladder is not involved in hearing (particle motion detection)	(*Near*) High (*Intermediate*) Moderate (*Far*) Low	(*Near*) Moderate (*Intermediate*) Moderate (*Far*) Low
Fish: where swim bladder is involved in hearing (primarily pressure detection)	(*Near*) High (*Intermediate*) High (*Far*) Moderate	(Near) High (Intermediate) Moderate (Far) Low
Sea turtles	(*Near*) High (*Intermediate*) Moderate (*Far*) Low	(*Near*) High (*Intermediate*) Moderate (*Far*) Low
Eggs and larvae	(*Near*) Moderate (*Intermediate*) Low (*Far*) Low	(*Near*) Moderate (*Intermediate*) Moderate (*Far*) Low

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 noise of a particular type (e.g. piling) would result in the same predicted potential impact, no matter the level of noise produced or the propagation characteristics.

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

[5] 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.

It is important to note that this threshold is for onset of potential effects, and not necessarily an 'adverse effect' threshold.

1.5 Source sound levels

Underwater sound sources are usually quantified in dB scale with values generally referenced to 1 µPa pressure amplitude as if measured at a hypothetical distance of 1 m from the source (called the Source Level, (SL)). In practice, it is not usually possible to measure at 1 m from a source, but the metric allows comparison and reporting of different source levels on a like-for-like basis. In reality, for a large sound source this imagined point at 1 m from the 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 for 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 SL.

A wealth of experimental data and literature-based information is available for quantifying the noise emission from different construction operations. This information, which allows us to predict with a good degree of accuracy the sound generated by a noise source at discrete frequencies in one-third octave bands, will be employed to characterise their acoustic emission in the underwater environment. Sections 1.5.1 to 1.6 will detail the types of noise sources present during different parts of the construction activities, their potential signatures in different frequency bands, and acoustic levels.

1.5.1 Types of noise sources

The noise sources and activities which were investigated during the subsea noise assessment study are summarised in Table 1-7.

Table 1-7: Summary of noise sources and activities included in the subsea noise assessment.

Phase	Source/Activity
Construction	• Impact and/or drill monopiled foundations for Wind Turbine Generators (WTGs) and Offshore Substation (OSS). • Vessels used for a range of construction activities including e.g. boulder clearance, sand wave clearance, drilling and trenching. • Range of construction vessels including: – installation vessels; – cargo barges; – support vessels; – tug/anchor handlers; – cable installation vessels; – guard vessels; – survey vessels; – crew transfer vessels; – scour/cable protection installation vessels; and – resupply vessels.
Operational and maintenance	• Operational noise from wind turbines. • Operational and maintenance vessels, including: – crew transfer vessels; – jack up vessel; – support vessels; – cable repair vessel; – service operations vessels and daughter craft; – cable survey vessel; and – excavator/backhoe dredger. • Geophysical surveys (of seabed and cable protection)
Decommissioning	• Vessels for a range of decommissioning activities, assumed as per vessel activity described for construction phase.

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

1.5.2 Construction phase

Impact piling

The sound generated and radiated by a pile as it is driven into the ground is complex, due to the many components which make up the generation and radiation mechanisms. However, a wealth of experimental data are available which allow us to predict with a good degree of accuracy the sound generated by a pile at discrete frequencies. Third-octave band noise spectra have been presented in literature for various piling activities (e.g. Matuschek and Betke 2009; De Jong and Ainslie 2008; Wyatt 2008; J. R. Nedwell *et al*., 2007; J. Nedwell and Howell 2004; Jeremy Nedwell *et al*., 2003; CDoT 2001; Nehls *et al*., 2007; Thomsen *et al*., 2006).

For this Project, the assessments have been carried out for the installation of 9.6 m diameter monopiles with a hammer energy of up to 3,500 kJ (maximum spatial scenario). The assumption used for the modelling is that approximately 1% of the hammer energy is converted into sound in order to derive the SEL (based on a review of literature from Robinson *et al*., 2009, Robinson *et al*., 2013, Lepper, 2007, Lepper *et al*., 2012 and Bailey *et al*., 2010). Root mean square (rms) sound pressure levels were calculated assuming a typical T90 pulse duration (i.e. the period that contains 90% of the total cumulative sound energy) of 100 ms.

The source Sound Exposure Level is calculated according to the methodology described in De Jong and Ainslie (2008), as follows:

$$\text{SEL} = 120 + 10\log_{10}\left(\frac{\beta E c_0 \rho}{4\pi}\right)$$

Where β is the acoustic energy conversion efficiency (in this case taken to be 0.5%), c_0 is the speed of sound in seawater in m/s, and ρ is the density of seawater in kg/m^3.

The source zero-to-peak level is calculated from an empirical correction to the SEL, derived from field measurements and using the method described by Lippert *et al*. (2015). Linear regression coefficients A and B are derived from measurements taken at a range of distances for a range of pile diameters and piling energies in order to define a source peak sound pressure level as follows:

$$\text{SPL}_{\text{peak}} = 1.43 \cdot \text{SEL} - 44.0$$

The piling scenarios for the Project and resulting source sound levels are set out in Table 1-8.

Table 1-8: Monopile noise source levels used in assessment (un-weighted).

Phase	Duration (minutes)	Hammer Energy (kJ)	Strike Rate (strikes per minute)	No. of strikes	Notes	SEL per strike (dB re 1 µPa^{2}s)	Peak (dB re 1 µPa)
Pile Self-weight penetration	N/A	0	0	0	Pile self-weight penetration where the monopile will fall into the seabed under its own weight.	N/A	N/A
Soft start initiation	1	525	6	6	Initial slow start at low energy and low strike rate to allow for alignment	205	246
Soft start	20	525	30	600	Slow start at low hammer energy for 20 minutes	205	246
Ramp up	9	525 - 2500	30	270	Ramp up energy after the soft start period	205 - 212	246 - 255
Piling	150	2500	30	4500	Steady driving using an energy level of circa 2500 kJ	212	255
Full power piling	120	3500	30	3600	Hard driving into a bedrock layer, hammer is operating at 3500 kJ	213	258

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

The piling of wind turbine foundations described in Table 1-8 was also modelled with the inclusion of an Acoustic Deterrant Device (ADD) before commencement of piling. Use of an ADD was modelled for a duration of 15 minutes prior to commencement of piling, all other stages of piling remained the same, and the ADD itself was assumed to not contribute towards any animal injury.

Drilled piles

For drilled piling, source sound levels have been based on pile drilling for the Oyster 800 project (Kongsberg, 2011). The hydraulic rock breaking source sound levels are based on those measured by Lawrence (2016). The source levels used in the assessment are summarised in Table 1-9. Rotary drilling is non-impulsive in character and therefore the non-impulsive injury and behavioural thresholds have been adopted for the assessment.

Table 1-9: Drilled pile noise source levels used in assessment (Un-Weighted).

Parameter	Source Level at 1 m
SEL per second of operation @ 1 m, dB re 1 μPa²s	163
Peak sound pressure level @ 1 m, dB re 1 μPa	166
rms_{T90} sound pressure level @ 1 m, dB re 1 μPa	163

The other noise source potentially active during the construction phase are related to cable installation (i.e. trenching and cable laying activities). The SEL based source levels are presented in Table 1-10.

Table 1-10: SEL based source levels for other noise sources.

Sources	Data Source	RMS (dB re 1 μPa)	Frequency (Hz)											
			16	31.5	63	125	250	500	1k	2k	4k	8k	16k	31.5k
Cable laying	Wyatt (2008)	188	176	174	174	173	170	165	161	162	146	139	133	169
Cable trenching / cutting	Nedwell *et al.* (2003)	178	135	135	148	161	167	169	167	162	157	148	142	141

1.5.3 Operational and maintenance phase

Geophysical surveys

There is the potential for sonar like survey source types to be used for the geophysical surveys. During the survey a transmitter emits an acoustic signal directly toward the seabed (or at an angle in the case of some types of survey). 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. 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.

The characteristics assumed for the device modelled in this assessment is summarised in Table 1-11. For the purpose of potential impacts, these sources are considered to be continuous (non-impulsive).

Table 1-11: Typical sonar like survey equipment parameters used in assessment.

Survey Type	Unit	Frequency (kHz)	Source Level (dB re 1μPa (rms))	Pulse Rate (s^{-1})	Pulse Width (ms)	Beam Width	Swathe Beamwidth
MBES	Kongsberg EM710	105	231	30	0.2	2°	140°

Operation noise from Turbines

A review of publicly available information on the potential for operation wind turbines to produce noise has been undertaken and is presented in section 1.9.6.

1.6 Vessels (all phases)

The noise emissions from the types of vessels that may be used for the Project are quantified in Table 1-12, 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.

In Table 1-12, a correction of +3 dB has been applied to the rms sound pressure level to estimate the likely peak sound pressure level. 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). 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 Project 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 was 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 1-12: Source sound data for construction and installation vessels.

Item	Description/ Assumptions	Data Source	Source SPL at 1 m		
			RMS (dB re 1 µPa)	Peak (dB re 1 µPa)	SEL(24h) (dB re 1 µPa^{2}s)
Sand wave clearance	'Gerardus Mercator' trailer hopper suction dredger using DP as proxy	Wyatt (2008)	180	183	229
Boulder clearance	Back-hoe dredger used as proxy	Nedwell *et al.* (2008)	163	166	212
Main Installation Vessels (Jack-up Barge/DP vessel)	'Gerardus Mercator' trailer hopper suction dredger using DP as proxy	Wyatt (2008)	180	183	229
Jack up rig	Jack up rig	Evans (1996)	163	166	212
Tug/Anchor Handlers	Tug used as proxy	Richardson (1995)	172	175	221
Cable Installation Vessels	'Gerardus Mercator' trailer hopper suction dredger using DP as proxy	Wyatt (2008)	180	183	229
Rock Placement Vessels	'Gerardus Mercator' trailer hopper suction dredger using DP as proxy	Wyatt (2008)	180	183	229
Guard Vessels	Tug used as proxy	Richardson (1995)	172	175	221
Survey Vessels	Offshore support vessel used as proxy	McCauley (1998)	179	182	228

Crew Transfer Vessels	Offshore support vessel used as proxy	McCauley (1998)	179	182	228
Scour / Cable Protection / Seabed Preparation / Installation Vessels	Offshore support vessel used as proxy	McCauley (1998)	179	182	228

1.7 Sound propagation modelling methodology

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 according to a 10 log (r) or 20 log (r) relationship (as discussed above) 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 which lie somewhere in between these two extremes in terms of complexity.

In choosing which 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 and Farcas *et al*., 2016). Thus, in some situations (e.g. low risk due to underwater noise, range dependent bathymetry is not an issue, non-impulsive sound) a simple (N log R) model will be sufficient, particularly where other uncertainties outweigh the uncertainties due to modelling. On the other hand, some situations (e.g. 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.

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

- Balancing of errors/uncertainties;
- Range dependent bathymetry;
- Frequency dependence; and
- Source characteristics.

For impulsive sound, such as that produced by impact piling, the sound propagation is rather more complex than can be modelled using a simple N log (R) relationship. For example, the rms sound pressure level of an impulsive sound wave will depend upon the integration window used or, in other words, the measurement time for the rms. Using a longer duration measurement would result in a lower rms sound pressure level than using a shorter one. An additional phenomenon occurs where the seismic waveform elongates with distance from the source due to a combination of dispersion and multiple reflections. This temporal "smearing" can significantly affect the peak pressure level and reduces the rms amplitude with distance (because the rms window is longer).

Sound propagation modelling for this assessment was therefore based on an established, peer reviewed sound propagation model which utilises the model developed by Weston (1971) for regions where the changes in seafloor depth are slow or gradual. The model provides a robust balance between complexity and technical rigour over a wide range of frequencies, has been validated by numerous field studies, and has been subjected to the scrutiny of European regulators and Statutory Nature Conservation Bodies (SNCBs). Furthermore, the Weston energy-flux model has been benchmarked, with good agreement, against other transmission loss models including the Range-dependent Acoustic Model (RAM) implementation of the Parabolic Equation (PE) solution (Collins, 1993), an image source model (Urick, 1983), a wavenumber integration transmission loss model (Schmidt, 1990), a normal mode model (Kraken), further propagation (e.g. Etter, 2013; Toso, Casari, and Zorzi 2014; Schulkin and Mercer 1985), against measurement data, as detailed in Wang *et al*. (2014). It has previously been used in underwater noise assessments for wind and tidal energy developments.

The propagation loss is calculated using one of the four formulae detailed in the table below, depending on the distance from the source, and related to the frequency and the seafloor conditions such as depth and composition.

Table 1-13: 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	$TL = 10\log_{10}\left[\frac{RH_aH_b}{\lambda}\right] + \frac{\lambda^2\alpha}{8}\int_0^R \frac{dR}{H^3}$	$R > \frac{27k^2{H_a}^3}{(2\pi)^2\alpha}$

Where 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).

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, single mode region, all but the lowest mode have been fully attenuated.

The level of detail presented in terms of noise 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 ones (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 line beyond which no effect can occur, and it would be equally misleading to present any noise modelling results in such a way.

It should be borne in mind that noise 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 worst case scenario. Taking into account 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 an impact definitely will or will not occur. (This is a similar approach to that adopted for airborne noise where a typical worst case is taken, though it is known that day to day levels may vary to those calculated by 5 to 10 dB depending on wind direction etc.).

As well as calculating the sound pressure levels at various distances from the source, it is also necessary to calculate the SEL for a mammal or fish using the relevant weightings described previously taking into account the amount of sound energy to which it is exposed over the course of a 24-hour period. In order to carry out this calculation, it has been assumed that a mammal will swim away from the noise source at an average speed of 1.5 ms^{-1} (or 0.5 ms^{-1} for fish). The calculation considers each pulse exposure separately resulting in a series of discrete SEL values of decreasing magnitude. As the mammal or fish swims away, the noise will become progressively quieter; the cumulative SEL is worked out 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 a marine mammal or fish in order for it to be exposed to sufficient sound energy to result in the onset of potential injury. It should be noted that the sound exposure calculations are based on the simplistic assumption that the source is active continuously over each piling period and that the animal will continue to swim away at a fairly constant relative speed without re-entering the area during breaks in activity. The real-world situation is more complex and the noise source will vary in space and time and the animal is likely to move in a more complex manner[6].

1.7.1 Exposure calculations

As well as calculating the un-weighted sound levels at various distances from different source, it is also necessary to calculate the acoustic signal in the SEL metric (where necessary and possible) for a mammal using the relevant hearing weightings to which it is exposed. For operation of the different sources, the SEL sound data was numerically equal to the SPL rms value integrated over one second window as the sources are continuous and non-impulsive. These SEL values are employed for calculation of cumulative SEL (cSEL) metric for different marine mammal groups to assess potential impact ranges.

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

It should be noted that the sound exposure calculations are based on the simplistic assumption that the noise source is active continuously (or intermittently based on shot-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 the piling vessel.

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 and, therefore, the assessment of sound exposure level is conservative.

In order to carry out the swimming mammal calculation, it has been assumed that a mammal will swim away from the noise source at the onset of activities. For impulsive sounds of piledriving the calculation considers each pulse to be established separately resulting in a series of discrete SEL values of decreasing magnitude (see Figure 1-6).

[6] Swim speeds of marine mammals have been shown to be up to 5 ms^{-1} (e.g. cruising minke whale 3.25 ms^{-1} (Cooper *et al*. 2008) and, harbour porpoise up to 4.3 ms^{-1} (Otani *et al*. 2000)). The more conservative swim speed of 1.5 ms^{-1} used in this assessment allows some headroom to account for the potential that the marine mammal might not swim directly away from the source, could change direction or does not maintain a fast swim speed over a prolonged period

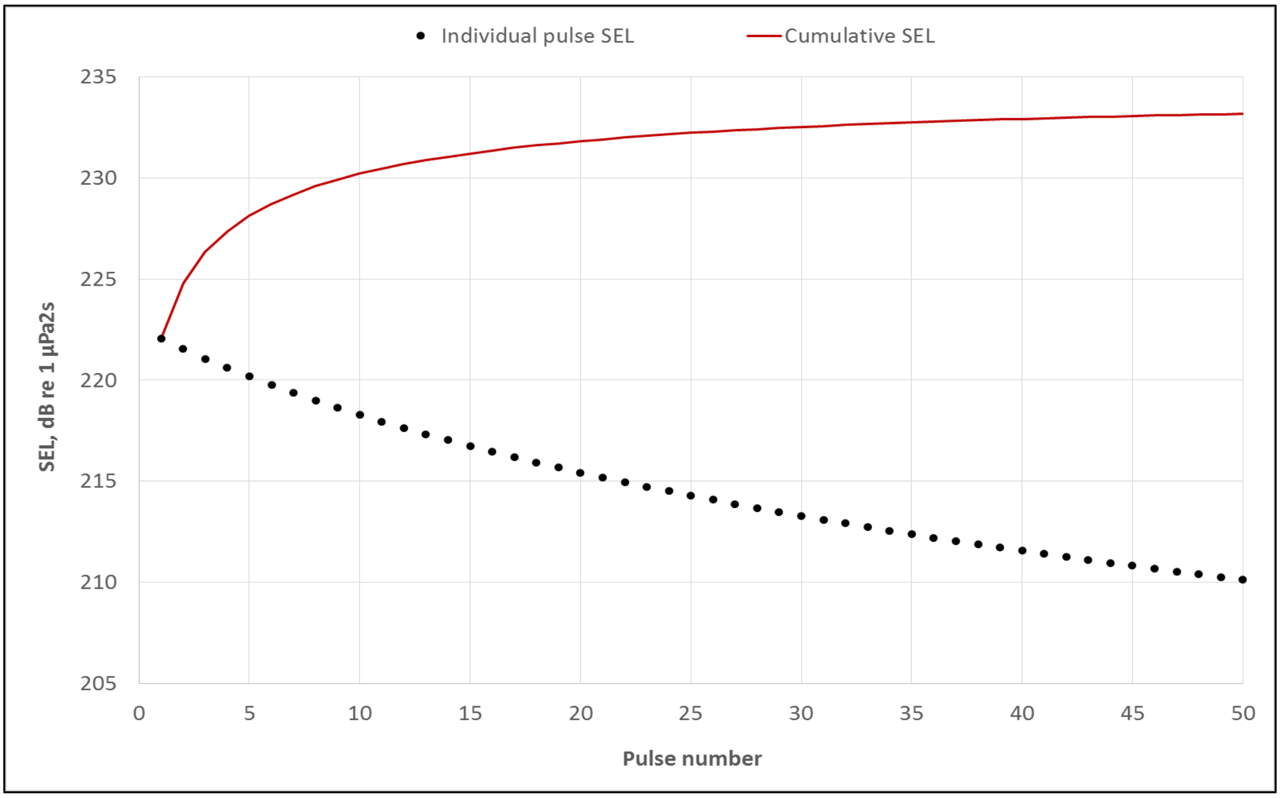


Figure 1-6: A comparison of discrete "Pulse" based SEL and a cumulative of SEL values.

As a marine mammal swims away from the sound source, the noise it experiences will become progressively 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 a marine mammal in order for it to be exposed to sufficient sound energy to result in the onset of potential 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.

The swim speeds used in the assessment are summarised in Table 1-14 along with the source papers for the assumptions.

Table 1-14: Swim speeds assumed for exposure modelling.

Species	Hearing Group	Swim Speed (m/s)	Source Reference
Harbour porpoise	VHF	1.5	Otani *et al.,* 2000
Harbour seal	PCW	1.8	Thompson, 2015
Grey seal	PCW	1.8	Thompson, 2015
Minke whale	LF	2.3	Boisseau *et al.,* 2021
Bottlenose dolphin	HF	1.52	Bailey and Thompson, 2010
White-beaked dolphin	HF	1.52	Bailey and Thompson, 2010
Basking shark	Group 1 fish	1.0	Sims, 2000
All other fish groups	All fish groups	0.5	Popper *et al.,* 2014

To perform this calculation, the first step is to parameterise the m-weighted sound exposure levels for single strikes of a given energy via a line of best fit. This function is then used to predict the exposure level for each strike in the planned hammer schedule (periods of slow start, ramp up and full power).

1.8 Baseline noise

Background or “ambient” underwater noise is generated by a number of natural sources, such as rain, breaking waves, wind at the surface, seismic noise, biological noise and thermal noise. Biological sources include marine mammals (which use sound to communicate, build up an image of their environment and detect prey and predators) as well as certain fish and shrimp. Anthropogenic sources also add to the background noise, such as fishing boats, ships, industrial noise, seismic surveys and leisure activities. Generalised ambient noise spectra (Wenz, 1962) attributable to various noise sources including both natural and anthropogenic sources are shown in Figure 1-7.

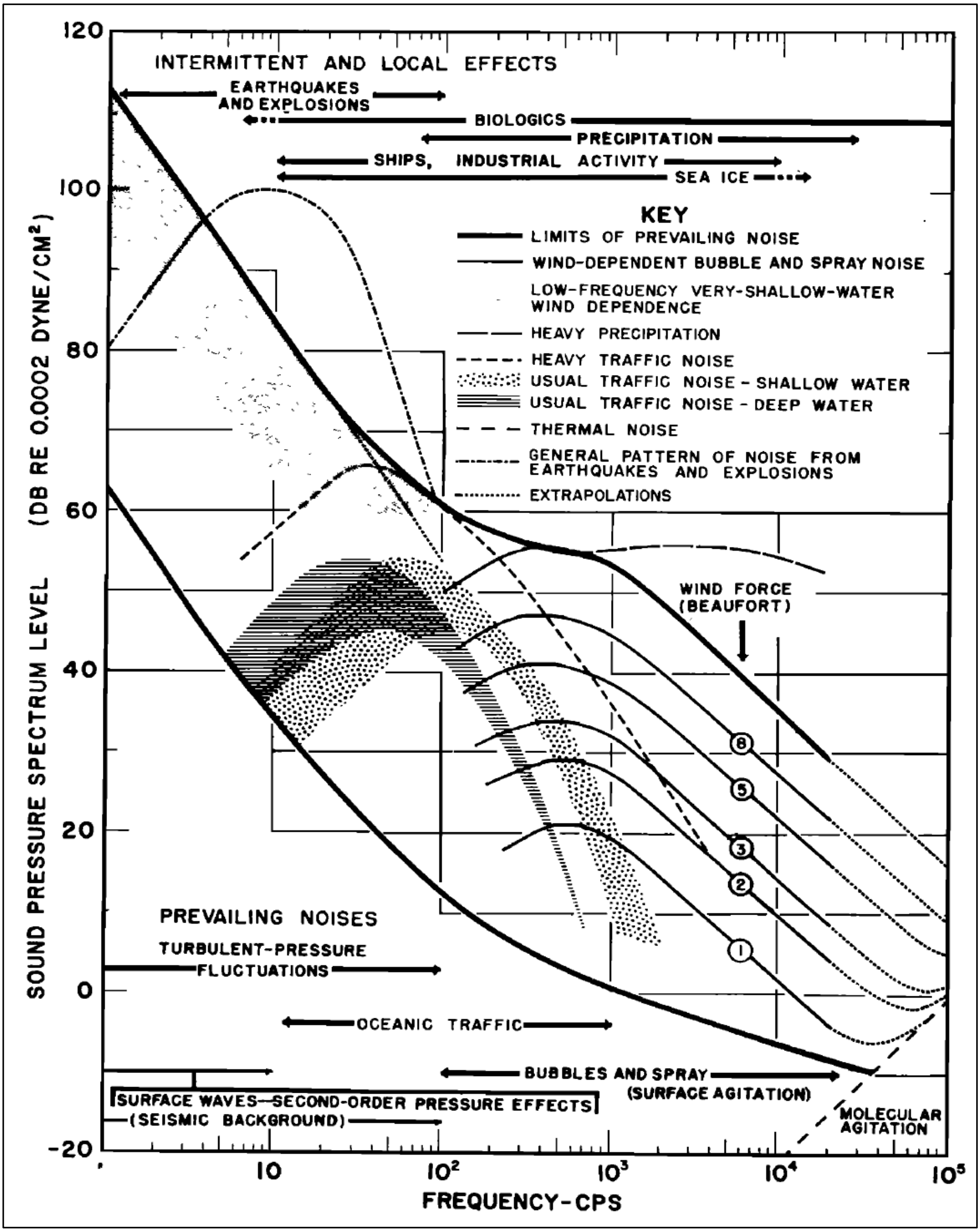


Figure 1-7: Generalised ambient noise spectra attributable to various noise sources (Wenz, 1962).

The vast majority of research relating to both physiological effects and behavioural disturbance due to noise on marine species is based on determining the absolute noise level for the onset of that effect. As a result, criteria for assessing the effects of noise on marine mammals and fish tend to be based on the absolute noise criteria, as opposed to the difference between the baseline noise level and the specific noise being assessed (e.g. Southall *et al*., 2007). Given the lack of evidence-based studies investigating the effects of noise relative to background on marine wildlife, the value of establishing the precise baseline noise level is somewhat diminished. It is important to understand that baseline noise levels will vary significantly depending on, amongst other factors, seasonal variations and different sea states, meaning that the usefulness of establishing such a value would be very limited. Nevertheless, it can be useful (though not essential) when undertaking an assessment of underwater noise, to have an understanding of the range of noise levels likely to be prevailing in the area, so that any noise predictions can be placed in the context of the baseline. It is important to note however, that even if an accurate baseline noise level could be determined, there is a paucity of scientific understanding regarding how various species distinguish anthropogenic sound relative to masking noise.

An animal's perception of sound is likely to depend on numerous factors including the hearing integration time, the character of the sound, and hearing sensitivity. It is not known for example, to what extent marine mammals and fish can detect tones of lower magnitude than the background masking noise, or how they distinguish time varying sound. Therefore, it is necessary to exercise considerable caution if attempting any comparison between noise from the Project and the baseline noise level. For example, it does not follow that because the broadband sound pressure level due to the source being considered is below the numeric value of the baseline level, that this means that marine mammals or fish cannot detect that sound. This is particularly true where the background noise is dominated by low frequency sound which is outside the animal's range of best hearing acuity. Until such a time as further research is conducted to determine a dose response relationship between the "signal-to-noise" level and behavioural response, a precautionary approach should be adopted.

For the reasons given above, it was considered that it would be disproportionate and unnecessary to undertake baseline noise measurements as part of this study. Alternatively, as detailed below, RPS has reviewed baseline noise studies carried out in UK waters for other projects in order to determine the likely magnitude of noise encountered in such waters.

A review of noise data relating to other sites in coastal waters was undertaken for the Beatrice Offshore Wind Farm (Brooker *et al*., 2012). These noise data are summarised in Table 1-15 and power spectral density levels are shown graphically in Figure 1-8 (Sea State 1) and Figure 1-9 (Sea State 3).

Table 1-15: Summary of average background levels of noise around the UK coast (Brooker *et al*., 2012).

	Overall (Un-Weighted) Average Background Noise Levels (dB re 1 µPa (rms))	
	Sea State 1	**Sea State 3**
Minimum	92	94
Maximum	126	132
Mean	111	112

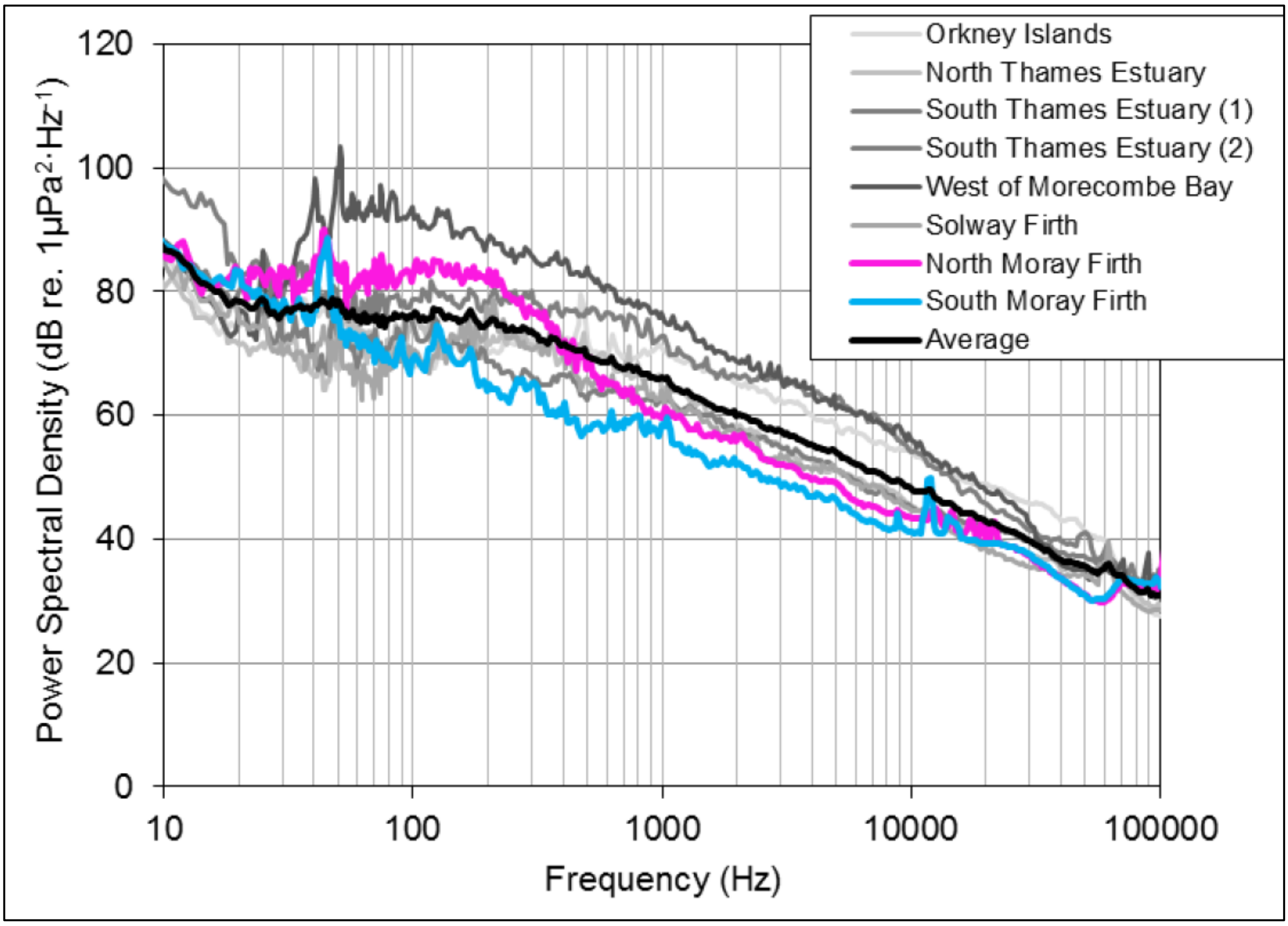


Figure 1-8: Summary of Power Spectral Density levels of background underwater noise at Sea State 1 at sites around the UK coast (Brooker, Barham, and Mason 2012).

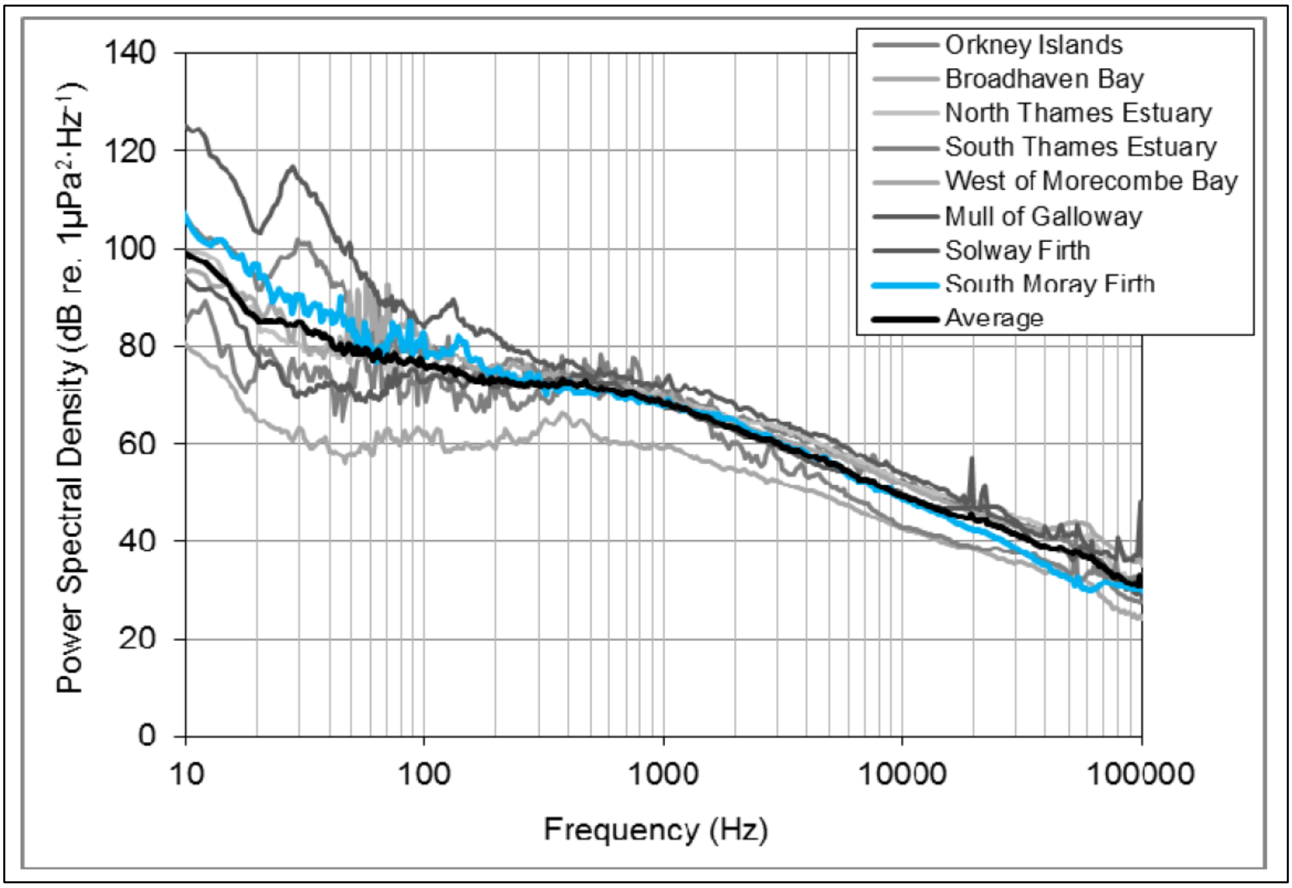


Figure 1-9: Summary of Power Spectral Density levels of background underwater noise at Sea State 3 at sites around the UK coast (Brooker *et al*., 2012).

The measured power spectral density levels (maximum values in red, mean values in black and minimum values in green, in dB re 1 μPa^{2}Hz^{-1}) and third octave band sound pressure levels (light blue, in dB re 1 μPa) are shown in Figure 1-10 taken from Kongsberg (2012).

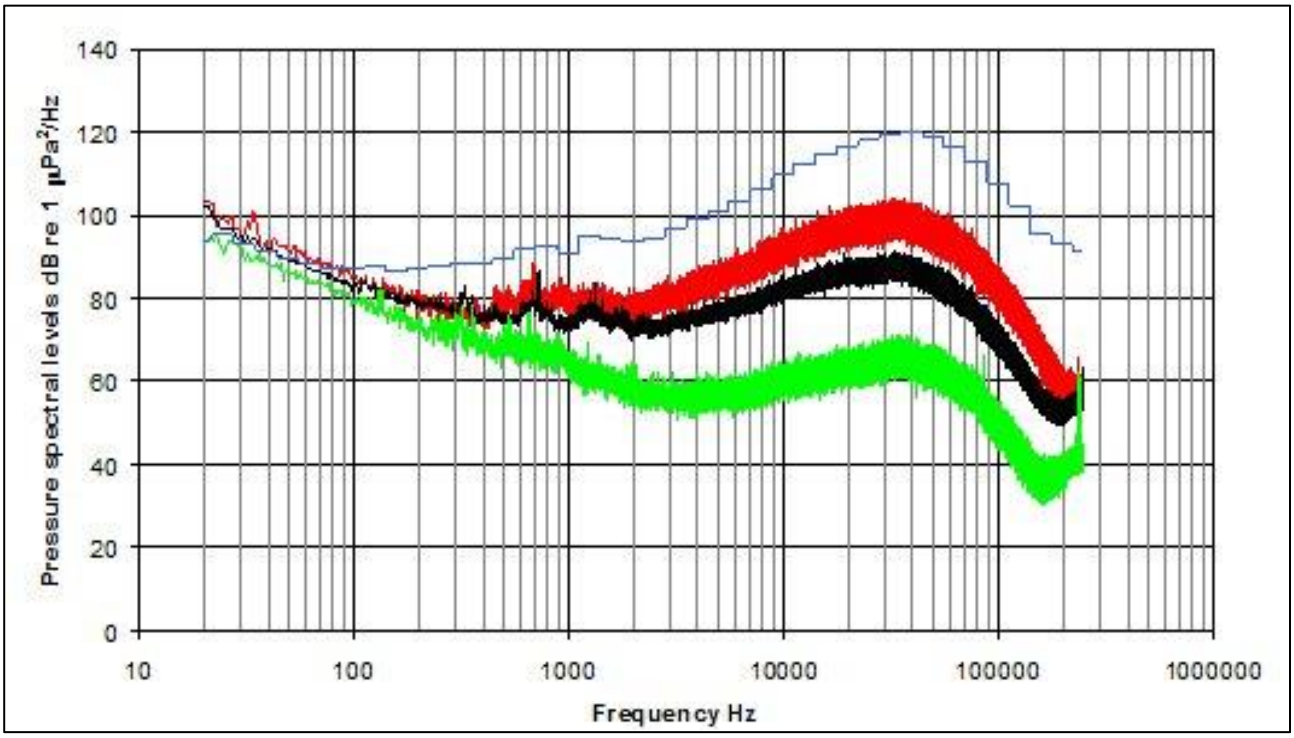


Figure 1-10: Summary of power spectral density levels and third octave band sound pressure levels of background underwater noise measured in the Inner Sound (Meygen), August 2011 (Kongsberg, 2012).

A “drifting-buoy” style assessment of background noise was undertaken by the Low Carbon Research Institute (LCRI) marine division in July 2014. Over an eleven-hour period, noise levels at the Inner Sound site were seen to vary from 91 dB re 1µPa during periods of low tidal flow speed to 121 dB re 1µPa at high tidal flow speeds.

1.9 Results and assessment

1.9.1 Construction phase – impact piling

Based on the modelling, the resultant PTS injury ranges for impact piling activities at the westernmost and easternmost extremes of the Offshore Wind Farm Area (based on hypothetical wind turbine locations in order to provide the most extreme case) are summarised in Table 1-16 to Table 1-23 for single piling events (i.e. installation of one pile). Cumulative SELs are assessed in terms of two scenarios: a mitigated scenario in which all soft start and low energy phases of piling are applied; and a mitigated plus ADD scenario[7], which includes the same mitigation but with the addition of a 15 minute period of ADD (see chapter 10: Marine Mammals and Megafauna for discussion on mitigation options).

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

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

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

Table 1-16: Summary of SEL injury ranges for marine mammals due to installation of one 9.6 m diameter monopile at the west of the Offshore Wind Farm Area (N/E = threshold not exceeded).

Species / Group	Threshold (Weighted SEL_{cum})	Range (m)	
		No ADD	15 min ADD
LF	PTS - 183 dB re 1 µPa²s	155	N/E
	TTS - 168 dB re 1 µPa²s	3,720	1,655
HF	PTS - 185 dB re 1 µPa²s	N/E	N/E
	TTS - 170 dB re 1 µPa²s	24	N/E
VHF	PTS - 155 dB re 1 µPa²s	273	N/E
	TTS - 140 dB re 1 µPa²s	5,640	4,300
PCW	PTS - 185 dB re 1 µPa²s	26	N/E
	TTS - 170 dB re 1 µPa²s	930	N/E
OCW	PTS - 203 dB re 1µ Pa²s	N/E	N/E
	TTS - 188 dB re 1 µPa²s	19	N/E

[7] Acoustic Deterrent Device – a device of lower acoustic energy used to encourage marine mammals away from an area before high energy industrial activities begin.

Table 1-17: Summary of SEL injury ranges for marine mammals due to installation of one 9.6 m diameter monopile at the east of the Offshore Wind Farm Area (N/E = threshold not exceeded).

Species / Group	Threshold (Weighted SEL_{cum})	Range (m)	
		No ADD	15 min ADD
LF	PTS - 183 dB re 1 µPa²s	394	N/E
	TTS - 168 dB re 1 µPa²s	8,060	5,980
HF	PTS - 185 dB re 1 µPa²s	N/E	N/E
	TTS - 170 dB re 1 µPa²s	12	N/E
VHF	PTS - 155 dB re 1 µPa²s	168	N/E
	TTS - 140 dB re 1 µPa²s	5,980	4,620
PCW	PTS - 185 dB re 1 µPa²s	19	N/E
	TTS - 170 dB re 1 µPa²s	1,330	N/E
OCW	PTS - 203 dB re 1µ Pa²s	N/E	N/E
	TTS - 188 dB re 1 µPa²s	< 10	N/E

It can be seen here, and in all sets of results below, that the injury and disturbance ranges are generally shorter for the piling location at the west of the Offshore Wind Farm Area than at the east. This is due to the bathymetry to the west (18 m to the west compared with 29 m to the east)[8], resulting in greater interactions with the seafloor and surface causing the sound to attenuate faster.

The injury ranges for marine mammals based on peak pressure are summarised in Table 1-18 and Table 1-19. These ranges represent the potential zone for instantaneous injury. The injury ranges for peak sound pressure are based on both the first strike the animal experiences at the closest point during each phase of the pile installation, as well as for the maximum hammer energy over the entire installation.

Table 1-18: Summary of peak pressure injury ranges for marine mammals due to impact piling of 9.6 m diameter monopiles at the west of the Offshore Wind Farm Area (N/E = threshold not exceeded).

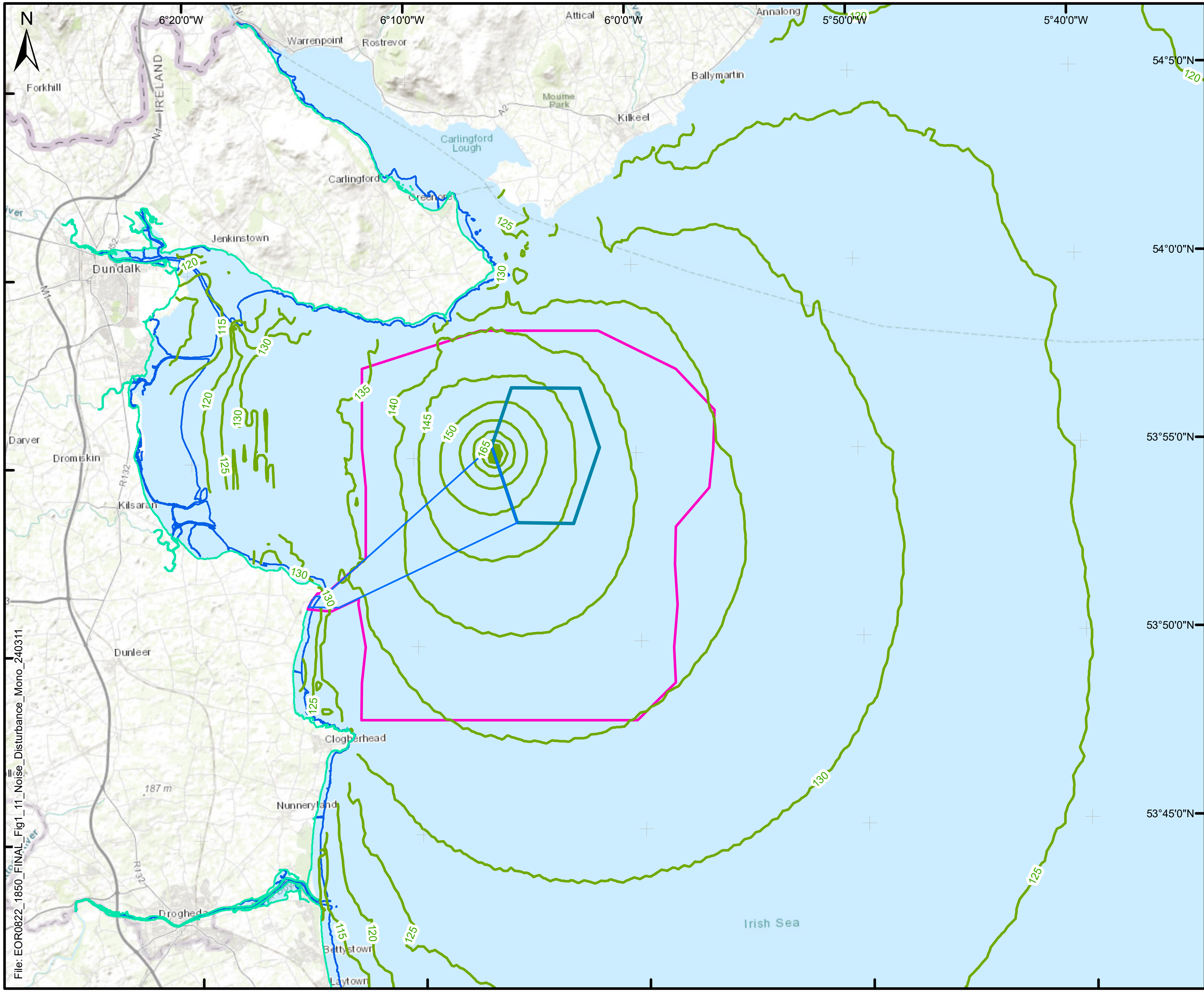
Species / Group	Threshold (Unweighted Peak)	Range (m)	
		First Strike	Max Energy
LF	PTS - 219 dB re 1 µPa (pk)	65	75
	TTS - 213 dB re 1 µPa (pk)	95	109
HF	PTS - 230 dB re 1 µPa (pk)	32	37
	TTS - 224 dB re 1 µPa (pk)	47	54
VHF	PTS - 202 dB re 1 µPa (pk)	190	219
	TTS - 196 dB re 1 µPa (pk)	278	320
PCW	PTS - 218 dB re 1 µPa (pk)	69	79
	TTS - 212 dB re 1 µPa (pk)	101	116
OCW	PTS - 232 dB re 1µ Pa (pk)	28	33
	TTS - 226 dB re 1 µPa (pk)	42	48

[8] Bathymetry data sourced from the General Bathymetric Chart of the Oceans https://www.gebco.net.

Table 1-19: Summary of peak pressure injury ranges for marine mammals due to impact piling of 9.6 m diameter monopiles at the east of the Offshore Wind Farm Area (N/E = threshold not exceeded).

Species / Group	Threshold (Unweighted Peak)	Range (m)	
		First Strike	Max Energy
LF	PTS - 219 dB re 1 µPa (pk)	81	168
	TTS - 213 dB re 1 µPa (pk)	118	245
HF	PTS - 230 dB re 1 µPa (pk)	41	84
	TTS - 224 dB re 1 µPa (pk)	59	123
VHF	PTS - 202 dB re 1 µPa (pk)	236	489
	TTS - 196 dB re 1 µPa (pk)	344	713
PCW	PTS - 218 dB re 1 µPa (pk)	86	179
	TTS - 212 dB re 1 µPa (pk)	126	261
OCW	PTS - 232 dB re 1µ Pa (pk)	36	74
	TTS - 226 dB re 1 µPa (pk)	52	108

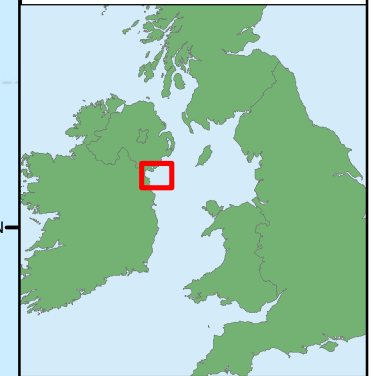
The single pulse unweighted SEL noise contours are shown in Figure 1-11 and Figure 1-12, in steps of 5 dB.



Legend

- Offshore Wind Farm Area
- Offshore Cable Corridor
- Noise Contour (dB re 1μ Pa (rms))
- Marine Megafauna Study Area
- Mean High Water
- Mean Low Water

Data Sources: Client. Marine Scotland



Client

ORIEL WINDFARM
OFFSHORE RENEWABLE ENERGY

Project

Oriel Wind Farm Project

Title **Figure 1-11**
Unweighted single pulse SEL contours due to impact piling of 9.6 m diameter monopiles at the west of the Offshore Wind Farm Area (dB re μ1 Pa)

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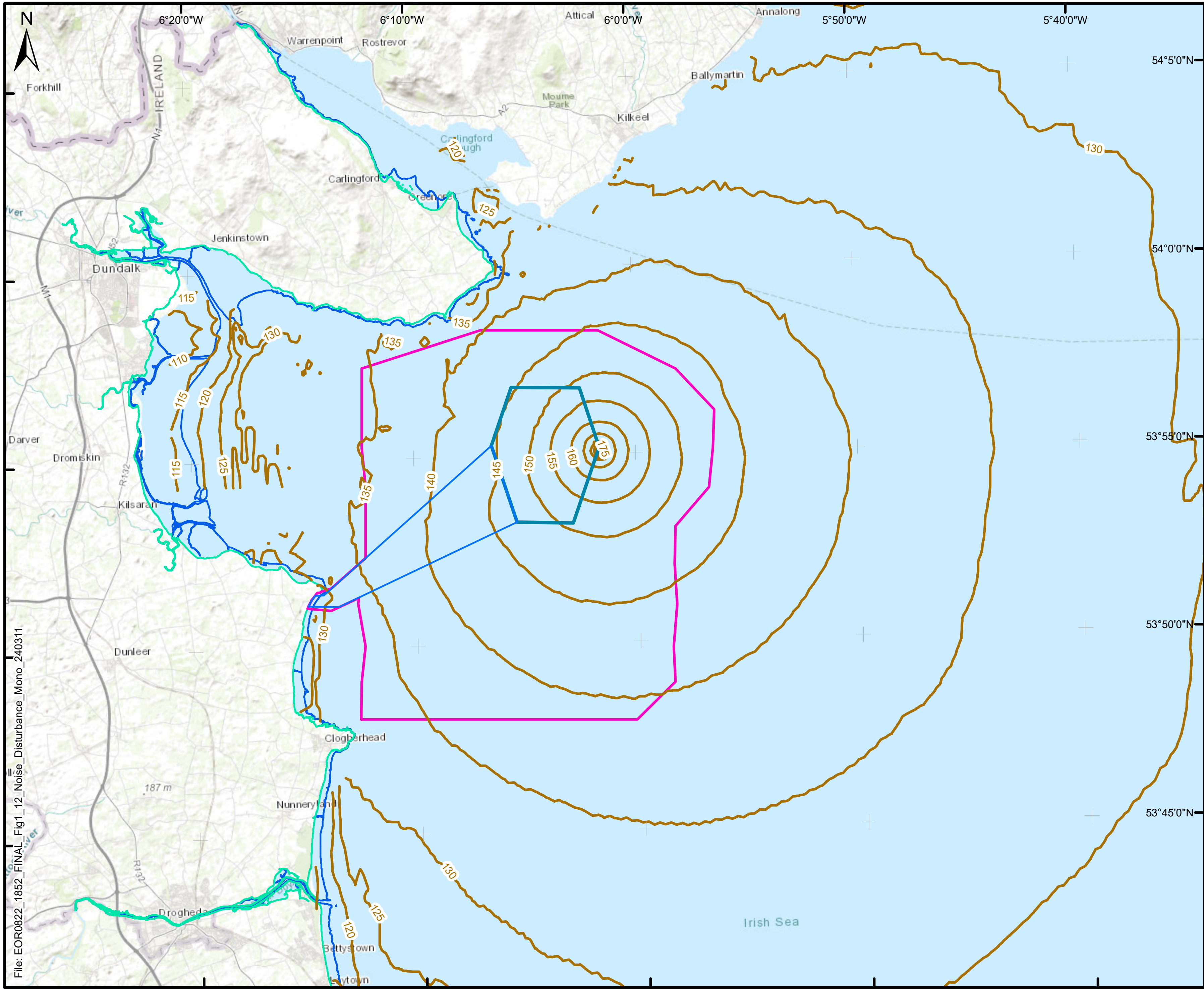
Issue Details

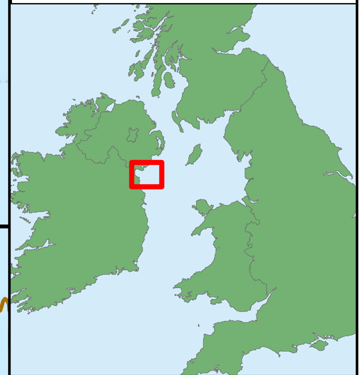
Drawn By: NG	**Project No.** EOR0822 (MDR1520B)
Checked By: NG	**File Ref:**
Approved By: AOS	EOR0822_SNO_T_1850_FINAL
Scale: 1:250,000 @ A4	**Projection:** ITM (IRENET95)
Date: 11/03/2024	Geographic Co-ordinates: ETRS89



Legend

- Offshore Wind Farm Area
- Offshore Cable Corridor
- Noise Contour (dB re 1µ Pa (rms))
- Marine Megafauna Study Area
- Mean High Water
- Mean Low Water

Data Sources: Client. Marine Scotland



Client

ORIEL WINDFARM
OFFSHORE RENEWABLE ENERGY

Project

Oriel Wind Farm Project

Title Figure 1-12

Unweighted single pulse SEL contours due to impact piling of 9.6 m diameter monopiles at the east of the Offshore Wind Farm Area (dB re µ1 Pa)

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Issue Details

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Checked By: NG	**File Ref:**
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Scale: 1:250,000 @ A4	**Projection:** ITM (IRENET95)
Date: 11/03/2024	Geographic Co-ordinates: ETRS89

File: EOR0822_1852_FINAL_Fig1_12_Noise_Disturbance_Mono_240311

The results of the noise modelling for fish and turtles are shown in Table 1-20 and Table 1-21 based on the cumulative SEL thresholds.

Table 1-20: Summary of injury ranges for fish and turtles due to installation of one 9.6 m diameter monopile at the west of the Offshore Wind Farm Area (N/E = threshold not exceeded).

Hearing Group	Response	Threshold (SEL, dB re 1 µPa²s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection) – [*basking shark ranges shown in square brackets*].	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	690 *[272]*
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	N/E
	Recoverable injury	203	19
	TTS	186	690
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	< 10
	Recoverable injury	203	19
	TTS	186	690
Sea turtles	Mortality	210	N/E
Fish eggs and larvae (static)	Mortality	210	362

Table 1-21: Summary of injury ranges for fish and turtles due to installation of one 9.6 m diameter monopile at the east of the Offshore Wind Farm Area (N/E = threshold not exceeded).

Hearing Group	Response	Threshold (SEL, dB re 1 µPa²s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection) – [*basking shark ranges shown in square brackets*].	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	1,750 *[770]*
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	17
	Recoverable injury	203	64
	TTS	186	1,750
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	28
	Recoverable injury	203	64
	TTS	186	1,750
Sea turtles	Mortality	210	17
Fish eggs and larvae (static)	Mortality	210	590

The results of the noise modelling for fish and turtles are shown in Table 1-22 to Table 1-23 based on the peak sound pressure thresholds.

Table 1-22: Summary of the peak pressure injury ranges for fish and turtles due to installation of one 9.6 m diameter monopile at the west of the Offshore Wind Farm Area.

Hearing Group	Response	Threshold (SPL_{pk}, dB re 1 µPa)	Range (m)	
			First Strike	Max
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	213	70	148
	Recoverable injury	213	70	148
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	207	103	217
	Recoverable injury	207	103	217
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	103	217
	Recoverable injury	207	103	217
Sea turtles	Mortality	207	103	217
Fish eggs and larvae	Mortality	207	103	217

Table 1-23: Summary of the peak pressure injury ranges for fish and turtles due to installation of one 9.6 m diameter monopile at the east of the Offshore Wind Farm Area.

Hearing Group	Response	Threshold (SPL_{pk}, dB re 1 µPa)	Range (m)	
			First Strike	Max
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	213	118	245
	Recoverable injury	213	118	245
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	207	172	357
	Recoverable injury	207	172	357
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	172	357
	Recoverable injury	207	172	357
Sea turtles	Mortality	207	172	357
Fish eggs and larvae	Mortality	207	172	357

1.9.2 Construction phase – drilled piling

The potential impact ranges for drilled piling are small (or not exceeded) for all marine mammal species groups, due to the low broadband SEL levels expected from these operations, at 160 dB re 1 µPa²s (see Table 1-24). The behavioural threshold range for all marine mammal groups is also reported.

Table 1-24: Potential impact ranges (m) for marine mammal exposed to drilled piling.

Source	Potential Impact Ranges (m)										
	LF		HF		VHF		PCW		OCW		All
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Behaviour
Drilled piling	N/E	N/E	N/E	N/E	40	N/E	N/E	N/E	N/E	N/E	1,083

The ranges for recoverable injury and TTS for Group 3 and 4 Fish are presented in Table 1-25 based on the thresholds contained in Popper *et al.* (2014). Note that the guidance only states numerical thresholds for Group 3 and 4 Fish. 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.

Table 1-25: Median potential impact ranges (m) for Group 3 and 4 fish exposed to drilled piling.

Source	Recoverable Injury	TTS
	170 dB rms for 48 hrs	158 dB for 12 hrs
Drilled piling	N/E	< 15

1.9.3 Other construction activities

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 1-26. The potential impact ranges for fish are presented in Table 1-27.

Table 1-26: Potential impact ranges (m) for marine mammals during other construction related operations.

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	965	<15	N/E	N/E	N/E	N/E	5.8 km
Cable laying	N/E	N/E	N/E	N/E	566	<15	N/E	N/E	N/E	N/E	3.6 km

Table 1-27: Median potential impact ranges (m) for Group 3 and 4 fish exposed to other construction related operations.

Source	Recoverable Injury	TTS
	170 dB rms for 48 hrs	158 dB for 12 hrs
Cable trenching	17	69
Cable laying	20	71

1.9.4 Vessel noise assessment

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

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.

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 1-28. The exposure metrics for different marine mammal and flee speeds (as detailed in section 1.7.1) were employed.

Table 1-28: Estimated PTS and TTS ranges from different vessels for marine mammals.

Source/Vessel	Range (m)										
	LF		HF		VHF		PCW		OCW		All
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
Sand wave clearance	N/E	N/E	N/E	N/E	566	<15	N/E	N/E	N/E	N/E	3.6 km
Boulder clearance	N/E	N/E	N/E	N/E	< 15	N/E	N/E	N/E	N/E	N/E	755 m
Installation vessel, construction vessel (DP)	N/E	N/E	N/E	N/E	566	<15	N/E	N/E	N/E	N/E	3.6 km
Jack up rig	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	< 20 m
Tug/anchor handlers	N/E	N/E	N/E	N/E	282	N/E	N/E	N/E	N/E	N/E	3.4 km
Rock placement vessel and cable installation vessels	N/E	N/E	N/E	N/E	566	<15	N/E	N/E	N/E	N/E	3.6 km
Guard vessels	N/E	N/E	N/E	N/E	282	N/E	N/E	N/E	N/E	N/E	3.4 km
Survey vessel and support vessels	N/E	N/E	N/E	N/E	1,670	<15	N/E	N/E	N/E	N/E	8.5 km
Crew transfer vessel	N/E	N/E	N/E	N/E	1,670	<15	N/E	N/E	N/E	N/E	8.5 km
Scour / Cable Protection / Seabed Preparation / Installation Vessels	N/E	N/E	N/E	N/E	1,670	<15	N/E	N/E	N/E	N/E	8.5 km

The ranges for recoverable injury and TTS for Groups 3 and 4 Fish are presented in Table 1-29 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.

Table 1-29: Estimated recoverable injury and TTS ranges from vessels for Groups 3 and 4 fish.

Source/Vessel	Injury Zone Radius (m)	
	Recoverable Injury 170 dB rms for 48 hrs	TTS 158 dB rms for 12 hrs
Sand wave clearance	20	71
Boulder clearance	N/E	N/E
Installation vessel, construction vessel (DP)	20	71
Jack up rig	N/E	N/E
Tug/anchor handlers	< 10	31
Rock placement vessel and cable installation vessels	20	71
Guard vessels	< 10	31
Survey vessel and support vessels	19	79
Crew transfer vessel	19	79
Scour / Cable Protection / Seabed Preparation / Installation Vessels	19	79

1.9.5 Geophysical survey

Geophysical surveying includes sonar like sound sources and the resulting injury and disturbance ranges for marine mammals are presented in Table 1-30, based on a comparison to the non-impulsive thresholds set out in Southall *et al*. (2019). 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 or directly within the swathe. Once the animal moves outside of the main beam, there is significantly reduced potential for injury.

Table 1-30: Potential impact ranges (m) for marine mammals during the MBES geophysical investigation, based on comparison to Southall *et al*. (2019) SEL thresholds (N/E = threshold not exceeded).

Species / Group	SEL Threshold (dB re 1 µPa^{2}s)		Distance (m)	
	PTS	TTS	PTS	TTS
LF	*199*	*179*	12	107
MF	*198*	*178*	124	172
HF	*173*	*153*	227	449
PW	*201*	*181*	34	123
OW	*219*	*199*	N/E	28
Disturbance	*SPL Threshold - 120 dB re 1 µPa^{2}s (rms)*		1,410	

1.9.6 Operational noise

The primary sources of underwater sound during the operational and maintenance phase of an offshore wind farm are vibration of the wind turbine's gear box and generator, and vessel noise associated with operational and maintenance activities.

Vibration of the wind turbine's gear box and generator is transmitted down the tower and radiated as sound from the tower wall. Sound radiation by surface waves is difficult to quantitatively predict, in particular for the boundary regions, and is highly dependent upon the conditions of both the wind turbine itself, including generator and tower condition, and on the seawater conditions. There have been few empirical investigations of operational offshore wind farms, and as such measurement data is also scarce.

The distances and exposures of mammals and fish reported by studies that investigate the impact of operational offshore wind farms present a range of values, but the majority conclude that in the order of hundreds of metres distance from the wind turbines, sound levels would likely be audible but not at a level sufficient to cause injury or behavioural changes (Betke, 2006; Nedwell *et al*., 2007; Ward *et al*., 2006, Norro *et al*., 2011; Jansen and De Jong, 2016). Norro *et al*. (2011) compared measurements of a range of different foundation types and wind turbine ratings in the Belgian part of the North Sea, as well as comparing those to other European waters. The authors found a slight increase in SPL compared to the ambient noise measured before the construction of the wind farms. They concluded that even the highest increases found within the dataset (20 to 25 dB re 1µ Pa) are unlikely to cause a significant impact and are significantly lower than those during the construction phase. They do however caution that this noise is of a much longer duration, in the order of 20 to 25 years over the operational lifespan of the wind farm, and that little is known of the long term impacts to aquatic life.

Table 1-31: Desktop study of operational noise from wind turbines.

Paper	Turbine	Foundation type	Location	Notes
Betke, 2006	Vestas V80-2 MW 70 m hub height	Monopiles	Horns Rev	118 dB re 1 µPa @ 150 Hz

Paper	Turbine	Foundation type	Location	Notes
Nedwell *et al*., 2007	Vestas V80-2 MW	Monopiles	North Hoyle	Inside wind farm 128 dB re. 1 µPa Outside 120 dB re. 1 µPa No tonal components
	Vestas V80-2 MW 68 m hub height	Steel monopiles 4.8 m diameter	Scroby Sands	Inside wind farm 130 dB re. 1 µPa Outside 132 dB re. 1 µPa States that the background level is higher inside the wind farm, perhaps due to shallow water No tonal component
	Vestas V90-3 MW 70 m hub height	Monopiles	Kentish Flats	Inside wind farm 114 dB re. 1 µPa Outside 113 dB re. 1 µPa Clear tonal components dependent upon separation
	Vestas V90-3 MW 75 m hub height	Steel monopiles 4.75 m diameter	Barrow	Inside wind farm 124 dB re. 1 µPa Outside 122 dB re. 1 µPa No tonal components. No consistent relationship between distance and level, thought due to wind noise
Norro *et al*., 2011	Senvion (Repower) 5 MW 95 m hub height	Gravity base	Thorntonbank	Increase of 8 dB above background
	Vestas V90-3 MW 72 m hub height	Steel monopile foundations	Belwind Bligh Bank	Increase of 20-25 dB above background
Jansen and De Jong, 2016	Vestas V80-2 MW	Steel monopiles 4 m diameter	Princess Amalia wind farm	Noted to be next to busy shipping lanes - no difference in level between 100 m and 3.8 km

Vessels used during the operational and maintenance phase are likely to include similar vessels to the construction phase. Generally, vessels will be limited to CTVs for day to day basis for routine inspection and maintenance activities. However, larger vessels will be required to support major component replacement activities or cable repair/reburial activities. The vessels anticipated for the operational and maintenance phase include jack-up vessels, cable installation (repair) vessels, service operation vessels and CTVs. Jack-up vessels and cable installation (repair) vessels will be used to facilitate any component replacement works (average of two events per year) or cable repair/remediation works (one inter-array cable repair and reburial events in the offshore wind farm area every five years of operation, and three offshore cable repair and reburial events along the offshore cable corridor over the lifetime of the Project). Vessel noise associated with operational and maintenance activities is likely to be similar to that assessed for the construction phase above.

1.10 Summary and conclusions

Noise modelling has been undertaken to determine the range of potential effects on marine mammals, fish and turtles due to noise from piling activities associated with construction of the Project. The results are summarised in Table 1-32, which shows the maximum injury range for each group of mammals, fish and turtles, for installation of monopiles, with and without mitigation (the worst case scenario of SEL or peak, east or west).

Table 1-32: Summary of maximum PTS injury ranges for marine mammals, and mortality for fish and turtles due to impact piling of single pile based on highest range of peak pressure or SEL (N/E = threshold not exceeded).

Species group	Injury range / m	
	No ADD	With 15 mins ADD
Low frequency cetacean	394	168
High frequency cetacean	84	84
Very high frequency cetacean	489	489
Phocid carnivores	179	179
Other carnivores	74	74
Group 1 Fish: no swim bladder	245	245
Group 2 Fish: where swim bladder is not involved in hearing	357	357
Group 3 to 4 Fish: where swim bladder is involved in hearing	357	357
Sea turtles	357	357
Eggs and larvae	357	357

Underwater noise emissions from the wind turbines and vessels during the operational and maintenance phase is unlikely to be at a level sufficient to cause injury or behavioural changes to marine mammals, fish or turtles.

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