codling wind park

Environmental Impact Assessment Report

Volume 4

Appendix 9.4 Underwater Noise Assessment

Codling Wind Park: Underwater noise assessment

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Units

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

Glossary

Term	Definition
Decibel (dB)	A customary scale commonly used (in various ways) for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be $10\log_{10}(actual/reference)$ where $(actual/reference)$ is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is $20\log_{10}(actual\,pressure/reference\,pressure)$. The standard reference for underwater sound is 1 micro pascal (µPa). The dB symbol is followed by a second symbol identifying the specific reference value (e.g., re 1 µPa).
Peak pressure	The highest pressure above or below ambient that is associated with a sound wave.
Peak-to-peak pressure	The sum of the highest positive and negative pressures that are associated with a sound wave.
Permanent Threshold Shift (PTS)	A permanent total or partial loss of hearing caused by acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the air, and thus a permanent reduction of hearing acuity.
Root Mean Square (RMS)	The square root of the arithmetic average of a set of squared instantaneous values. Used for presentation of an average sound pressure level.
Sound Exposure Level (SEL)	The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.
Sound Exposure Level, cumulative (SEL_{cum})	Single value for the collected, combined total of sound exposure over a specified time or multiple instances of a noise source.
Sound Exposure Level, single strike (SEL_{ss})	Calculation of the sound exposure level representative of a single noise impulse, typically a pile strike.
Sound Pressure Level (SPL)	The sound pressure level is an expression of sound pressure using the decibel (dB) scale; the standard frequency pressures of which are 1 µPa for water and 20 µPa for air.
Sound Pressure Level Peak (SPL_{peak})	The highest (zero-peak) positive or negative sound pressure, in decibels.
Temporary Threshold Shift (TTS)	Temporary reduction of hearing acuity because of exposure to sound over time. Exposure to high levels of sound over relatively short time periods could cause the same level of TTS as exposure to lower levels of sound over longer time periods. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory cells. The duration of TTS varies depending on the nature of the stimulus.
Unweighted sound level	Sound levels which are "raw" or have not been adjusted in any way, for example to account for the hearing ability of a species.
Weighted sound level	A sound level which has been adjusted with respect to a "weighting envelope" in the frequency domain, typically to make an unweighted level relevant to a particular species. Examples of this are the dB(A), where the overall sound level has been adjusted to account for the hearing ability of humans in air, or the filters used by Southall *et al*. (2019) for marine mammals.

Acronyms

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

1 Introduction

Codling Wind Park (Codling) is a proposed offshore wind farm (OWF) situated in the Irish Sea. As part of the Environmental Impact Assessment (EIA) process, Subacoustech Environmental Ltd. have undertaken detailed underwater noise modelling and analysis in relation to marine mammals and fish at the Codling site.

The Codling site covers an area of approximately 125 km^2 and is situated between 13 and 22 km from the County Wicklow coast on the east of Ireland. The location of Codling is shown in Figure 1-1.

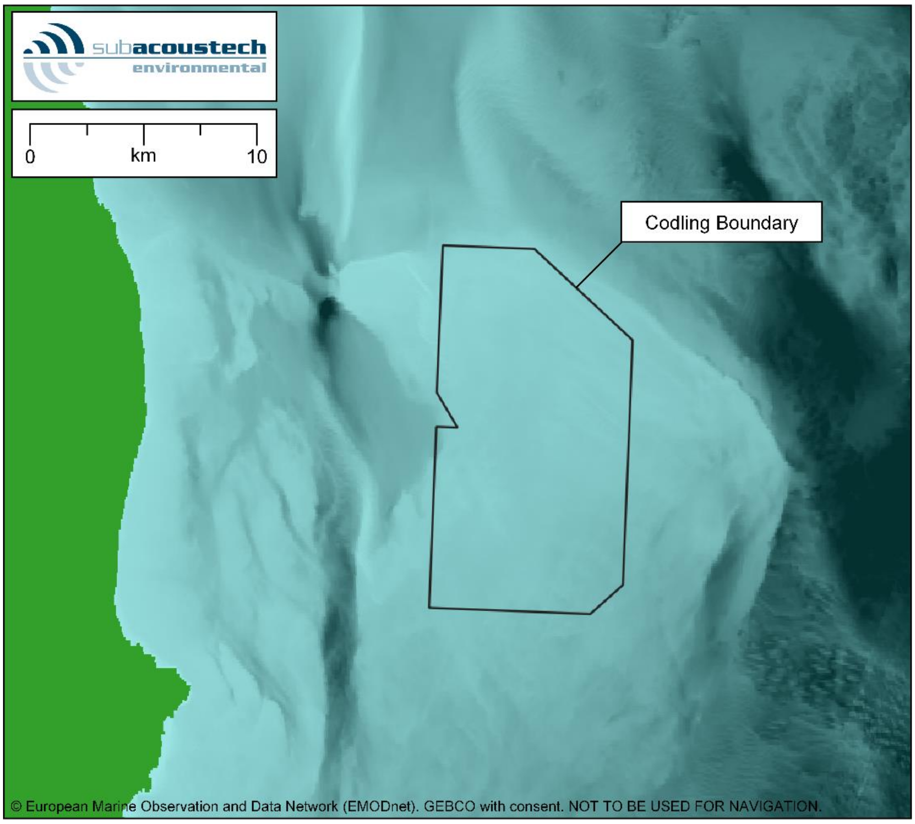

Figure 1-1 Overview map showing the Codling boundary and the surrounding bathymetry

This report presents a detailed assessment of the potential underwater noise during the installation of WTG foundations at Codling, and includes the following:

- Background information covering the units for measuring and assessing underwater noise and a review of the underwater noise metrics and criteria used to assess the possible environmental effects in marine receptors (Section 2);
- Discussion of the approach, input parameters and assumptions for the detailed noise modelling undertaken (Section 3);
- Presentation and interpretation of the detailed subsea noise modelling for impact piling with regards to its effects on marine mammals and fish (Section 4)
- Noise modelling of the other noise sources expected to be present around the construction and operation of Codling including cable laying, dredging, rock placement, trenching, vessel movements, operational WTG noise and unexploded ordnance (UXO) clearance (section 5); and
- Summary and conclusions (Section 6).

Additional modelling results are also provided in Appendices A and B of this report. These present results to older marine mammal guidance (Southall *et al*. 2007) and non-impulsive modelling. See section 2.2.1 for details.

2 Background to underwater noise metrics

2.1 Underwater noise

Sound travels much faster in water (approximately 1500 ms^{-1}) than in air (340 ms^{-1}). Since water is a relatively incompressible, dense medium, the pressure associated with underwater sound tends to be much higher than in air. It should be noted that stated underwater noise levels should not be confused with noise levels in air, which use a different scale.

2.1.1 Units of measurement

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

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

The fundamental definition of the dB scale is given by:

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

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

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

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

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

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

2.1.2 Sound Pressure Level (SPL)

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

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

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

2.1.3 Peak Sound Pressure Level (SPL_{peak})

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

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

2.1.4 Sound Exposure Level (SEL)

When considering the noise from transient sources, the issue of the duration of the pressure wave is often addressed by measuring the total acoustic energy (energy flux density) of the wave. This form of analysis was used by Bebb and Wright (1953, 1954a, 1954b, 1955), and later by Rawlins (1987), to explain the apparent discrepancies in the biological effect of short and long-range blast waves on human divers. More recently, this form of analysis has been used to develop criteria for assessing injury ranges for fish and marine mammals from various noise sources (Popper *et al*., 2014; Southall *et al*., 2019; Southall *et al*., 2007).

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

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

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

To express the SE on a logarithmic scale by means of a dB, it must be compared with a reference acoustic energy (${p^2}_{ref}$) and a reference time (T_{ref}). The SEL is then defined by:

$$SEL = 10 \times \log_{10}\left(\frac{\int_0^T p^2(t)dt}{{p^2}_{ref}T_{ref}}\right)$$

By using a common reference pressure (p_{ref}) of 1 µPa for assessments of underwater noise, the SEL and SPL can be compared using the expression:

$$SEL = SPL + 10 \times \log_{10} T$$

where the SPL is a measure of the average level of broadband noise and the SEL sums the cumulative broadband noise energy.

This means that, for continuous sounds of less than (i.e., fractions of) one second, the SEL will be lower than the SPL. For periods greater than one second, the SEL will be numerically greater than the SPL (i.e., for a continuous sound of 10 seconds duration, the SEL will be 10 dB higher than the SPL; for a sound of 100 seconds duration the SEL will be 20 dB higher than the SPL, and so on).

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

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

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

2.2 Analysis of environmental effects

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

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

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

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

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

- Southall *et al*. (2019) marine mammal exposure criteria
- NOAA (2005) covering disturbance in marine mammals; and
- Popper *et al*. (2014) sound exposure guidelines for fishes and sea turtles.

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

In addition, the older, superseded, Southall *et al*. (2007) criteria, has also been included in line with the current guidance from the Department of Arts, Heritage and the Gaeltacht (2014).

2.2.1 Marine mammals

2.2.1.1 Southall et al. (2019) criteria

The Southall *et al*. (2019) paper is effectively an update of the previous Southall *et al.* (2007) paper and provides identical thresholds to those from the National Marine Fisheries Service (NMFS) (2018) guidance for marine mammals. The concepts presented here for Southall *et al.* (2019) are also relevant for Southall *et al.* (2007), which is described separately in Section 2.2.1.3.

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

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

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

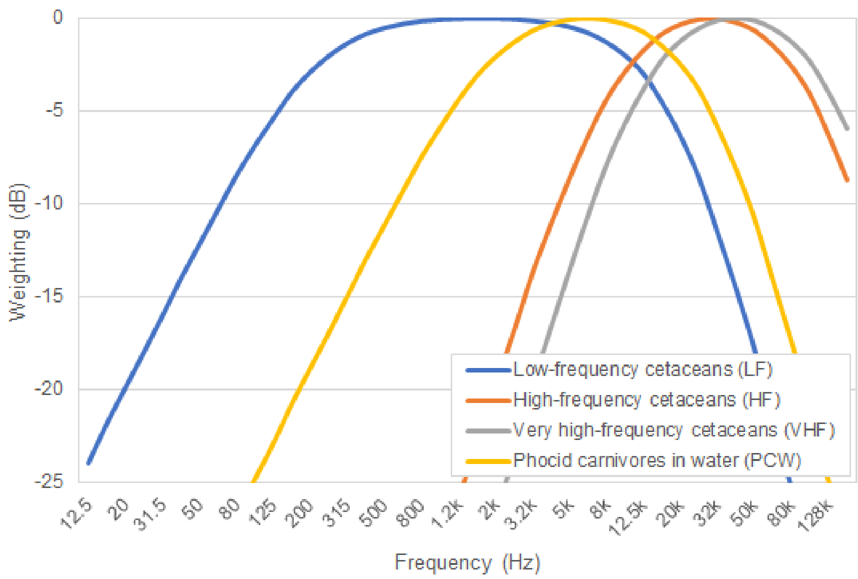

Figure 2-1 Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al., 2019).

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

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

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

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

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

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

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

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

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

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

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

Finally, it is worth noting that, comparing Southall *et al.* (2019) to NMFS (2018), the guidance documents apply different names to otherwise identical marine mammal groups and weightings, which are otherwise numerically identical. For example, what Southall *et al*. (2019) calls high-frequency cetaceans (HF), NMFS (2018) calls mid-frequency cetaceans (MF), and what Southall *et al*. (2019) calls very high-frequency cetaceans (VHF), NMFS (2018) refers to as high-frequency cetaceans (HF). As such, care should be taken when comparing results using the Southall *et al*. (2019) and NMFS (2018) criteria, especially as the HF groupings and criteria cover different species depending on which study is being used. A similar disparity between the naming conventions is present when using the Southall *et al*. (2007) criteria; this is discussed in the following section.

2.2.1.2 NOAA (2005) criteria

Limited data is available for behavioural disturbance on species of marine mammal. Recognising this, the NOAA (2005) Level B (behavioural disturbance) harassment criterion for impulsive noise on marine mammals has been included to cover disturbance effects. This criterion is 160 dB unweighted SPL_{RMS}.

2.2.1.3 Southall et al. (2007) criteria

In line with the most up to date guidance from the Department of Arts, Heritage and the Gaeltacht (2014), the criteria from the Southall *et al*. (2007) study have also been included in this assessment. The Southall *et al*. (2007) criteria are a precursor to the Southall *et al*. (2019) and NMFS (2018) studies and have been superseded by these publications. It is recommended that the Southall *et al.* (2019) guidance be considered the best available at the time of writing.

Southall *et al*. (2007) defined a set of auditory injury and behavioural response criteria based on unweighted SPL_{peak} and M-weighted SELs. The M-weightings are a series of generalised frequency response filters, that, when applied to noise data, can represent the levels of underwater noise perceived by marine mammals. Southall *et al*. (2007) group marine mammals into five categories, four of which are relevant to underwater noise (the fifth is for pinnipeds in air). For each group an approximate frequency range of hearing is given based on known audiogram data or inferred from other information such as auditory morphology. A summary of the M-weighting functions is given in Table 2-4Table 2-4 and illustrated in Figure 2-2.

Table 2-4 Marine mammal hearing groups and genera represented in each M-weighting group (from Southall et al., 2007).

Functional hearing group	Est. auditory bandwidth	Genera represented (Number species/subspecies)	Frequency-weighting network
Low-frequency cetaceans	7 Hz to 22 kHz	*Balaena, Caperea, Eschrichtius, Megaptera, Balaenoptera* (13 species/subspecies)	M_{lf} (lf: low-frequency cetaceans)
Mid-frequency cetaceans	150 Hz to 160 kHz	*Steno, Sousa, Sotalia, Tursiops, Stenella, Delphinus, Lagenodelphis, Lagenorhynchus, Lissodelphis, Grampus, Peponocephala, Feresa, Pseudorca, Orcinus, Globicephala, Orcaella, Physeter, Delphinapterus, Monodon, Ziphius, Berardius, Tasmacetus, Hyperoodon, Mesoplodon* (57 species/subspecies)	M_{mf} (mf: mid-frequency cetaceans)
High-frequency cetaceans	200 Hz to 180 kHz	*Phocoena, Neophocaena, Phocoenoides, Platanista, Inia, Kogia, Lipotes, Pontoporia, Cephalorhynchus* (20 species/subspecies)	M_{hf} (hf: high-frequency cetaceans)
Pinnipeds in water	75 Hz to 75 kHz	*Arctocephalus, Callorhinus, Zalophus, Eumetopias, Neophoca, Phocarctos, Otaria, Erignathus, Phoca, Pusa, Halichoerus, Histriophoca, Pagophilus, Cystophora, Monachus, Mirounga, Leptonychotes, Ommatophoca, Lobodon, Hydrurga, Odobenus* (41 species/subspecies)	M_{pw} (pw: pinnipeds in water)

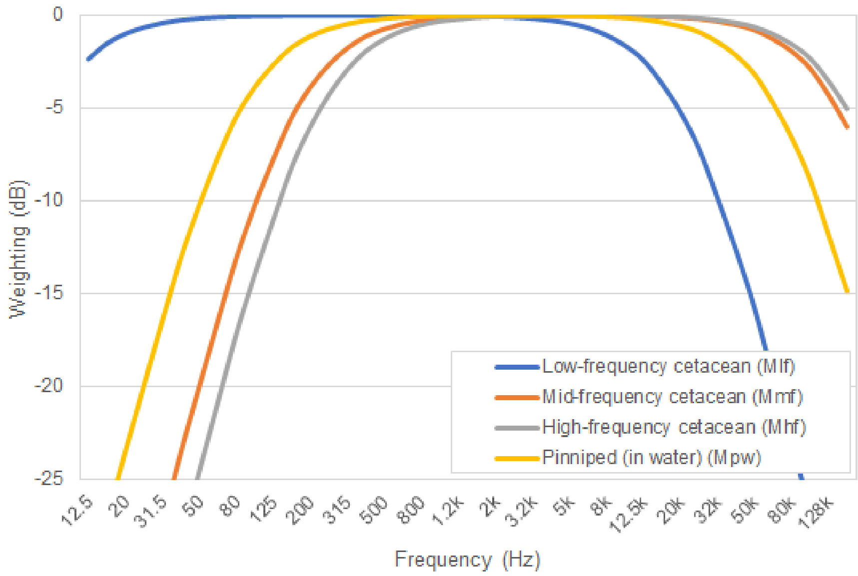

Figure 2-2 The M-weighting functions from Southall et al. (2007) for the marine mammal hearing groups considered.

The criteria from Southall *et al*. (2007) are presented in Table 2-5 and Table 2-6 for injury and behavioural response respectively. For each hearing group, criteria are given for single pulses, multiple pulses and non-pulses; results for all of these sound types have been included, as at greater ranges pulsed sound can be classified as non-impulsive, or non-pulses, as discussed in Section 2.2.1.1.

Table 2-5 Unweighted SPL_{peak} and M-weighted SEL injury criteria for individual marine mammals (Southall et al., 2007).

Marine mammal group		Sound type		
		Single pulses	Multiple pulses	Nonpulses
Low-frequency cetaceans	SPL	230 dB re 1 µPa (peak)	230 dB re 1 µPa (peak)	230 dB re 1 µPa (peak)
	SEL	198 dB re 1 µPa²s (M_{lf})	198 dB re 1 µPa²s (M_{lf})	215 dB re 1 µPa²s (M_{lf})
Mid-frequency cetaceans	SPL	230 dB re 1 µPa (peak)	230 dB re 1 µPa (peak)	230 dB re 1 µPa (peak)
	SEL	198 dB re 1 µPa²s (M_{mf})	198 dB re 1 µPa²s (M_{mf})	215 dB re 1 µPa²s (M_{mf})
High-frequency cetaceans	SPL	230 dB re 1 µPa (peak)	230 dB re 1 µPa (peak)	230 dB re 1 µPa (peak)
	SEL	198 dB re 1 µPa²s (M_{hf})	198 dB re 1 µPa²s (M_{hf})	215 dB re 1 µPa²s (M_{hf})
Pinnipeds in water	SPL	218 dB re 1 µPa (peak)	218 dB re 1 µPa (peak)	218 dB re 1 µPa (peak)
	SEL	186 dB re 1 µPa²s (M_{pw})	186 dB re 1 µPa²s (M_{pw})	203 dB re 1 µPa²s (M_{pw})

Table 2-6 Unweighted SPL_{peak} and M-weighted SEL behavioural response criteria for individual marine mammals (Southall et al., 2007).

Marine mammal group		Sound type
		Single pulses
Low-frequency cetaceans	SPL	224 dB re 1 µPa (peak)
	SEL	183 dB re 1 µPa²s (M_{lf})
Mid-frequency cetaceans	SPL	224 dB re 1 µPa (peak)
	SEL	183 dB re 1 µPa²s (M_{mf})
High-frequency cetaceans	SPL	224 dB re 1 µPa (peak)
	SEL	183 dB re 1 µPa²s (M_{hf})
Pinnipeds in water	SPL	224 dB re 1 µPa (peak)
	SEL	171 dB re 1 µPa²s (M_{pw})

As with the Southall *et al*. (2019) criteria, where SEL_{cum} are required, a fleeing animal model has been used. The same constant fleeing speeds of 3.25 ms^{-1} (LF cetaceans) and 1.5 ms^{-1} (all other species groups) have been used to keep consistency throughout the modelling (Blix and Folkow, 1995; Otani *et al*., 2000).

It is also worth noting the differences in the naming conventions between Southall *et al*. (2019) and Southall *et al*. (2007). As with the NMFS (2018) criteria and explained in the previous section, special care should be taken when comparing results using the Southall *et al*. (2019) and Southall *et al*. (2007) criteria, especially as the "high-frequency" groupings and criteria cover different species depending on which guidance document is being used. The differences are summarised in Table 2-7.

Table 2-7 Comparison of the naming conventions used for Southall et al. (2019) and Southall et al. (2007).

Southall *et al*. (2019) group names	Southall *et al*. (2007) group names	Example species
Low-frequency cetaceans (LF)	Low-frequency cetaceans (M_{lf})	Baleen whales
High-frequency cetaceans (HF)	Mid-frequency cetaceans (M_{mf})	Dolphins, toothed whales, beaked whales, bottlenose whales (including bottlenose dolphin)
Very high-frequency cetaceans (VHF)	High-frequency cetaceans (M_{hf})	True porpoises (including harbour porpoise)
Phocid carnivores in water (PCW)	Pinniped in water (M_{pw})	True seals (including harbour seal)

As both sets of guidance are presented in this study, in each case the respective criteria set in use has been clearly identified.

2.2.2 Fish

2.2.2.1 Popper et al. (2014) criteria

The large number of, and variation in, fish species leads to a greater challenge in production of a generic noise criterion, or range of criteria, for the assessment of noise impacts. The publication of Popper *et al*. (2014) provides an authoritative summary of the latest research and guidelines for fish exposure to sound and uses categories for fish that are representative of the species present in Irish waters.

The Popper *et al*. (2014) study groups species of fish by whether they possess a swim bladder, and whether it is involved in its hearing; groups for sea turtles and fish eggs and larvae are also included. The guidance also gives specific criteria (as both unweighted SPL_{peak} and unweighted SEL_{cum} values) for a variety of noise sources. (It is recognised that these are related to sound pressure, whereas more recent documents (e.g., Popper and Hawkins (2019) clearly state that many fish species are most sensitive to particle motion; this is discussed in section 2.2.2.2.)

For this study, criteria for impact piling, continuous noise sources, and explosions have been considered; these are summarised in Table 2-8 to Table 2-10.

Table 2-8 Criteria for mortality and potential mortal injury, recoverable injury, and TTS in species of fish from impact piling noise (Popper et al., 2014).

Type of animal	Mortality and potential mortal injury	Impairment	
		Recoverable injury	TTS
Fish: no swim bladder	> 219 dB SEL_{cum} > 213 dB SPL_{peak}	> 216 dB SEL_{cum} > 213 dB SPL_{peak}	>> 186 dB SEL_{cum}
Fish: swim bladder is not involved in hearing	210 dB SEL_{cum} > 207 dB SPL_{peak}	203 dB SEL_{cum} > 207 dB SPL_{peak}	> 186 dB SEL_{cum}
Fish: swim bladder involved in hearing	207 dB SEL_{cum} > 207 dB SPL_{peak}	203 dB SEL_{cum} > 207 dB SPL_{peak}	186 dB SEL_{cum}
Sea turtles	> 210 dB SEL_{cum} > 207 dB SPL_{peak}	See Table 2-11	
Eggs and larvae	> 210 dB SEL_{cum} > 207 dB SPL_{peak}		

Table 2-9 Criteria for recoverable injury and TTS in species of fish from continuous noise sources (Popper et al., 2014).

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

Table 2-10 Criteria for potential mortal injury in species of fish from explosions (Popper et al., 2014).

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

Where insufficient data are available, Popper *et al*. (2014) also gives qualitative criteria that summarise the effect of the noise as having either a high, moderate, or low effect on an individual in either the near-field (tens of metres), intermediate-field (hundreds of metres), or far-field (thousands of metres). These qualitative effects are reproduced in Table 2-11 to Table 2-13.

Table 2-11 Summary of the qualitative effects on species of fish from impact piling noise (Popper et al., 2014) (N = Near-field; I = Intermediate-field; F = Far-field).

<table>
<tr><th rowspan="2">Type of animal</th><th colspan="3">Impairment</th><th rowspan="2">Behaviour</th></tr>
<tr><th>Recoverable injury</th><th>TTS</th><th>Masking</th></tr>
<tr><td>Fish: no swim bladder</td><td colspan="2" rowspan="3">See Table 2-8</td><td>(N) Moderate
(I) Low
(F) Low</td><td>(N) High
(I) Moderate
(F) Low</td></tr>
<tr><td>Fish: swim bladder is not involved in hearing</td><td>(N) Moderate
(I) Low
(F) Low</td><td>(N) High
(I) Moderate
(F) Low</td></tr>
<tr><td>Fish: swim bladder involved in hearing</td><td>(N) High
(I) High
(F) Moderate</td><td>(N) High
(I) High
(F) Moderate</td></tr>
<tr><td>Sea turtles</td><td>(N) High
(I) Low
(F) Low</td><td>(N) High
(I) Low
(F) Low</td><td>(N) High
(I) Moderate
(F) Low</td><td>(N) High
(I) Moderate
(F) Low</td></tr>
<tr><td>Eggs and larvae</td><td>(N) Moderate
(I) Low
(F) Low</td><td>(N) Moderate
(I) Low
(F) Low</td><td>(N) Moderate
(I) Low
(F) Low</td><td>(N) Moderate
(I) Low
(F) Low</td></tr>
</table>

Table 2-12 Summary of the qualitative effects on fish from continuous noise from Popper et al. (2014) (N = Near-field; I = Intermediate-field; F = Far-field).

<table>
<tr><th rowspan="2">Type of animal</th><th rowspan="2">Mortality and potential mortal injury</th><th colspan="3">Impairment</th><th rowspan="2">Behaviour</th></tr>
<tr><th>Recoverable injury</th><th>TTS</th><th>Masking</th></tr>
<tr><td>Fish: no swim bladder</td><td>(N) Low
(I) Low
(F) Low</td><td>(N) Low
(I) Low
(F) Low</td><td>(N) Moderate
(I) Low
(F) Low</td><td>(N) High
(I) High
(F) Moderate</td><td>(N) Moderate
(I) Moderate
(F) Low</td></tr>
<tr><td>Fish: swim bladder is not involved in hearing</td><td>(N) Low
(I) Low
(F) Low</td><td>(N) Low
(I) Low
(F) Low</td><td>(N) Moderate
(I) Low
(F) Low</td><td>(N) High
(I) High
(F) Moderate</td><td>(N) Moderate
(I) Moderate
(F) Low</td></tr>
<tr><td>Fish: swim bladder involved in hearing</td><td>(N) Low
(I) Low
(F) Low</td><td colspan="2">See Table 2-9</td><td>(N) High
(I) High
(F) High</td><td>(N) High
(I) Moderate
(F) Low</td></tr>
<tr><td>Sea turtles</td><td>(N) Low
(I) Low
(F) Low</td><td>(N) Low
(I) Low
(F) Low</td><td>(N) Moderate
(I) Low
(F) Low</td><td>(N) High
(I) High
(F) Moderate</td><td>(N) High
(I) Moderate
(F) Low</td></tr>
<tr><td>Eggs and larvae</td><td>(N) Low
(I) Low
(F) Low</td><td>(N) Low
(I) Low
(F) Low</td><td>(N) Low
(I) Low
(F) Low</td><td>(N) High
(I) Moderate
(F) Low</td><td>(N) Moderate
(I) Moderate
(F) Low</td></tr>
</table>

Table 2-13 Summary of the qualitative effects on species of fish from explosions (Popper et al., 2014) (N = Near-field; I = Intermediate-field; F = Far-field).

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

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

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

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

2.2.2.2 Particle motion

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

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

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

The primary reason for the continuing use of sound pressure as the criteria, despite particle motion appearing to be the physical measure to which so many fish react or sense, is a lack of data (Popper and Hawkins, 2018) with respect to noise as measured in terms of particle motion. Work is continuing on particle motion, but at the present time Popper and Hawkins (2019) state that “since there is an immediate need for updated criteria and guidelines on potential effects of anthropogenic sound on fishes, we recommend, as do our colleagues in Sweden (Andersson *et al*., 2017), that the criteria proposed by Popper *et al*. (2014) [in terms of sound pressure] should be used.”

3 Modelling methodology

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

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

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

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

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

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

Simpler modelling approaches have been used for noise sources other than impact piling that may be present during the construction and operation of Codling; these are discussed in section 5.

3.1 Modelling confidence

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

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

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

Previous iterations of the INSPIRE model have endeavoured to give a worst-case estimate of underwater noise levels produced by various permutations of impact piling parameters. There is always some natural variability with underwater noise measurements, even when considering measurements of pile strikes under the same conditions (i.e., at the same energy through, taken at the same range). For example, there can be variations in noise level of up to five or even 10 dB, as seen in Bailey *et al*. (2010) and the data shown in Figure 3-1. When modelling using the upper bounds of this range, in combination with other worst-case parameter selections, conservatism can be compounded to create excessively overcautious predictions, especially when calculating SEL_{cum}. With this in mind, the current version of INSPIRE attempts to calculate closer to the average fit of the measured noise levels at all ranges.

Figure 3-1 presents a small selection of the measured impact piling noise data plotted against outputs from INSPIRE. The plots show data points from measured data (in blue) plotted alongside modelled data (in orange) using INSPIRE v5.2, matching the pile size, energy through and position of the measured data. These show the fit to the data, with the INSPIRE data points sitting, more or less, in the middle of the measured noise levels at each range. When combined with the worst-case assumptions in parameter selection, modelled results will remain precautionary.

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

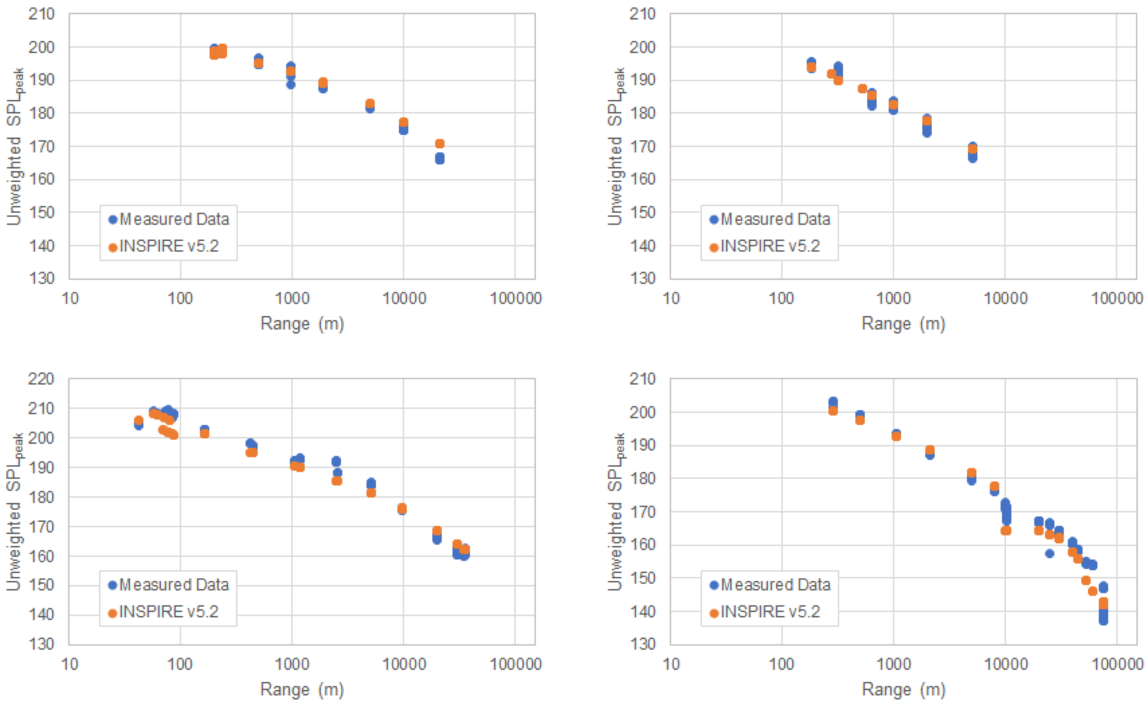

Figure 3-1 Comparison between example measured impact piling data (blue points) and modelled data using INSPIRE version 5.2 (orange points)[1].

[1] Top Left: 6.0 m pile, off the Suffolk coast, North Sea, 2009; Top Right: 1.8 m pile, West of Barrow-in-Furness, Irish Sea, 2010; Bottom Left: 5.3 m pile, off the North Welsh coast, 2012; Bottom Right: 6.0 m pile, off the coast of Cumbria, 2010.

3.2 Modelling parameters

3.2.1 Modelling locations

Modelling for WTG foundation impact piling has been undertaken at four representative locations covering proposed WTG locations at the extents of the Codling site. These locations are summarised in Table 3-1 and illustrated in Figure 3-2.

Table 3-1 Summary of the underwater noise modelling locations used for this study.

Modelling locations	**South East (SE)**	**South West (SW)**	**North East (NE)**	**North West (NW)**
Latitude	53.013	53.002	53.107	53.142
Longitude	-005.719	-005.841	-005.719	-005.841
Water depth	26.0 m	16.8 m	15.6 m	13.6 m

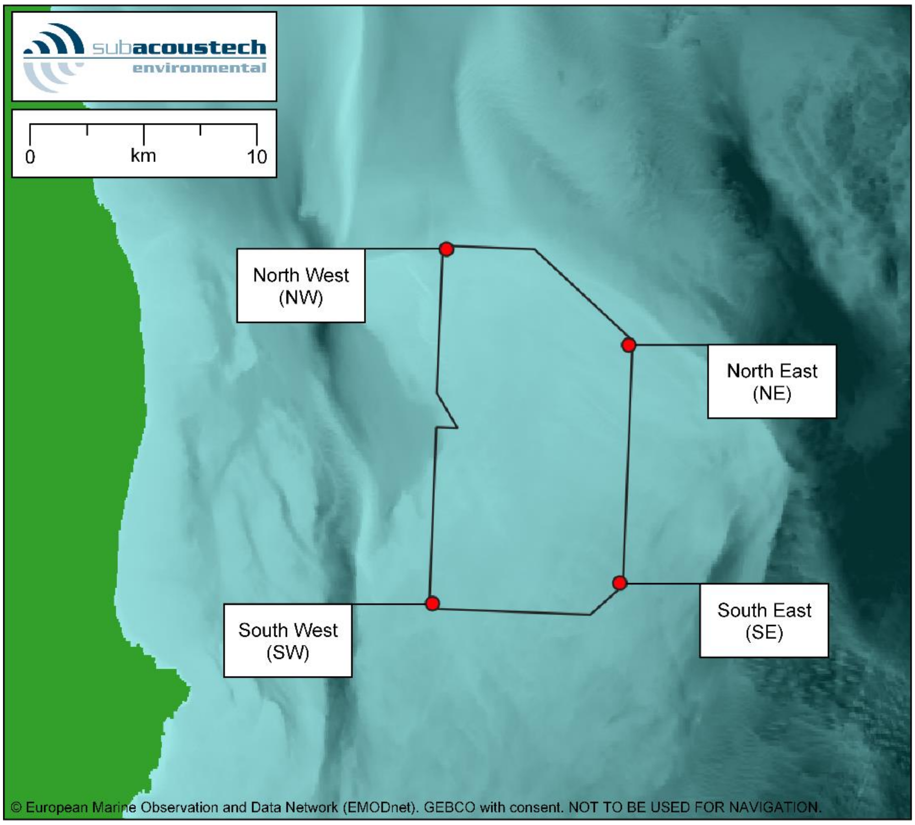

Figure 3-2 Approximate positions of the modelling locations at Codling

3.2.2 WTG foundation and impact piling parameters

Three foundation installation scenarios have been considered for this study. All the scenarios consist of 9.5 m diameter monopile foundations installed using a maximum hammer energy through (enthru) of 4,400 kJ.

For SEL_{cum} criteria, the soft start and ramp up of blow energies along with the total duration of piling and strike rate must also be considered. The three modelling scenarios have been developed in order to mitigate underwater noise impacts, with more restrictive piling parameters maintained for areas of greater depth (e.g., the SE corner) through to a greater flexibility in the shallower waters (e.g., the NW corner). Scenario 1 is applicable only to foundations in the SE corner, Scenario 2 only to foundation locations in the band covering the NE corner to the SW corner, and Scenario 3 only to foundation locations in the NW corner. These modelling scenarios are summarised in Table 3-2 to Table 3-4, and illustrated in Figure 3-3.

Table 3-2 Summary of the soft start and ramp up scenario used for the scenario 1 monopile foundation modelling (SE only).

Scenario 1	**440 kJ**		**1,100 kJ**	**2,200 kJ**	**3,300 kJ**	**4,400 kJ**
No. of strikes	200	1,248	1,151	1,143	899	953
Duration	20 minutes	36 minutes	33 minutes	33 minutes	30 minutes	38 minutes
Strike rate	10 bl/min	~35 bl/min			~30 bl/min	~25 bl/min
5,594 strikes over 3 hours 10 minutes						

Table 3-3 Summary of the soft start and ramp up scenario used for the scenario 2 monopile foundation modelling (SW and NE only).

Scenario 2	**440 kJ**		**1,100 kJ**	**2,200 kJ**	**3,300 kJ**	**4,400 kJ**
No. of strikes	200	277	279	277	240	3,461
Duration	20 minutes	8 minutes	8 minutes	8 minutes	8 minutes	138 minutes
Strike rate	10 bl/min	~35 bl/min			30 bl/min	~25 bl/min
4,734 strikes over 3 hours 10 minutes						

Table 3-4 Summary of the soft start and ramp up scenario used for the scenario 3 monopile foundation modelling (NW only).

Scenario 3	**440 kJ**		**1,100 kJ**	**2,200 kJ**	**3,300 kJ**	**4,400 kJ**
No. of strikes	200	277	279	277	240	3,461
Duration	20 minutes	8 minutes	8 minutes	8 minutes	8 minutes	138 minutes
Strike rate	10 bl/min	~35 bl/min			30 bl/min	~25 bl/min
9,468 strikes over 6 hours 20 minutes (two piles installed in a 24-hour period)						

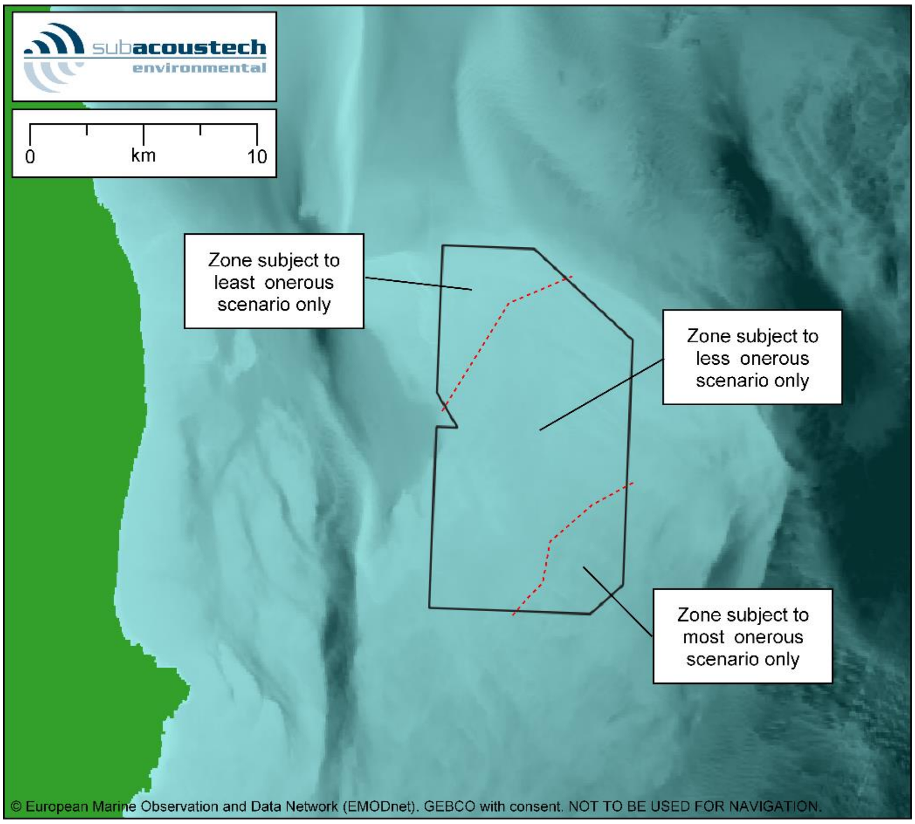

Figure 3-3 Map showing the zones where each modelling scenario applies

3.2.3 Source levels

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

It is worth noting that the 'source level' does not technically exist in the contest of many shallow water (< 100 m) noise sources (Heaney *et al*., 2020); there is no single noise source level at a theoretical 'point' associated with a large sound source such as a pile. In practice, for underwater noise modelling such as this, it is effectively an 'apparent source level' that is used – the sonic equivalent of seeing a large object from a great distance, with it appearing to be only a spot on the horizon – essentially a value that can be used to produce correct noise levels at range (for a specific model), as required in impact assessments.

The unweighted SPL_{peak} and SEL_{ss} source levels estimated for this study are provided in Table 3-5. These figures are presented in accordance with the typical requirements given by regulatory authorities, although as indicated above, they are not necessarily compatible with any other model or predicted source level. In each case, the differences in source level for each location are minimal. Also, as the same pile diameter and maximum energy through has been assumed for all three modelling scenarios, only a single source level has been given for each location.

Table 3-5 Summary of the unweighted source levels used for modelling.

Source levels	**Location**	**Monopile foundation** 9.5 m / 4,400 kJ
Unweighted SPL_{peak}	SE location	242.6 dB re 1 µPa @ 1 m
	SW location	242.6 dB re 1 µPa @ 1 m
	NE location	242.5 dB re 1 µPa @ 1 m
	NW location	242.5 dB re 1 µPa @ 1 m
Unweighted SEL_{ss}	SE location	223.6 dB re 1 µPa²s @ 1 m
	SW location	223.6 dB re 1 µPa²s @ 1 m
	NE location	223.6 dB re 1 µPa²s @ 1 m
	NW location	223.6 dB re 1 µPa²s @ 1 m

3.2.4 Environmental conditions

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

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

3.3 Cumulative SELs and fleeing receptors

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

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

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

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

As an example, the graphs in Figure 3-4 and Figure 3-5 show the difference in the received SEL from a stationary receptor and a fleeing receptor travelling at a constant speed of 1.5 ms^{-1}, using the scenario 1 parameters at the SE location.

The received SEL_{ss} from the stationary receptor, as illustrated in Figure 3-4, shows the noise level gradually increasing as the energy through increases throughout the piling operation. These step changes are also visible for the fleeing receptor, but as the receptor is further from the noise source by the time the levels increase, the total received exposure reduces, resulting in progressively lower received noise levels. As an example, for the first 20 minutes of piling, where the energy through is 440 kJ, fleeing at a rate of 1.5 ms^{-1}, a receptor has the potential to move 1.8 km from the noise source. After the full 3 hours and 10 minutes, the receptor has the potential to be over 17 km from the noise source.

Figure 3-5 shows the effect these different received levels have when calculating the SEL_{cum}. It clearly shows the difference in cumulative effect between the receptor remaining still, as opposed to fleeing. To use an extreme example, starting at a range of 1 m, the first strike results in a received level of 215.0 dB re 1 μPa^2s. If the receptor were to remain stationary throughout the piling operation it would receive a cumulative level of 258.6 dB re 1 μPa^2s, whereas when fleeing at 1.5 ms^{-1} over the same scenario, a cumulative received level of just 218.6 dB re 1 μPa^2s is achieved.

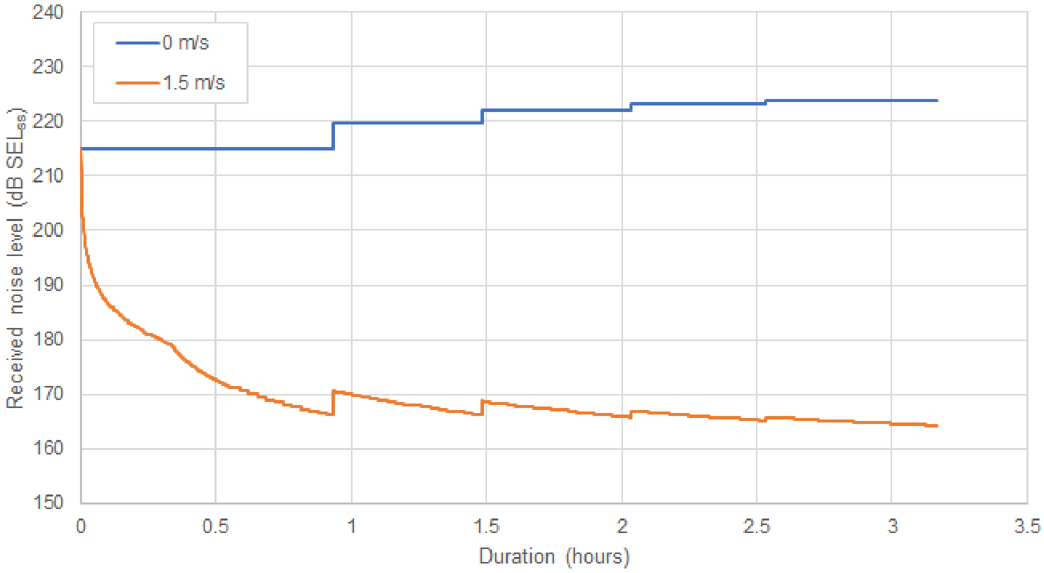

Figure 3-4 Received single-strike noise levels (SEL_{ss}) for receptors during the monopile foundation parameters at the NE location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source.

To summarise, if the receptor were to start fleeing in a straight line from the noise source starting at a range closer than the modelled value it would receive a noise exposure in excess of the criteria, and if the receptor were to start fleeing from a range further than the modelled value it would receive a noise exposure below the criteria. This is illustrated in Figure 3-6.

Some modelling approaches include the effects of Acoustic Deterrent Devices (ADDs) that cause receptors to flee from the immediate area around the pile before activity commences. Subacoustech Environmental's modelling approach does not include this, however the effects of using an ADD can still be inferred from the results. For example, if a receptor were to flee for 20 minutes from an ADD at a rate of 1.5 ms^{-1}, it would travel 1.8 km before piling begins. If a cumulative SEL impact range from INSPIRE was calculated to be below 1.8 km, it can safely be assumed that the ADD will be effective in eliminating the risk of injury on the receptor. The noise from an ADD is of a much lower level than impact piling, and as such the overall effect on the SEL_{cum} exposure on a receptor would be minimal.

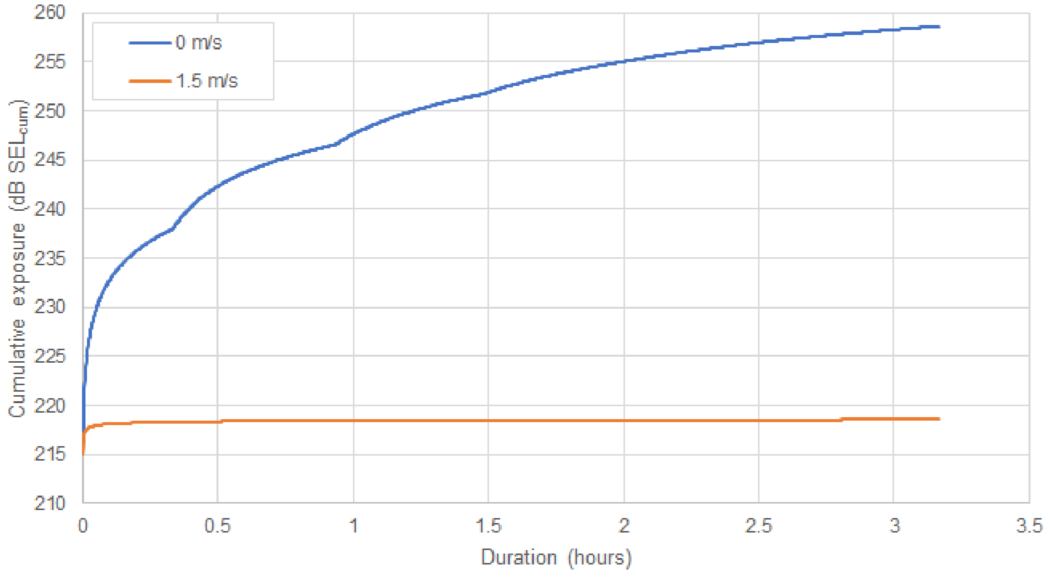

Figure 3-5 Cumulative received noise levels (SEL_{cum}) for receptors during monopile foundation parameters at the NE location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source.

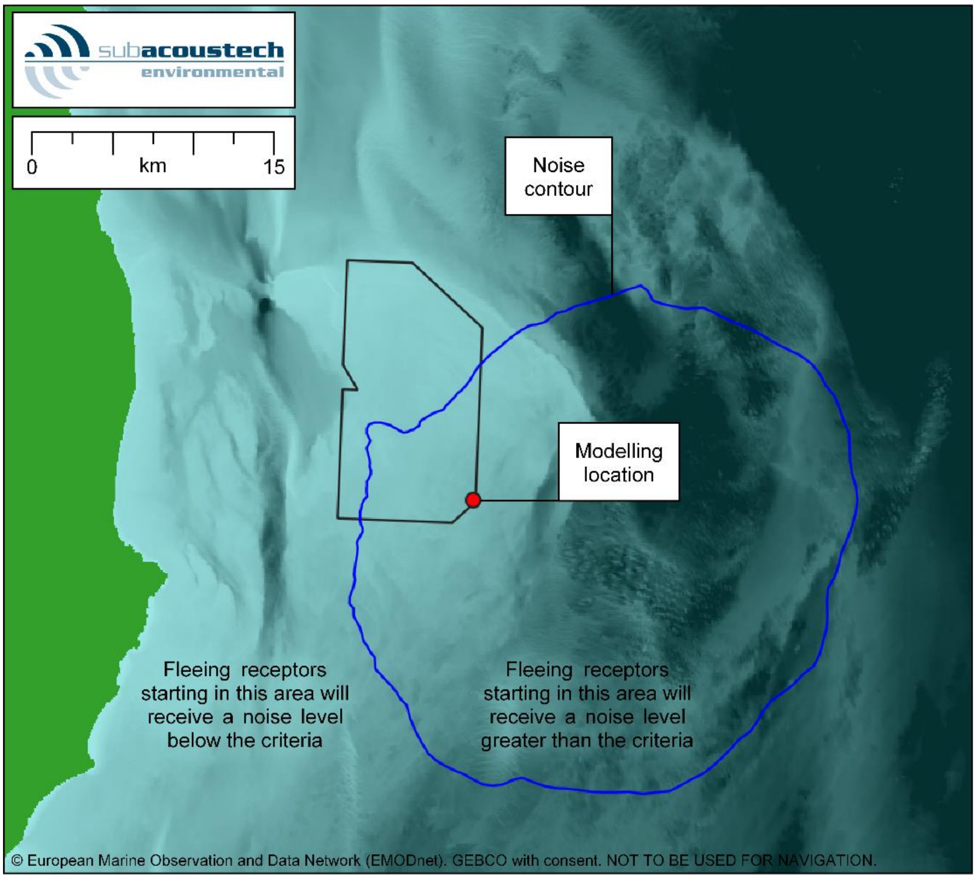

Figure 3-6 Example plot showing a fleeing animal SEL_{cum} criteria contour and the areas where the cumulative noise exposure will exceed the impact criteria.

3.3.1 *The effect of input parameters on SELs and fleeing receptors*

As discussed in section 3.2.2, parameters such as bathymetry, hammer blow energies, piling ramp up, strike rate and duration all have an effect on predicted noise levels. When considering SEL_{cum} and a fleeing animal model, some of these parameters can have a greater influence than others.

Parameters like energy through can have a clear effect on impact ranges, with higher energies resulting in higher source noise levels and therefore larger impact ranges. When considering cumulative noise levels, these higher levels are compounded sometimes thousands of times due to the number of pile strikes. With this in mind, the ramp up from low blow energies to higher ones requires careful consideration for fleeing animals, as the levels while the receptors are relatively close to the noise source will have a greater effect on the overall cumulative exposure level. Figure 3-7 summarises the energy through ramp up for scenarios 1 and 2 (scenario 3 uses the same ramp up as scenario 2, but includes two piles installed sequentially), showing how scenario 2 reaches the higher blow energies much earlier.

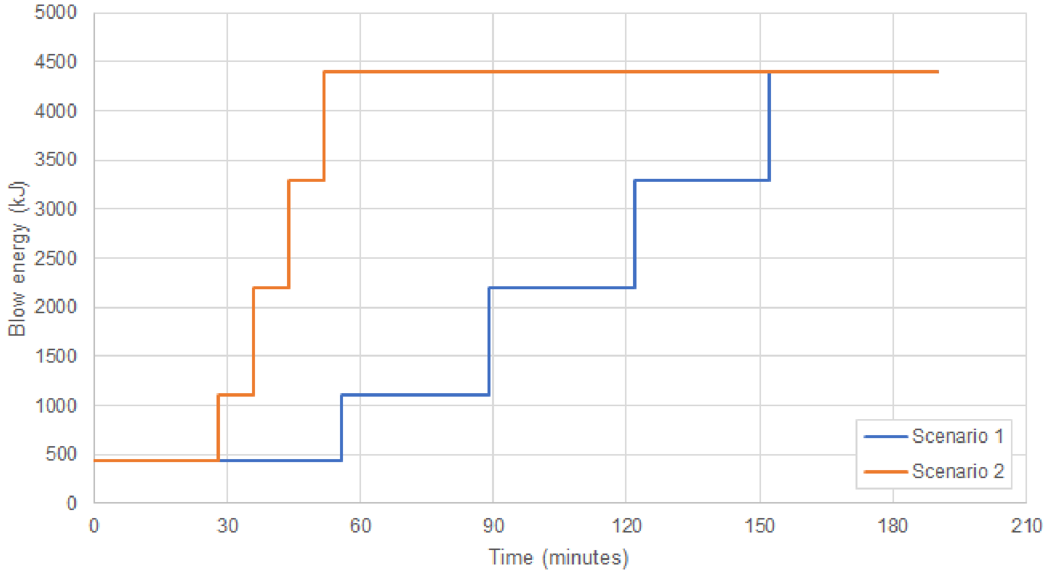

Figure 3-7 Graphical representation of the modelled ramp up scenarios.

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

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

The other main element that can cause big differences in calculated impact ranges is the bathymetry, as deep water results in a slower attenuation of noise (i.e., they remain higher for longer distances). However, it is not always feasible to limit piling activity in or near to deep water.

4 Modelling results

This section presents the modelled impact ranges for impact piling noise following the parameters in section 3.2, covering the Southall *et al*. (2019) marine mammal criteria (section 2.2.1.1) and the Popper *et al*. (2014) fish criteria (section 2.2.2.1). To aid navigation Table 4-1 contains a list of the impact range tables included in this section. The biggest modelled ranges are predicted at the SE location, due to the deep water to the south and east of this location, and for Scenario 3 due to its worst-case parameters and the sequential installation of three piles in a 24-hour period. Slightly smaller ranges are predicted for Scenario 2, and Scenario 1 predicts the smallest ranges of the three sets of parameters.

The modelling results for Southall *et al*. (2019) non-impulsive criteria and the older Southall *et al*. (2007) marine mammal criteria (section 2.2.1.3), included in line with the guidance from the Department of Arts, Heritage and the Gaeltacht, 2014, are presented in Appendices A and B respectively.

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

Table 4-1 Summary of the impact piling modelling results tables presented in this section.

Table (page)	Parameters (section)		Criteria	
Table 4-3 (p25)	Scenarios 1, 2 and 3 (4.2.1)	SE	Southall *et al*. (2019) -- Marine mammals	Unweighted SPL_{peak}
Table 4-4 (p25)		SW		
Table 4-5 (p26)		NE		
Table 4-6 (p26)		NW		
Table 4-7 (p26)	Scenario 1 (4.2.2)	SE		Weighted SEL_{cum} (Impulsive) (Fleeing animal)
Table 4-8 (p27)	Scenario 2 (4.2.3)	SW		
Table 4-9 (p27)		NE		
Table 4-10 (p27)	Scenario 3 (4.2.4)	NW		
Table 4-11 (p28)	Scenarios 1, 2 and 3 (4.2.5)	SE	NOAA (2005) – Marine mammals	Unweighted SPL_{RMS}
Table 4-12 (p28)		SW		
Table 4-13 (p28)		NE		
Table 4-14 (p28)		NW		
Table 4-15 (p28)	Scenarios 1, 2 and 3 (4.3.1)	SE	Popper *et al*. (2014) -- Fish	Unweighted SPL_{peak}
Table 4-16 (p29)		SW		
Table 4-17 (p29)		NE		
Table 4-18 (p29)		NW		
Table 4-19 (p29)	Scenario 1 (4.3.2)	SE		Unweighted SEL_{cum} (Pile driving) (Fleeing and Stationary animal)
Table 4-20 (p30)	Scenario 2 (4.3.3)	SW		
Table 4-21 (p30)		NE		
Table 4-22 (p31)	Scenario 3 (4.3.4)	NW		

4.1 Predicted noise level at 750 m from the noise source

In addition to the source levels presented in section 3.2.3, it is useful to look at the potential noise levels at a range of 750 m from the noise source, which is a common consideration for underwater noise studies at offshore wind farms, and has the added advantage of being comparable with other modelling or measurements. A summary of the modelled unweighted levels at a range of 750 m are given in Table

4-2, considering the transect with the greatest noise transmission at each location while piling using the maximum energy through.

Table 4-2 Summary of the maximum predicted unweighted SPL_{peak} and SEL_{ss} noise levels at a range of 750 m from the noise source when considering the maximum energy through.

Predicted level at 750 m range	**Location**	**Monopile foundation** 9.4 m / 4,400 kJ
Unweighted SPL_{peak}	SE location	200.7 dB re 1 µPa
	SW location	198.8 dB re 1 µPa
	NE location	198.0 dB re 1 µPa
	NW location	197.5 dB re 1 µPa
Unweighted SEL_{ss}	SE location	181.9 dB re 1 µPa²s
	SW location	180.1 dB re 1 µPa²s
	NE location	180.5 dB re 1 µPa²s
	NW location	178.9 dB re 1 µPa²s

4.2 Marine mammal criteria (Southall *et al*., 2019; NOAA, 2005)

Table 4-3 to Table 4-14 present the Codling impact piling modelling results in terms of the Southall *et al*. (2019) and NOAA (2005) criteria for marine mammals (section 2.2.1.1).

The largest marine mammal impact ranges are predicted at the SE location, due to the deep water to the south and east into the Irish Sea. Maximum PTS ranges are predicted for LF and VHF cetaceans out to 9.5 km and 4.7 km at the SE location (Scenario 1) respectively.

4.2.1 Southall et al. (2019) single strike (SPL_{peak}) criteria (all scenarios)

Table 4-3 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for modelling at the SE location.

Southall *et al*. (2019) Unweighted SPL_{peak}		**SE location**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.2 km²	620 m	600 m	610 m
	PCW (218 dB)	0.01 km²	50 m	50 m	50 m
TTS (Impulsive)	LF (213 dB)	0.04 km²	110 m	110 m	110 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	7.1 km²	1.5 km	1.5 km	1.5 km
	PCW (212 dB)	0.05 km²	130 m	130 m	130 m

Table 4-4 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for modelling at the SW location.

Southall *et al*. (2019) Unweighted SPL_{peak}		**SW location**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.65 km²	460 m	450 m	460 m
	PCW (218 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km²	90 m	90 m	90 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	3.7 km²	1.1 km	1.1 km	1.1 km
	PCW (212 dB)	0.03 km²	100 m	100 m	100 m

Table 4-5 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for modelling at the NE location.

Southall *et al*. (2019) Unweighted SPL_{peak}		NE location			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.55 km^2	420 m	420 m	420 m
	PCW (218 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km^2	90 m	80 m	90 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	3.0 km^2	1.0 km	970 m	990 m
	PCW (212 dB)	0.03 km^2	100 m	100 m	100 m

Table 4-6 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for modelling at the NW location.

Southall *et al*. (2019) Unweighted SPL_{peak}		NW location			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.43 km^2	390 m	360 m	370 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS (Impulsive)	LF (213 dB)	0.02 km^2	80 m	80 m	80 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	2.3 km^2	930 m	800 m	860 m
	PCW (212 dB)	0.02 km^2	90 m	90 m	90 m

4.2.2 *Southall et al. (2019) multiple pulse (SEL_{cum}) criteria (Scenario 1)*

Table 4-7 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the Scenario 1 modelling at the SE location assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		SE location, Scenario 1			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	82 km^2	9.5 km	450 m	3.8 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	26 km^2	4.7 km	1.2 km	2.6 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	6,200 km^2	69 km	10 km	39 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	3,300 km^2	48 km	11 km	29 km
	PCW (170 dB)	850 km^2	25 km	6.5 km	15 km

4.2.3 Southall et al. (2019) multiple pulse (SEL_{cum}) criteria (Scenario 2)

Table 4-8 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the Scenario 2 modelling at the SW location assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		**SW location, Scenario 2**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	8.5 km^2	3.0 km	300 m	1.4 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	11 km^2	2.5 km	1.2 km	1.8 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	3,100 km^2	52 km	6.0 km	27 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	1,400 km^2	32 km	7.9 km	19 km
	PCW (170 dB)	170 km^2	10 km	4.4 km	7.0 km

Table 4-9 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the Scenario 2 modelling at the NE location assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		**NE location, Scenario 2**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	26 km^2	5.8 km	150 m	2.0 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	12 km^2	3.2 km	700 m	1.7 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	4,600 km^2	66 km	8.5 km	34 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	2,200 km^2	42 km	8.8 km	24 km
	PCW (170 dB)	220 km^2	13 km	3.2 km	7.5 km

4.2.4 Southall et al. (2019) multiple pulse (SEL_{cum}) criteria (Scenario 3)

Table 4-10 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) impulsive criteria for the Scenario 3 modelling at the NW location assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		**NW location, Scenario 3**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Impulsive)	LF (183 dB)	1.1 km^2	2.0 km	100 m	430 m
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	3.4 km	2.2 km	280 m	870 m
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS (Impulsive)	LF (168 dB)	1,900 km^2	49 km	6.0 km	21 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	1,000 km^2	33 km	7.9 km	16 km
	PCW (170 dB)	72 km^2	9.2 km	1.9 km	4.3 km

4.2.5 NOAA (2005) single strike (SPL_{peak}) criteria (all scenarios)

Table 4-11 Summary of the unweighted SPL_{RMS} impact ranges for marine mammals using the NOAA (2005) impulsive criteria for modelling at the SE location.

NOAA (2005) Unweighted SPL_{RMS}		SE location			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B harassment	160 dB	2,300 km^2	27 km	15 km	16 km

Table 4-12 Summary of the unweighted SPL_{RMS} impact ranges for marine mammals using the NOAA (2005) impulsive criteria for modelling at the SW location.

NOAA (2005) Unweighted SPL_{RMS}		SW location			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B harassment	160 dB	880 km^2	22 km	11 km	16 km

Table 4-13 Summary of the unweighted SPL_{RMS} impact ranges for marine mammals using the NOAA (2005) impulsive criteria for modelling at the NE location.

NOAA (2005) Unweighted SPL_{RMS}		NE location			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B harassment	160 dB	1,400 km^2	31 km	11 km	20 km

Table 4-14 Summary of the unweighted SPL_{RMS} impact ranges for marine mammals using the NOAA (2005) impulsive criteria for modelling at the NW location.

NOAA (2005) Unweighted SPL_{RMS}		NW location			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Level B harassment	160 dB	580 km^2	19 km	9.5 km	13 km

4.3 Fish criteria (Popper *et al*., 2014)

Table 4-15 to Table 4-22 present the Codling impact piling modelling results in terms of the Popper *et al*. (2014) criteria for fish (section 2.2.2.1).

The largest impact ranges for fish are predicted at the SE location, due to the deep water to the south and east into the Irish Sea,. Maximum recoverable injury ranges (203 dB SEL_{cum} threshold) are predicted out to 3.8 km for this SE location (Scenario 1) when considering a stationary receptor, reducing to less than 100 m when a fleeing animal model is assumed.

4.3.1 Popper et al (2014) single strike (SPL_{peak}) criteria (all scenarios)

Table 4-15 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for modelling at the SE location.

Popper *et al*. (2014) Unweighted SPL_{peak}	SE location			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.04 km^2	110 m	110 m	110 m
207 dB	0.25 km^2	280 m	280 m	280 m

Table 4-16 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for modelling at the SW location.

Popper *et al*. (2014) Unweighted SPL_{peak}	SW location			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.02 km^2	90 m	90 m	90 m
207 dB	0.15 km^2	220 m	220 m	220 m

Table 4-17 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for modelling at the NE location.

Popper *et al*. (2014) Unweighted SPL_{peak}	NE location			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.02 km^2	90 m	80 m	90 m
207 dB	0.13 km^2	200 m	200 m	200 m

Table 4-18 Summary of the unweighted SPL_{peak} impact ranges for fish using the Popper et al. (2014) pile driving criteria for modelling at the NW location.

Popper *et al*. (2014) Unweighted SPL_{peak}	NW location			
	Area	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.02 km^2	80 m	80 m	80 m
207 dB	0.1 km^2	190 m	180 m	180 m

4.3.2 Popper et al (2014) multiple pulse (SEL_{cum}) criteria (Scenario 1)

Table 4-19 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the Scenario 1 modelling at the SE location assuming both a fleeing and stationary animal.

Popper *et al*. (2014) Unweighted SEL_{cum}		SE location, Scenario 1			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	740 km^2	24 km	5.7 km	14 km
Stationary	219 dB	0.4 km^2	380 m	350 m	360 m
	216 dB	1.0 km^2	580 m	550 m	560 m
	210 dB	5.8 km^2	1.4 km	1.3 km	1.4 km
	207 dB	14 km^2	2.2 km	2.0 km	2.1 km
	203 dB	40 km^2	3.8 km	3.4 km	3.6 km
	186 dB	1,800 km^2	34 km	14 km	24 km

4.3.3 Popper et al (2014) multiple pulse (SEL_{cum}) criteria (Scenario 2)

Table 4-20 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the Scenario 2 modelling at the SW location assuming both a fleeing and stationary animal.

Popper *et al*. (2014) Unweighted SEL_{cum}		**SW location, Scenario 2**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	220 km^2	12 km	4.9 km	8.1 km
Stationary	219 dB	0.3 km^2	330 m	300 m	310 m
	216 dB	0.7 km^2	480 m	450 m	460 m
	210 dB	3.6 km^2	1.1 km	1.0 km	1.1 km
	207 dB	8.0 km^2	1.7 km	1.6 km	1.6 km
	203 dB	23 km^2	2.9 km	2.5 km	2.7 km
	186 dB	800 km^2	20 km	11 km	16 km

Table 4-21 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the Scenario 2 modelling at the NE location assuming both a fleeing and stationary animal.

Popper *et al*. (2014) Unweighted SEL_{cum}		**NE location, Scenario 2**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	330 km^2	17 km	3.7 km	9.3 km
Stationary	219 dB	0.3 km^2	300 m	280 m	290 m
	216 dB	0.6 km^2	450 m	430 m	440 m
	210 dB	3.0 km^2	1.0 km	950 m	970 m
	207 dB	6.6 km^2	1.5 km	1.4 km	1.5 km
	203 dB	19 km^2	2.6 km	2.3 km	2.4 km
	186 dB	990 km^2	25 km	10 km	17 km

4.3.4 Popper et al (2014) multiple pulse (SEL_{cum}) criteria (Scenario 3)

Table 4-22 Summary of the unweighted SEL_{cum} impact ranges for fish using the Popper et al. (2014) pile driving criteria for the Scenario 3 modelling at the NW location assuming both a fleeing and stationary animal.

Popper *et al*. (2014) Unweighted SEL_{cum}		**NW location, Scenario 3**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Fleeing (1.5 ms^{-1})	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	186 dB	120 km^2	11 km	2.6 km	5.6 km
Stationary	219 dB	0.5 km^2	400 m	380 m	390 m
	216 dB	1.0 km^2	600 m	550 m	580 m
	210 dB	5.1 km^2	1.4 km	1.2 km	1.3 km
	207 dB	11 km^2	2.2 km	1.7 km	1.9 km
	203 dB	28 km^2	3.7 km	2.6 km	3.0 km
	186 dB	870 km^2	24 km	11 km	16 km

5 Other noise sources

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

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

Table 5-1 Summary of the possible noise making activities at Codling other than impact piling.

Activity	Description
Cable laying	Noise from the cable laying vessel and any other associated noise during the offshore cable installation.
Dredging	Dredging may be required on site for seabed preparation work for certain foundation options, as well as for the export cable, array cables and interconnector cable installation. Suction dredging has been assumed as a worst-case.
Rock placement	Potentially required on site for installation of offshore cables (cable crossings and cable protection) and scour protection around foundation structures.
Trenching	Plough trenching may be required during offshore cable installation.
Vessel noise	Jack-up barges for piling substructure and WTG installation. Other large and medium sized vessels to carry out other construction tasks and anchor handling. Other small vessels for crew transport and maintenance on site.
Operational WTG	Noise transmitted through the water from operational WTG. The project design envelope gives WTGs with power outputs of between 15 and 21 MW.
UXO clearance	There is a possibility that Unexploded Ordnance (UXO) may exist within the Codling boundary, which would need to be cleared before construction can begin.

Most of these activities are considered in section 5.1, with operational WTG noise and UXO clearance assessed in sections 5.2 and 5.3 respectively.

As with the previous section, where applicable, results for the Southall *et al*. (2019) non-impulsive criteria and the older Southall *et al*. (2007) marine mammal criteria (section 2.2.1.3), included in line with the guidance from the Department of Arts, Heritage and the Gaeltacht, 2014, are presented in Appendices A and B respectively.

The NPL Good Practice Guide 133 for underwater noise measurements (Robinson *et al*., 2014) indicates that under certain circumstances, a simple modelling approach may be considered acceptable. Such an approach has been used for these noise sources, which are variously either quiet compared to impact piling (e.g., cable laying and dredging), or where detailed modelling would imply unjustified accuracy (e.g., where data is limited such as with UXO detonation). The high-level overview of modelling that has been presented here is considered sufficient and there would be little benefit in using a more detailed model at this stage. The limitations of this approach are noted, including the lack of frequency or bathymetric dependence.

5.1 Noise making activities

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

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

Predicted source levels and propagation calculations for the construction activities are presented in Table 5-2 along with a summary of the number of datasets used in each case. As previously, all SEL_{cum} criteria use the same assumptions as presented in section 2.2, and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. It should be reiterated that this modelling approach does not take bathymetry or any other environmental conditions into account, and as such can be applied to any location at, or surrounding, the Codling site.

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

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

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

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

To account for the weightings required for modelling using the Southall *et al*. (2019) criteria (see section 2.2.1.1), reductions in source level have been applied to the various noise sources; Table 5-1 shows the representative noise measurements used for this, which have been adjusted for the source levels given in Table 5-2. Details of the reductions in sources levels for each of the weightings used for modelling are given in Table 5-3.

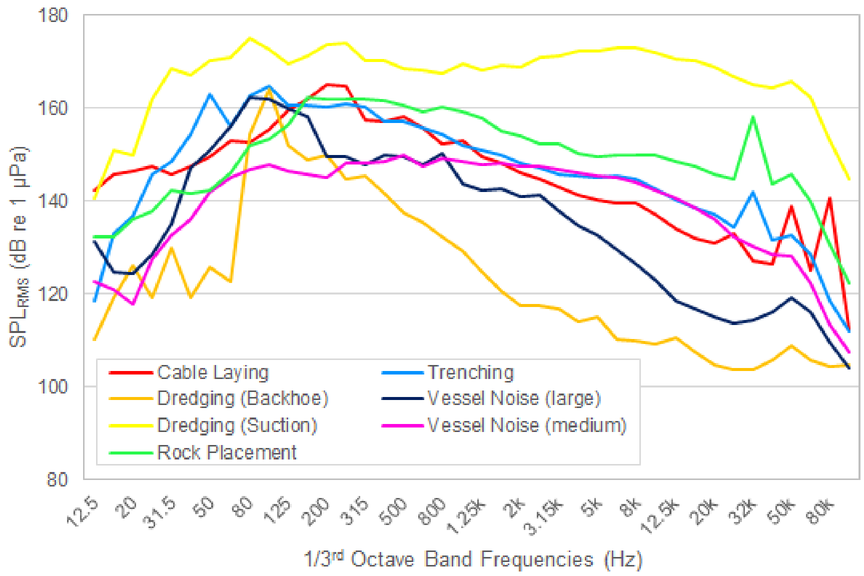

Figure 5-1 Summary of the 1/3rd octave frequency bands to which the Southall et al. (2019) weightings were applied in the simple modelling.

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

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

Table 5-4 to Table 5-6 summarise the predicted impact ranges for these noise sources. All the sources in this section are considered non-impulsive or continuous. As with the previous results, ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented.

Given the modelled impact ranges, almost any marine mammal would have to be closer than 100 m from the continuous noise source at the start of the activity to acquire the necessary exposure to induce PTS as per Southall *et al*. (2019). The exposure calculation assumes the same receptor swim speeds as the impact piling modelling in section 4. As explained in section 3.3, this would only mean that the receptor reaches the 'onset' stage at these ranges, which is the minimum exposure that could potentially lead to the start of an effect and may only be marginal. In most hearing groups, the noise levels are low enough that there is a minimal risk.

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

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

Table 5-4 Summary of the impact ranges for the different noise sources related to construction using the non-impulsive criteria from Southall et al. (2019) for marine mammals assuming a fleeing animal.

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

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

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

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

Table 5-6 Summary of the impact ranges for the different noise sources related to construction using the continuous noise criteria from Popper et al. (2014) for fish (swim bladder involved in hearing).

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

5.2 Operational WTG noise

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

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

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

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

For this study, two pile sizes have been considered, a smaller WTG with a rotor diameter of 250 m and a larger WTG with a rotor diameter of 276 m; the power outputs of these turbines have been assumed based on those from similar projects.

The maximum turbine sizes considered at Codling are much larger than those used for the estimation above, so caution must be used when considering the results presented in this section; no empirical data is available for large wind turbines close to the specification proposed here. Figure 5-2 presents a level against range plot for the two turbine sizes using the Tougaard *et al*. (2020) calculation, assuming 9.7 ms^{-1} wind speed, which is the speed expected at 130 m above sea level at Codling.

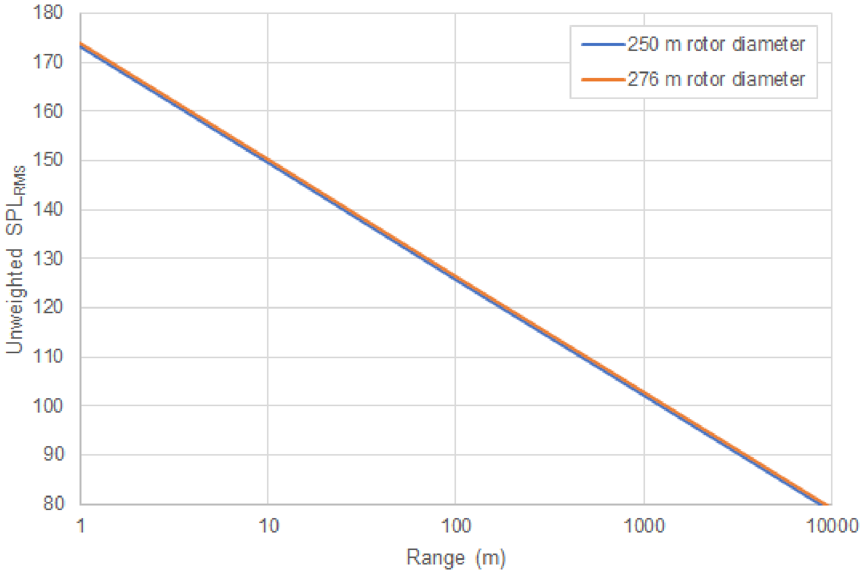

Figure 5-2 Predicted unweighted SPL_{RMS} from operational WTGs with rotor diameters of 250 m and 276 m based on the calculation from Tougaard et al. (2020).

Using this data, a summary of the predicted impact ranges has been produced, shown in Table 5-7 and Table 5-8. All SEL_{cum} criteria use the same assumptions as presented in section 2.2, and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. The operational WTG source is considered a non-impulsive or continuous source. For SEL_{cum} calculations, a stationary animal has been used and it is assumed that the operational WTG noise is present 24 hours a day.

Table 5-7 Summary of the operational WTG noise impact ranges using the non-impulsive noise criteria from Southall et al. (2019) for marine mammals assuming a stationary receptor.

Southall *et al.* (2019) Weighted SEL_{cum}		**Operational WTG (250 m rotor diameter)**	**Operational WTG (276 m rotor diameter)**
PTS (non-impulsive)	199 dB (LF SEL_{cum})	< 100 m	< 100 m
	198 dB (HF SEL_{cum})	< 100 m	< 100 m
	173 dB (VHF SEL_{cum})	< 100 m	< 100 m
	201 dB (PCW SEL_{cum})	< 100 m	< 100 m
TTS (non-impulsive)	179 dB (LF SEL_{cum})	< 100 m	< 100 m
	178 dB (HF SEL_{cum})	< 100 m	< 100 m
	153 dB (VHF SEL_{cum})	< 100 m	< 100 m
	181 dB (PCW SEL_{cum})	< 100 m	< 100 m

Table 5-8 Summary of the operational WTG noise impact ranges using the continuous noise criteria from Popper et al. (2014) for fish (swim bladder involved in hearing).

Popper *et al.* (2014) Unweighted SPL_{RMS}	**Operational WTG (250 m rotor diameter)**	**Operational WTG (276 m rotor diameter)**
Recoverable injury 170 dB (48 hours) Unweighted SPL_{RMS}	< 50 m	< 50 m
TTS 158 dB (12 hours) Unweighted SPL_{RMS}	< 50 m	< 50 m

These results show that, for operational WTGs, injury risk is minimal. Taking the results from this and the previous section (5.1), and comparing them to the impact piling results in section 4, it is clear that noise from impact piling results in much greater noise levels and impact ranges, and hence should be considered the activity which has the potential to have the greatest effect in this assessment.

Stöber & Thomsen (2021) produced a similar study of an operational wind turbine dataset and raises the potential for behavioural disturbance caused by larger wind turbines. While prospective turbine sizes are increasing, Stöber and Thomsen (2021) conclude that these might only have limited impacts related to behavioural response on marine mammals and fish, although there is considerable uncertainty in criteria available to assess these. However, based on the highly precautionary National Oceanic and Atmospheric Administration (NOAA) Level B behavioural threshold (120 dB SPL_{RMS}; see NOAA, 2005) that the study utilises, it is estimated that the WTGs may only reach this threshold at around 180 m away. As the distance between turbines is considerably greater than this at Codling any array effect from the turbines is not expected.

5.3 UXO clearance

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

5.3.1 Estimation of underwater noise levels

5.3.1.1 High-order clearance

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

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

The maximum equivalent charge weight for the potential UXO devices that could be present within the site boundary has been estimated as 525 kg. This has been modelled alongside a range of smaller devices, at charge weights of 25, 55, 120, and 240 kg. In each case, an additional donor weight of 0.5 kg has been included to initiate detonation.

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

5.3.1.2 Low-order clearance

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

Deflagration is a safer technique for UXO disposal as it is intended to avoid the high pressures associated with an explosion, which would lead to an increased risk of adverse effects to marine life. Where the UXO device cannot be moved, deflagration represents a significant improvement over high-order clearance in respect to environmental effects.

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

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

5.3.2 *Estimation of underwater noise propagation*

For this assessment, the attenuation of the noise from UXO detonation has been accounted for in calculations using geometric spreading and a sound absorption coefficient, primarily using the methodologies cited in Soloway and Dahl (2014), which establishes a trend based on measured data in open water. These are, for SPL_{peak}:

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

and for SEL_{ss}

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

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

These equations give a relatively simple calculation which can be used to give an indication of the range of effect. The equation does not consider variable bathymetry or seabed type, and thus calculation results will be the same regardless of where it is used. An attenuation correction can be added to the Soloway and Dahl (2014) equations for the absorption over long ranges (i.e., of the order of thousands of metres), based on measurements of high intensity noise propagation taken in the Irish Sea and North Sea. This uses standard frequency-based absorption coefficients for the seawater conditions expected in the region.

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

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

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

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

A summary of the unweighted UXO clearance source levels, calculated using the equations above, are given in Table 5-9.

Table 5-9 Summary of the unweighted SPL_{peak} and SEL_{ss} source levels used for UXO clearance modelling.

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

5.3.3 Impact ranges

Table 5-10 to Table 5-12 present the impact ranges for UXO detonation, considering various charge weights and impact criteria. It should be noted that Popper *et al*. (2014) gives specific impact criteria for explosions (Table 2-10). A UXO detonation source is defined as a single pulse, and as such the SEL_{cum} criteria from Southall *et al*. (2019) have been given as SEL_{ss} in the tables below. Thus, fleeing animal assumptions do not apply. As with the previous sections, ranges smaller than 50 m have not been presented.

Although the impact ranges in Table 5-10 to Table 5-12 are large, the duration the noise is present must also be considered. For the detonation of a UXO, each explosion is a single noise event, compared to the multiple pulse nature and longer durations of impact piling.

Table 5-10 Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, unweighted SPL_{peak} noise criteria from Southall et al. (2019) for marine mammals.

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

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

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

Table 5-12 Summary of the impact ranges for UXO detonation using the unweighted SPL_{peak} explosion noise criteria from Popper et al. (2014) for species of fish.

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

5.3.4 Summary

The maximum PTS range calculated for UXO is 12 km for the VHF cetacean category, when considering the unweighted SPL_{peak} criteria for the largest high-order clearance. For SEL_{ss} criteria, the largest PTS range is calculated for LF cetaceans with a predicted impact of 9.5 km using the impulsive noise criteria. As explained earlier, this assumes no degradation of the UXO and no smoothing of the pulse over that distance, which is very precautionary.

Although an assumption of non-pulse (Appendix A, section A.2) could under-estimate the potential impact (Martin *et al*., 2020) (the equivalent range based on LF cetacean non-pulse criteria is 570 m; Table A 5), it is likely that the long-range smoothing of the pulse peak would reduce its potential harm and the maximum 'impulsive' range for all species is very precautionary.

6 Summary and conclusions

Subacoustech Environmental have undertaken a study to assess the potential underwater noise and its effects during the construction and operation of the proposed Codling Wind Park offshore wind farm, located off the east coast of Ireland.

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

Four representative modelling locations were chosen to give spatial variation across the site as well as accounting for changes in water depth. Three monopile foundation modelling scenarios were also considered.

The loudest levels of noise and the greatest impact ranges were generally predicted at the SE modelling location in the deepest part of the Codling site.

The results were analysed in terms of relevant noise metrics and criteria to assess the effects of the impact piling on marine mammals (Southall *et al*., 2019; Southall *et al*., 2007) and fish (Popper *et al*., 2014), which have been used to aid biological assessments.

For marine mammals, maximum ranges were predicted for the LF and VHF cetacean groups with PTS ranges out to maximum ranges of 9.5 km and 4.7 km respectively. For fish, the largest recoverable injury ranges (203 dB SEL_{cum}) were predicted to be 3.8 km for a stationary receptor, reducing to less than 100 m for a fleeing receptor.

Noise sources other than piling were considered using a high-level, simple modelling approach, including cable laying, dredging, drilling, rock placement, vessel movements, and operational WTG noise. The predicted noise levels for the other construction noise sources and during WTG operation are well below those predicted for impact piling noise. The risk of any potentially injurious effects to fish or marine mammals from these sources are expected to be minimal as the noise emissions from these are close to, or below, the appropriate injury criteria even when very close to the source of the noise.

UXO clearance has also been considered at the site, and for the expected UXO clearance noise, there is a risk of PTS up to 12 km from the largest, 525 kg, UXO device considered, using the unweighted SPL_{peak} criteria for VHF cetaceans. However, this is likely to be highly precautionary as the impact range is based on a worst-case criterion and calculation methodology that does not account for any smoothing of the pulse over long ranges, which would reduce the pulse peak and other characteristics of the sound that cause injury.

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

References

1. Andersson M H, Andersson S, Ahlsén J, Andersson B L, Hammar J, Persson L K G, Pihl J, Sigray P, Wikström A. (2016). *A framework for regulating underwater noise during pile driving.* A technical Vindval report, ISBN 978-91-620-6775-5, Swedish Environmental Protection Agency, Stockholm, Sweden.
2. Arons A B (1954). *Underwater explosion shock wave parameters at large distances from the charge.* J. Acoust. Soc. Am. 26, 343-346.
3. Bailey H, Senior B, Simmons D, Rusin J, Picken G, Thompson P M (2010). *Assessing underwater noise levels during pile-driving at an offshore wind farm and its potential effects on marine mammals.* Marine Pollution Bulletin 60 (2010), pp 888-897.
4. Bailey H, Brookes K L, Thompson P M (2014). *Assessing impacts of offshore wind farms: lessons learned and recommendations for the future.* Aquatic Biosystems 2014, 10:8.
5. Bebb A H, Wright H C (1953). *Injury to animals from underwater explosions.* Medical Research Council, Royal Navy Physiological Report 53/732, Underwater Blast Report 31, January 1953.
6. Bebb A H, Wright H C (1954a). *Lethal conditions from underwater explosion blast.* RNP Report 51/654, RNP 3/51, National Archives Reference ADM 298/109, March 1954.
7. Bebb A H, Wright H C (1954b). *Protection from underwater explosion blast. III: Animal experiments and physical measurements.* RNP Report 57/792, RNPL 2/54, March 1954.
8. Bebb A H, Wright H C (1955). *Underwater explosion blast data from the Royal Navy Physiological Labs 1950/1955.* Medical Research Council, April 1955.
9. Blix A S, Folkow L P (1995). *Daily energy expenditure in free living minke whales.* Acta Physio. Scard., 153: 61-66.
10. Cheong S-H, Wang L., Lepper P, Robinson S (2020). *Characterization of Acoustic Fields Generated by UXO Removal, Phase 2*. NPL Report AC 19, National Physical Laboratory.
11. Cudahy A E, Parvin S (2001). *The effects of underwater blast on divers.* Report 1218, Naval Submarine Medical Research Laboratory: #63706N M0099.001-5901.
12. Dahl P H, de Jong C A, Popper A N (2015). *The underwater sound field from impact pile driving and its potential effects on marine life.* Acoustics Today, Spring 2015, Volume 11, Issue 2.
13. Department of Arts, Heritage and the Gaeltacht (2014). *Guidance to manage the risk to marine mammals from man-made sound sources in Irish waters.* Retrieved on 10/05/2021 from https://www.npws.ie/sites/default/files/general/Underwater%20sound%20guidance_Jan%202014.pdf.
14. Goertner J F (1978). *Dynamical model for explosion injury to fish.* Naval Surface Weapons Center, White Oak Lab, Silver Spring, MD. Report No. NSWC/WOL.TR-76-155.
15. Goertner J F, Wiley M L, Young G A, McDonald W W (1994). *Effects of underwater explosions on fish without swim bladders.* Naval Surface Warfare Center. Report No. NSWC/TR-76-155.
16. Halvorsen M B, Casper B C, Matthew D, Carlson T J, Popper A N (2012). *Effects of exposure to pile driving sounds on the lake sturgeon, Nila tilapia, and hogchoker.* Proc. Roy. Soc. B 279: 4705-4714.
17. Hastie G, Merchant N D, Götz T, Russell D J F, Thompson P, Janik V M (2019). *Effects of impulsive noise on marine mammals: Investigating range-dependent risk.* DOI: 10.1002/eap.1906.

18. Hastings M C and Popper A N (2005). *Effects of sound on fish.* Report to the California Department of Transport, under Contract No. 43A01392005, January 2005.
19. Hawkins A D, Roberts L, Cheesman S (2014). *Responses of free-living coastal pelagic fish to impulsive sounds.* J. Acoust. Soc. Am. 135: 3101-3116.
20. Heaney K D, Ainslie M A, Halvorsen M B, Seger K D, Müller, R A J, Nijhof M J J, Lippert T (2020). *A Parametric Analysis and Sensitivity Study of the Acoustic Propagation for Renewable Energy Sources*. Sterling (VA): U.S. Department of the Interior, Bureau of Ocean Energy Management. Prepared by CSA Ocean Sciences Inc. OCS Study BOEM 2020-011, 165 p.
21. Hirata K (1999). *Swimming speeds of some common fish.* National Maritime Research Institute (Japan). Data sourced from Iwai T, Hisada M (1998). *Fishes – Illustrated book of Gakken* (in Japanese). Accessed on 14th December 2022 at https://www.nmri.go.jp/archives/eng/khirata/fish/general/speed/speede.htm
22. Kastelein R A, van de Voorde S, Jennings N (2018). *Swimming speed of a harbor porpoise (Phocoena phocoena) during playbacks of offshore pile driving sounds.* Aquatic Mammals. 2018, 44(1), 92-99, DOI 10.1578/AM.44.1.2018.92.
23. Marine Technical Directorate (MTD) (1996). *Guidelines for the safe use of explosives underwater.* MTD Publication 96/101. ISBN 1 870553 23 3.
24. Martin S B, Lucke K, Barclay D R (2020). *Techniques for distinguishing between impulsive and non-impulsive sound in the context of regulating sound exposure for marine mammals.* The Journal of the Acoustical Society of America 147, 2159.
25. National Marine Fisheries Service (NMFS) (2018). *Revisions to: Technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing (version 2.0): Underwater thresholds for onset of permanent and temporary threshold shifts.* U.S. Dept. of Commer., NOAA. NOAA Technical Memorandum NMFS-OPR-59.
26. National Oceanic Oceanic and Atmospheric Administration (NOAA) (2005). Endangered fish and wildlife; Notice of intent to prepare an Environmental Impact Statement. Federal Register 70: 1871-1875.
27. Nedelec S L, Campbell J, Radford A N, Simpson S D, Merchant N D (2016). *Particle motion: The missing link in underwater acoustic ecology.* Methods Ecol. Evol. 7, 836 – 842.
28. Nedwell J R, Langworthy J, Howell D (2003). *Assessment of subsea noise and vibration from offshore wind turbines and its impact on marine wildlife. Initial measurements of underwater noise during construction of offshore wind farms, and comparisons with background noise.* Subacoustech Report No. 544R0423, published by COWRIE, May 2003.
29. Otani S, Naito T, Kato A, Kawamura A (2000). *Diving behaviour and swimming speed of a free-ranging harbour porpoise (Phocoena phocoena)*. Marine Mammal Science, Volume 16, Issue 4, pp 811-814, October 2000.
30. Popper A N, Hawkins A D, Fay R R, Mann D A, Bartol S, Carlson T J, Coombs S, Ellison W T, Gentry R L, Halvorsen M B, Løkkeborg S, Rogers P H, Southall B L, Zeddies D G, Tavolga W N (2014). *Sound exposure guidelines for Fishes and Sea Turtles.* Springer Briefs in Oceanography, DOI 10.1007/978-3-319-06659-2.
31. Popper A N, Hawkins A D (2018). *The importance of particle motion to fishes and invertebrates.* J. Acoust. Soc. Am. 143, 470 – 486.
32. Popper A N, Hawkins A D (2019). *An overview in fish bioacoustics and the impacts of anthropogenic sounds on fishes.* Journal of Fish Biology, 1-22. DOI: 10.111/jfp.13948.

33. Radford C A, Montgomery J C, Caiger P, Higgs D M (2012). *Pressure and particle motion detection thresholds in fish: a re-examination of salient auditory cues in teleosts.* Journal of Experimental Biology, 215, 3429 – 3435.

34. Rawlins J S P (1987). *Problems in predicting safe ranges from underwater explosions.* Journal of Naval Science, Volume 13, No. 4, pp 235-246.

35. Robinson S P, Lepper P A, Hazelwood R A (2014). *Good practice guide for underwater noise measurement.* National Measurement Office, Marine Scotland, The Crown Estate. NPL Good Practice Guide No. 133, ISSNL 1368-6550.

36. Soloway A G, Dahl P H (2014). *Peak sound pressure and sound exposure level from underwater explosions in shallow water.* The Journal of the Acoustical Society of America, 136(3), EL219 – EL223. http://dx.doi.org/10.1121/1.4892668.

37. Southall B L, Bowles A E, Ellison W T, Finneran J J, Gentry R L, Green Jr. C R, Kastak D, Ketten D R, Miller J H, Nachtigall P E, Richardson W J, Thomas J A, Tyack P L (2007). *Marine mammal noise exposure criteria: Initial scientific recommendations.* Aquatic Mammals, 33 (4), pp 411-509.

38. Southall B L, Finneran J J, Reichmuth C, Nachtigall P E, Ketten D R, Bowles A E, Ellison W T, Nowacek D P, Tyack P L (2019). *Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects.* Aquatic Mammals 2019, 45 (20, 125-232) DOI 10.1578/AM.45.2.2019.125.

39. Southall B L (2021). *Evolutions in Marine Mammal Noise Exposure Criteria.* Acoustics Today 17(2) https://doi.org/10.1121/AT.2021.17.2.52.

40. Stephenson J R, Gingerich A J, Brown R S, Pflugrath B D, Deng Z, Carlson T J, Langeslay M J, Ahmann M L, Johnson R L, Seaburg A G (2010). *Assessing barotrauma in neutrally and negatively buoyant juvenile salmonids exposed to simulated hydro-turbine passage using a mobile aquatic barotrauma laboratory.* Fisheries Research Volume 106, Issue 3, pp 271-278, December 2010.

41. Stöber U, Thomsen F (2021). *How could operational underwater sound from future offshore wind turbines impact marine life.* The Journal of the Acoustical Society of America, 149, 1791-1795. https://doi.org/10.1121/10.0003760

42. Thompson P M, Hastie G D, Nedwell J, Barham R, Brookes K L, Cordes L S, Bailey H, McLean N (2013). *Framework for assessing impacts of pile-driving noise from offshore wind farm construction on a harbour seal population*. Environmental Impact Assessment Review 43 (2013) 73-85.

43. Tougaard J, Hermannsen L, Madsen P T (2020), *How loud is the underwater noise from operating offshore wind turbines?* J. Acoust. Soc. Am. 148 (5). doi.org/10.1121/10.0002453.

44. von Benda-Beckmann A M, Aarts G, Sertlek H Ö, Lucke K, Verboom W C, Kastelein R A, Ketten D R, van Bemmelen R, Lamm F-P A, Kirkwood R J, Ainslie M A (2015). *Assessing the impact of underwater clearance of unexploded ordnance on harbour porpoises (Phocoena phocoena) in the southern North Sea.* Aquatic Mammals 2015, 41(4), pp 503-523, DOI 10.1578/AM.41.4.2015.503.

Appendix A Southall *et al*. (2019) non-impulsive results

Further to the Southall *et al* (2019) impulsive criteria results presented in Sections 4.2 and 5 of the main report, the modelling results for the non-impulsive criteria are presented here, as discussed in section 2.2.1.1. The predicted non-impulsive ranges fall well below the impulsive criteria presented in the main report.

A.1 Impact piling

SEL_{cum} criteria (Scenario 1)

Table A 1 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the Scenario 1 modelling at the SE location assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		**SE location, Scenario 1**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	580 km²	23 km	2.3 km	11 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	80 km²	7.9 km	2.3 km	4.6 km
	PCW (181 dB)	0.8 km²	980 m	100 m	400 m

SEL_{cum} criteria (Scenario 2)

Table A 2 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the Scenario 2 modelling at the SW location assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		**SW location, Scenario 2**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	130 km²	11 km	2.1 km	5.6 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	33 km²	4.2 km	2.1 km	3.2 km
	PCW (181 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m

Table A 3 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the Scenario 2 modelling at the NE location assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		**NE location, Scenario 2**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	270 km²	17 km	1.1 km	7.4 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	39 km²	5.7 km	1.5 km	3.2 km
	PCW (181 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m

SEL_{cum} criteria (Scenario 3)

Table A 4 Summary of the weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2019) non-impulsive criteria for the Scenario 3 modelling at the NW location assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		**NW location, Scenario 3**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS (Non-impulsive)	LF (179 dB)	43 km²	8.0 km	530 m	2.9 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	13 km²	4.0 km	730 m	1.8 km
	PCW (181 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m

A.2 UXO clearance

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

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

Appendix B Southall *et al*. (2007) results

In line with the guidance from the Department of Arts, Heritage and the Gaeltacht (2014), the older Southall *et al*. (2007) marine mammal criteria have been modelled at Codling, using the parameters detailed in the previous sections.

B.1 Impact piling

Single strike criteria (all scenarios)

Table B 1 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2007) criteria at the SE location.

Southall *et al*. (2007) Unweighted SPL_{peak}		SE location			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Injury	M_{lf}, M_{mf}, M_{hf} (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	M_{pw} (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
Behaviour	M_{lf}, M_{mf}, M_{hf} (224 dB)	0.01 km²	50 m	50 m	50 m
	M_{pw} (212 dB)	0.05 km²	130 m	130 m	130 m

Table B 2 Summary of the M-weighted SEL_{ss} impact ranges for marine mammals using the Southall et al. (2007) single pulse criteria at the SE location.

Southall *et al*. (2007) M-weighted SEL_{ss}		SE location			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Injury (single pulse)	M_{lf} (198 dB)	0.01 km²	60 m	60 m	60 m
	M_{mf} (198 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	M_{hf} (198 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	M_{pw} (186 dB)	0.16 km²	230 m	220 m	230 m
Behaviour (single pulse)	M_{lf} (183 dB)	1.2 km²	630 m	620 m	620 m
	M_{mf} (183 dB)	0.15 km²	220 m	220 m	220 m
	M_{hf} (183 dB)	0.09 km²	170 m	170 m	170 m
	M_{pw} (171 dB)	15 km²	2.2 km	2.1 km	2.2 km

Table B 3 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2007) criteria at the SW location.

Southall *et al*. (2007) Unweighted SPL_{peak}		SW location			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Injury	M_{lf}, M_{mf}, M_{hf} (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	M_{pw} (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
Behaviour	M_{lf}, M_{mf}, M_{hf} (224 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
	M_{pw} (212 dB)	0.03 km²	100 m	100 m	100 m

Table B 4 Summary of the M-weighted SEL_{ss} impact ranges for marine mammals using the Southall et al. (2007) single pulse criteria at the SW location.

Southall *et al*. (2007) M-weighted SEL_{ss}		**SW location**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Injury (single pulse)	M_{lf} (198 dB)	0.01 km^2	50 m	50 m	50 m
	M_{mf} (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	M_{hf} (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	M_{pw} (186 dB)	0.1 km^2	180 m	180 m	180 m
Behaviour (single pulse)	M_{lf} (183 dB)	0.7 km^2	480 m	470 m	470 m
	M_{mf} (183 dB)	0.09 km^2	170 m	170 m	170 m
	M_{hf} (183 dB)	0.06 km^2	140 m	130 m	140 m
	M_{pw} (171 dB)	7.8 km^2	1.6 km	1.5 km	1.6 km

Table B 5 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2007) criteria at the NE location.

Southall *et al*. (2007) Unweighted SPL_{peak}		**NE location**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Injury	M_{lf}, M_{mf}, M_{hf} (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	M_{pw} (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
Behaviour	M_{lf}, M_{mf}, M_{hf} (224 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
	M_{pw} (212 dB)	0.03 km^2	100 m	100 m	100 m

Table B 6 Summary of the M-weighted SEL_{ss} impact ranges for marine mammals using the Southall et al. (2007) single pulse criteria at the NE location.

Southall *et al*. (2007) M-weighted SEL_{ss}		**NE location**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Injury (single pulse)	M_{lf} (198 dB)	0.01 km^2	60 m	60 m	60 m
	M_{mf} (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	M_{hf} (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	M_{pw} (186 dB)	0.13 km^2	200 m	200 m	200 m
Behaviour (single pulse)	M_{lf} (183 dB)	0.85 km^2	530 m	520 m	520 m
	M_{mf} (183 dB)	0.12 km^2	190 m	190 m	190 m
	M_{hf} (183 dB)	0.07 km^2	150 m	150 m	150 m
	M_{pw} (171 dB)	8.7 km^2	1.7 km	1.6 km	1.7 km

Table B 7 Summary of the unweighted SPL_{peak} impact ranges for marine mammals using the Southall et al. (2007) criteria at the NW location.

Southall *et al*. (2007) Unweighted SPL_{peak}		**NW location**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Injury	M_{lf}, M_{mf}, M_{hf} (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	M_{pw} (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
Behaviour	M_{lf}, M_{mf}, M_{hf} (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	M_{pw} (212 dB)	0.02 km^2	90 m	90 m	90 m

Table B 8 Summary of the M-weighted SEL_{ss} impact ranges for marine mammals using the Southall et al. (2007) single pulse criteria at the NW location.

Southall *et al*. (2007) M-weighted SEL_{ss}		**NW location**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Injury (single pulse)	M_{lf} (198 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
	M_{mf} (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	M_{hf} (198 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	M_{pw} (186 dB)	0.07 km^2	160 m	150 m	150 m
Behaviour (single pulse)	M_{lf} (183 dB)	0.48 km^2	410 m	380 m	390 m
	M_{mf} (183 dB)	0.07 km^2	150 m	150 m	150 m
	M_{hf} (183 dB)	0.04 km^2	120 m	120 m	120 m
	M_{pw} (171 dB)	4.9 km^2	1.4 km	1.1 km	1.2 km

<u>SEL_{cum} criteria (Scenario 1)</u>

Table B 9 Summary of the M-weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2007) multiple pulse and nonpulsed criteria for the Scenario 1 modelling at the SE location assuming a fleeing animal.

Southall *et al*. (2007) M-weighted SEL_{ss}		**SE location, Scenario 1**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Injury (multiple pulse)	M_{lf} (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{mf} (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{hf} (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{pw} (186 dB)	210 km^2	13 km	3.3 km	7.4 km
Injury (nonpulse)	M_{lf} (215 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{mf} (215 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{hf} (215 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{pw} (203 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m

<u>SEL_{cum} criteria (Scenario 2)</u>

Table B 10 Summary of the M-weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2007) multiple pulse and nonpulsed criteria for the Scenario 2 modelling at the SW location assuming a fleeing animal.

Southall *et al*. (2007) M-weighted SEL_{ss}		**SW location, Scenario 2**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Injury (multiple pulse)	M_{lf} (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{mf} (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{hf} (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{pw} (186 dB)	60 km^2	6.0 km	2.6 km	4.3 km
Injury (nonpulse)	M_{lf} (215 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{mf} (215 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{hf} (215 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{pw} (203 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m

Table B 11 Summary of the M-weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2007) multiple pulse and nonpulsed criteria for the Scenario 2 modelling at the NE location assuming a fleeing animal.

Southall *et al*. (2007) M-weighted SEL_{ss}		**NE location, Scenario 2**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Injury (multiple pulse)	M_{lf} (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{mf} (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{hf} (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{pw} (186 dB)	79 km^2	8.3 km	1.8 km	4.5 km
Injury (nonpulse)	M_{lf} (215 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{mf} (215 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{hf} (215 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{pw} (203 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m

SEL_{cum} criteria (Scenario 3)

Table B 12 Summary of the M-weighted SEL_{cum} impact ranges for marine mammals using the Southall et al. (2007) multiple pulse and nonpulsed criteria for the Scenario 3 modelling at the NW location assuming a fleeing animal.

Southall *et al*. (2007) M-weighted SEL_{ss}		**NW location, Scenario 3**			
		Area	**Maximum range**	**Minimum range**	**Mean range**
Injury (multiple pulse)	M_{lf} (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{mf} (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{hf} (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{pw} (186 dB)	24 km^2	5.6 km	830 m	2.4 km
Injury (nonpulse)	M_{lf} (215 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{mf} (215 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{hf} (215 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	M_{pw} (203 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m

B.2 Other noise sources

Table B 13 Summary of the injury ranges for the different noise sources related to construction using the nonpulse unweighted SPL_{peak} criteria from Southall et al. (2007) for marine mammals assuming both fleeing and stationary animal models.

Southall *et al.* (2007) Unweighted SPL_{peak}	**Injury** (nonpulse)			
	Fleeing animal			
	M_{lf}, M_{mf}, M_{hf} 230 dB		**M_{pw}** 218 dB	
Cable laying	< 50 m	< 50 m	< 50 m	< 50 m
Dredging (Backhoe)	< 50 m	< 50 m	< 50 m	< 50 m
Dredging (Suction)	< 50 m	< 50 m	< 50 m	< 50 m
Rock placement	< 50 m	< 50 m	< 50 m	< 50 m
Trenching	< 50 m	< 50 m	< 50 m	< 50 m
Vessel noise (large)	< 50 m	< 50 m	< 50 m	< 50 m
Vessel noise (medium)	< 50 m	< 50 m	< 50 m	< 50 m

Table B 14 Summary of the injury ranges for the different noise sources related to construction using the nonpulse M-weighted SEL_{cum} criteria from Southall et al. (2007) for marine mammals assuming both fleeing and stationary animal models.

Southall *et al.* (2007) M-weighted SEL_{cum}	**Injury** (nonpulse)							
	Fleeing animal				**Stationary animal**			
	M_{lf} 215 dB	**M_{mf}** 215 dB	**M_{hf}** 215 dB	**M_{pw}** 203 dB	**M_{lf}** 215 dB	**M_{mf}** 215 dB	**M_{hf}** 215 dB	**M_{pw}** 203 dB
Cable laying	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Dredging (Backhoe)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Dredging (Suction)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Rock placement	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Trenching	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Vessel noise (large)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
Vessel noise (medium)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m

B.3 Operational WTG noise

Table B 15 Summary of the operational WTG noise injury ranges using the nonpulse unweighted SPL_{peak} noise criteria from Southall et al. (2007) for marine mammals assuming a stationary receptor.

Southall *et al*. (2007) Unweighted SPL_{peak}		**Operational WTG (250 m rotor diameter)**	**Operational WTG (276 m rotor diameter)**
Injury (nonpulse)	230 dB (M_{lf}, M_{mf}, M_{hf})	< 50 m	< 50 m
	218 dB (M_{mf})	< 50 m	< 50 m

Table B 16 Summary of the operational WTG noise injury ranges using the nonpulse M-weighted SEL_{cum} noise criteria from Southall et al. (2007) for marine mammals assuming a stationary receptor.

Southall *et al*. (2007) M-weighted SEL_{cum}		**Operational WTG (250 m rotor diameter)**	**Operational WTG (276 m rotor diameter)**
Injury (nonpulse)	215 dB (M_{lf} SEL_{cum})	< 100 m	< 100 m
	215 dB (M_{mf} SEL_{cum})	< 100 m	< 100 m
	215 dB (M_{hf} SEL_{cum})	< 100 m	< 100 m
	203 dB (M_{pw} SEL_{cum})	< 100 m	< 100 m

B.4 UXO clearance

Table B 17 Summary of the injury and behavioural response ranges for UXO detonation using the single pulse, unweighted SPL_{peak} noise criteria from Southall et al. (2007) for marine mammals.

Southall *et al*. (2007) Unweighted SPL_{peak}	**Injury** (single pulse)		**Behaviour** (single pulse)	
	M_{lf}, M_{mf}, M_{hf} 230 dB	**M_{pw}** 218 dB	**M_{lf}, M_{mf}, M_{hf}** 224 dB	**M_{pw}** 212 dB
Low order (0.25 kg)	70 m	240 m	130 m	450 m
25 kg + donor	260 m	910 m	490 m	1.6 km
55 kg + donor	340 m	1.1 km	640 m	2.1 km
120 kg + donor	450 m	1.5 km	830 m	2.8 km
240 kg + donor	560 m	1.9 km	1.0 km	3.5 km
525 kg + donor	730 m	2.5 km	1.3 km	4.6 km

Table B 18 Summary of the injury and behavioural response ranges for UXO detonation using the single pulse, M-weighted SEL_{ss} noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al*. (2007) M-weighted SEL_{ss}	**Injury** (single pulse)				**Behaviour** (single pulse)			
	M_{lf} 198 dB	**M_{mf}** 198 dB	**M_{hf}** 198 dB	**M_{pw}** 186 dB	**M_{lf}** 183 dB	**M_{mf}** 183 dB	**M_{hf}** 183 dB	**M_{pw}** 171 dB
Low order (0.25 kg)	< 50 m	< 50 m	< 50 m	210 m	400 m	300 m	270 m	2.9 km
25 kg + donor	190 m	140 m	130 m	1.4 km	2.7 km	2.0 km	1.8 km	20 km
55 kg + donor	280 m	210 m	190 m	2.1 km	4.0 km	3.0 km	2.7 km	29 km
120 kg + donor	420 m	310 m	280 m	3.1 km	5.9 km	4.3 km	3.9 km	42 km
240 kg + donor	590 m	430 m	390 m	4.3 km	8.3 km	6.1 km	5.5 km	57 km
525 kg + donor	860 m	640 m	570 m	6.3 km	12 km	8.9 km	8.0 km	82 km

Table B 19 Summary of the injury and behavioural response ranges for UXO detonation using the nonpulse, M-weighted SEL_{ss} noise criteria from Southall et al. (2019) for marine mammals.

Southall *et al*. (2007) M-weighted SEL_{ss}	**Injury** (nonpulse)			
	M_{lf} 215 dB	**M_{mf}** 215 dB	**M_{hf}** 215 dB	**M_{pw}** 203 dB
Low order (0.25 kg)	< 50 m	< 50 m	< 50 m	< 50 m
25 kg + donor	< 50 m	< 50 m	< 50 m	70 m
55 kg + donor	< 50 m	< 50 m	< 50 m	100 m
120 kg + donor	< 50 m	< 50 m	< 50 m	150 m
240 kg + donor	< 50 m	< 50 m	< 50 m	210 m
525 kg + donor	< 50 m	< 50 m	< 50 m	310 m

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