Morecambe Offshore Windfarm: Generation Assets

Environmental Statement

Volume 5

Appendix 11.1 Underwater Noise Assessment

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Morecambe Offshore Windfarm: Generation Assets - Underwater noise assessment

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Glossary

Term	Definition
Decibel (dB)	A customary scale commonly used (in various ways) for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be 10 $\log_{10}$(actual/reference) where (actual/reference) is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is 20 $\log_{10}$(actual pressure/reference pressure). The standard reference for underwater sound is 1 micro pascal (µPa). The dB symbol is followed by a second symbol identifying the specific reference value (e.g., re 1 µPa).
Peak pressure	The highest pressure above or below ambient that is associated with a sound wave.
Peak-to-peak pressure	The sum of the highest positive and negative pressures that are associated with a sound wave.
Permanent Threshold Shift (PTS)	A permanent total or partial loss of hearing caused by acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the ear, 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.

Term	Definition
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.

1 Introduction

Morecambe Offshore Windfarm (OWF) Generation Assets (the Project) is a proposed offshore windfarm located in the east Irish Sea. As part of the Environmental Impact Assessment (EIA) process for the Project, Subacoustech Environmental Ltd. have undertaken detailed modelling and analysis in relation to the effect of underwater noise on marine mammals and fish at the site.

The Project windfarm site covers an area of approximately 87 km^2 and is situated, at its closest point, 30 km from the Lancashire coast. The Project has a proposed nominal capacity of 480 MW, potentially using up to 35 Wind Turbine Generators (WTGs) and up to two Offshore Substations (OSPs). All Generation Assets will be situated within the Project windfarm site, with the location of the windfarm site shown in Figure 1-1.

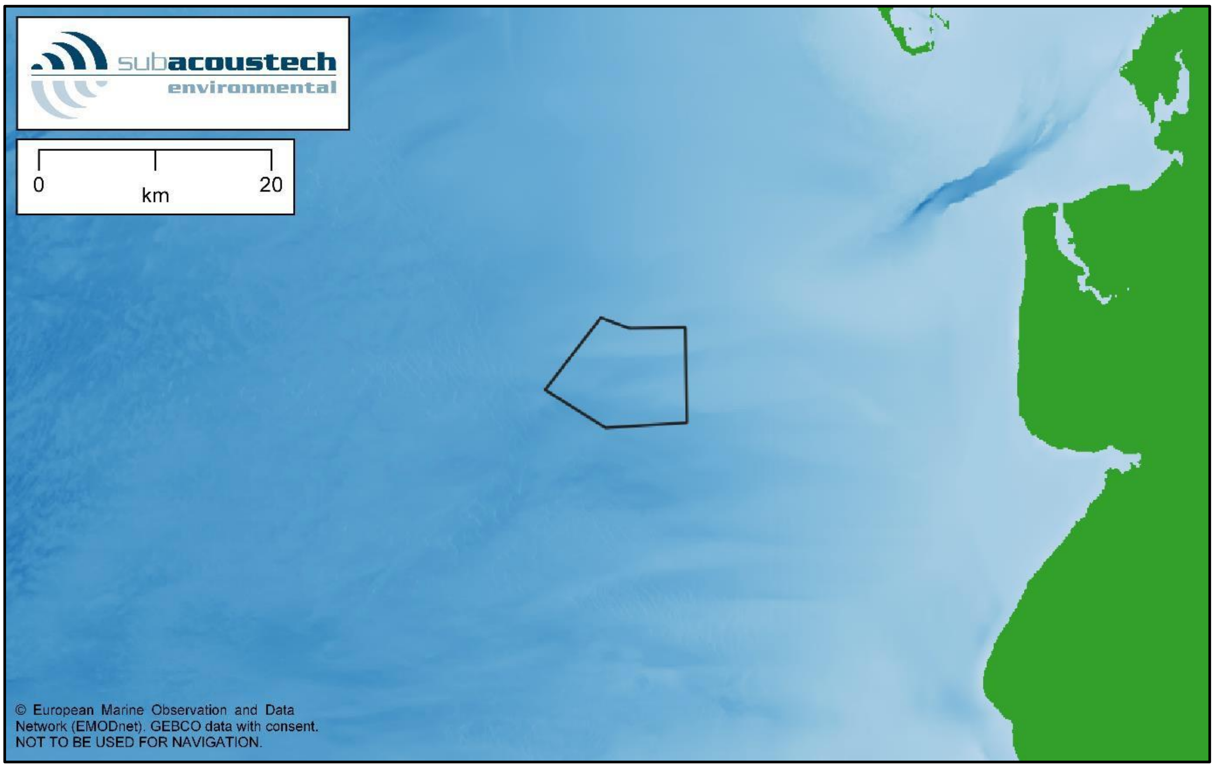

Figure 1-1 Overview map showing the Morecambe OWF windfarm site boundary and bathymetry

This report presents a detailed assessment of the potential underwater noise during the construction and operation of the Project (i.e. the Generation Assets of the Morecambe OWF), and includes:

- 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 other noise sources expected around the construction and operation of the Project, including cable laying, rock placement, dredging, trenching, vibro-piling, vessel activity, operational WTG noise, and Unexploded Ordnance (UXO) clearance (Section 5); and
- Summary and conclusions (Section 6).

Further modelling results are presented in Appendix A and Appendix B.

2 Background to underwater noise metrics

2.1 Underwater noise

Sound travels much faster in water (approximately 1,500 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. As an example, background noise levels in the sea of 130 dB re 1 µPa for UK coastal waters are not uncommon (Nedwell *et al*. 2003; Nedwell *et al.* 2007).

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 level having an equal increase in perceived 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, for instance an increase of 6 dB can be interpreted as "twice as much as…" (although this is a simplistic description). 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.

A refinement is that the scale, when used with sound pressure, is applied to the pressure squared rather than just the pressure. If this were not the case, when the acoustic power level of a source rose by 10 dB the sound pressure would rise by 20 dB. 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 level (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 selecting 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 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}.

Unless otherwise defined, all SEL noise levels in this report are referenced to 1 μPa^2s.

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 Morecambe OWF site.

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

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

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

Additionally, a 135 dB (single strike SEL) threshold has also been included for a short-term behavioural reaction to herring (using sprat as a proxy) based on measurements from Hawkins *et al*. (2014). Although, it should be noted that Hawkins *et al.* (2014) cautioned against using it as an explicit criterion due to limited evidence.

2.2.1 Marine mammals

The Southall *et al*. (2019) paper was effectively an update of the previous Southall *et al.* (2007) paper and provided identical thresholds to those from the National Marine Fisheries Service (NMFS) (2018) guidance for marine mammals.

The Southall *et al*. (2019) guidance grouped marine mammals into groups of similar species and applied filters to the unweighted noise to approximate the hearing sensitivities of the receptor in question. The hearing groups given by Southall *et al*. (2019) are summarised in Table 2-1 and Figure 2-1. Further groups for sirenians and other marine carnivores in water were given, but these have not been included in 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)

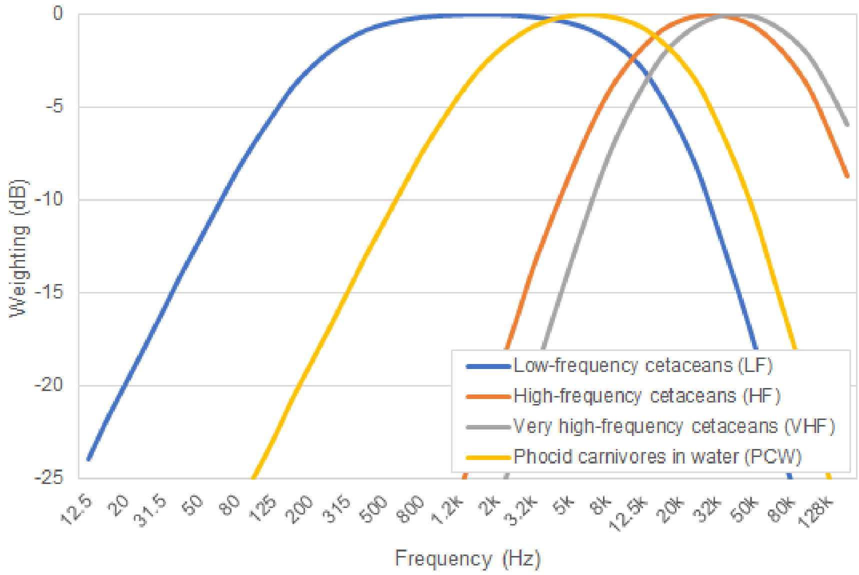

Figure 2-1 Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al., 2019)

Southall *et al*. (2019) also gave individual criteria based on whether the noise source was considered impulsive or non-impulsive. Southall *et al*. (2019) categorised 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 were considered impulsive noise sources and sonars, vibro-piling, drilling and other low-level continuous noises were considered non-impulsive. A non-impulsive noise does not necessarily have to have a long duration.

Southall *et al*. (2019) presented 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}) have only been used for impulsive noise: the criteria set giving the greatest calculated range was 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 discussed this. Active research was 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 was 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) discussed this further and suggested 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) casted doubt on these findings, showing that noise in this category should be considered impulsive as long as it were above effective quiet, or a noise sufficiently low enough that it did 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 was recommended for all but the clearly non-impulsive sources (such as drilling), it should be recognised that where calculated ranges were beyond 3.5 km, they would be expected to become increasingly less impulsive and harmful, and the impact range was therefore likely to be somewhere between the modelled impulsive and non-impulsive impact range. Where the impulsive impact range was significantly greater than 3.5 km, the non-impulsive range should be considered.

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

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

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

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

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

Where SEL_{cum} exposure thresholds were 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. For other receptors, a constant rate of 1.5 ms^{-1} has been assumed for flee speed, which represents a cruising speed for a harbour porpoise (Otani *et al*., 2000); part of the VHF cetacean group. A speed of 1.5 ms^{-1} has also been used for HF cetacean and PCW pinniped groups as a proxy. These were 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 to the noise source.

It is worth noting that, comparing Southall *et al.* (2019) to NMFS (2018), the two guidance papers applied different names to otherwise identical marine mammal groups and weightings, which were otherwise numerically identical. For example, what Southall *et al*. (2019) called high-frequency cetaceans (HF), NMFS (2018) called mid-frequency cetaceans (MF), and what Southall *et al*. (2019) called very high-frequency cetaceans (VHF), NMFS (2018) referred 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 covered different species depending on which study is being used.

2.2.2 Fish

The large number of, and variation in, fish species has led to a greater challenge in production of a generic noise criterion, or range of criteria, for the assessment of noise impacts. Whereas previous studies applied broad criteria based on limited studies of fish that were not present in UK waters (e.g., McCauley *et al*., 2000) or measurement data not intended to be used as criteria, the publication of Popper *et al*. (2014) provided an authoritative summary of the latest research and guidelines for fish exposure to sound and used categories for fish that were representative of the species present in UK waters.

The Popper *et al*. (2014) study grouped species of fish by whether they possess a swim bladder, and whether it is involved in its hearing; a group for fish eggs and larvae was also included. The guidance also gave specific criteria (as both unweighted SPL_{peak} and unweighted SEL_{cum} values) for a variety of noise sources.

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

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

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

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

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

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

Type of animal	Mortality and potential mortal injury
Fish: no swim bladder	229 – 234 dB peak
Fish: swim bladder is not involved in hearing	229 – 234 dB peak
Fish: swim bladder involved in hearing	229 – 234 dB peak
Sea turtles	229 – 234 dB peak
Eggs and larvae	> 13 mm/s peak velocity

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

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

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

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

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

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

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

Both fleeing animal and stationary animal models have been used to cover the SEL_{cum} criteria for fish. It has been recognised that there was 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 were 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} was relatively slow in relation to data from Hirata (1999) and thus was considered somewhat conservative.

Although it is feasible that some species will not flee, those that are likely to remain are thought more likely to be benthic species or species without a swim bladder; these are the least sensitive species.

For example, from Popper *et al*. (2014): "There is evidence (e.g., Goertner *et al*., 1994; Stephenson *et al*., 2010; Halvorsen *et al*., 2012) that little or no damage occurs to fish without a swim bladder except at very short ranges from an in-water explosive event. Goertner (1978) showed that the range from an explosive event over which damage may occur to a non-swim bladder fish is in the order of 100 times less than that for swim bladder fish."

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

Additionally, a threshold identified in Hawkins *et al.* (2014) has been included that could be indicative of a behavioural reaction in herring at 135 dB (SEL_{ss}). Tests were undertaken using a loudspeaker-simulated piling noise source in a quiet lough, where the researchers found a reaction in sprat (considered as a proxy species for herring) in 50% of presentations at this received noise level. Hawkins *et al*. urged caution to the use of the noise levels identified in the paper however, and that they should not be used as assessment criteria as the acquired data would be limited. The 135 dB threshold was therefore expected to be highly precautionary.

2.2.2.1 Particle motion

The criteria defined in the above section all 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) stated that in derivation of the sound pressure-based criteria in Popper *et al.* (2014) it may have been 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, has been a lack of data (Popper and Hawkins, 2018) both in respect of predictions of the particle motion level as a consequence of a noise source such as piling, and a lack of knowledge of the sensitivity of a fish, or a wider category of fish, to a particle motion value. There continue to be calls for additional research on the levels of and effects with respect to levels of particle motion. Until sufficient data are available to enable revised thresholds based on the particle motion metric, Popper *et al.* (2014) continues to be the best source of criteria in respect to fish impacts (Andersson *et al.,* 2016, Popper and Hawkins*,* 2019).

3 Modelling methodology

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

Of those considered, the noise source most important to consider was 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 activities was 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 5.1) is a semi-empirical underwater noise propagation model based around a combination of numerical modelling, based around a combined geometric and energy flow/hysteresis loss method, and actual measured data. It was designed to calculate the propagation of noise in shallow, mixed water, typical of the conditions around the UK and very well suited to the region around Morecambe OWF. The model has been tuned for accuracy using over 80 datasets of underwater noise propagation from monitoring around offshore piling activities.

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

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

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

A simple modelling approach has been used for noise sources other than piling that may be present during construction and operation of the Morecambe OWF generation assets, and these are discussed in Section 5.

3.1 Modelling confidence

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

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

The current version of INSPIRE (version 5.1) is the product of re-analysing all the impact piling noise measurements in Subacoustech Environmental's measurement database and cross-referencing it with blow energy data from piling logs. This gave a database of single strike noise levels referenced to a specific blow energy at a specific range. This analysis showed that, based on the most up to date measurement data for large piles at high blow energies, the previous versions of INSPIRE tended to overestimate the predicted noise levels at these blow energies.

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

Figure 3-1 and Figure 3-2 present a small selection of measured impact piling noise data plotted against outputs from INSPIRE in terms of unweighted SPL_{peak} and unweighted SEL_{ss}. The plots show data points from measured data (in blue) plotted alongside modelled data (in orange) using INSPIRE version 5.1, matching the pile size, blow energy and range from the measured data. These show the fit to the data, with the INSPIRE model 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.

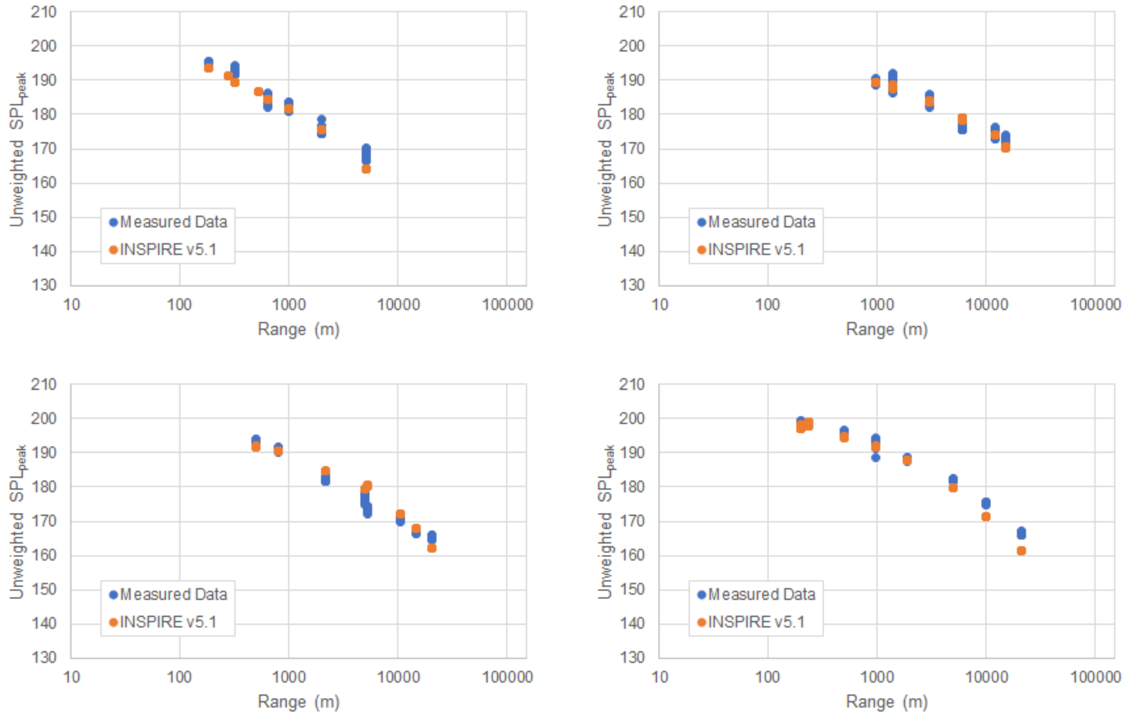

Figure 3-1 Comparison between example measured unweighted SPL_{peak} impact piling data (blue points) and modelled data using INSPIRE version 5.1 (orange points) Top Left: 1.8 m pile, 260 kJ maximum hammer energy, Irish Sea, 2010; Top Right: 9.5 m pile, 1,600 kJ maximum hammer energy, North Sea, 2020; Bottom Left: 6.1 m pile, 1,060 kJ maximum hammer energy, Southern North Sea, 2009; Bottom Right: 6 m pile, 1,100 kJ maximum hammer energy, Southern North Sea, 2009.

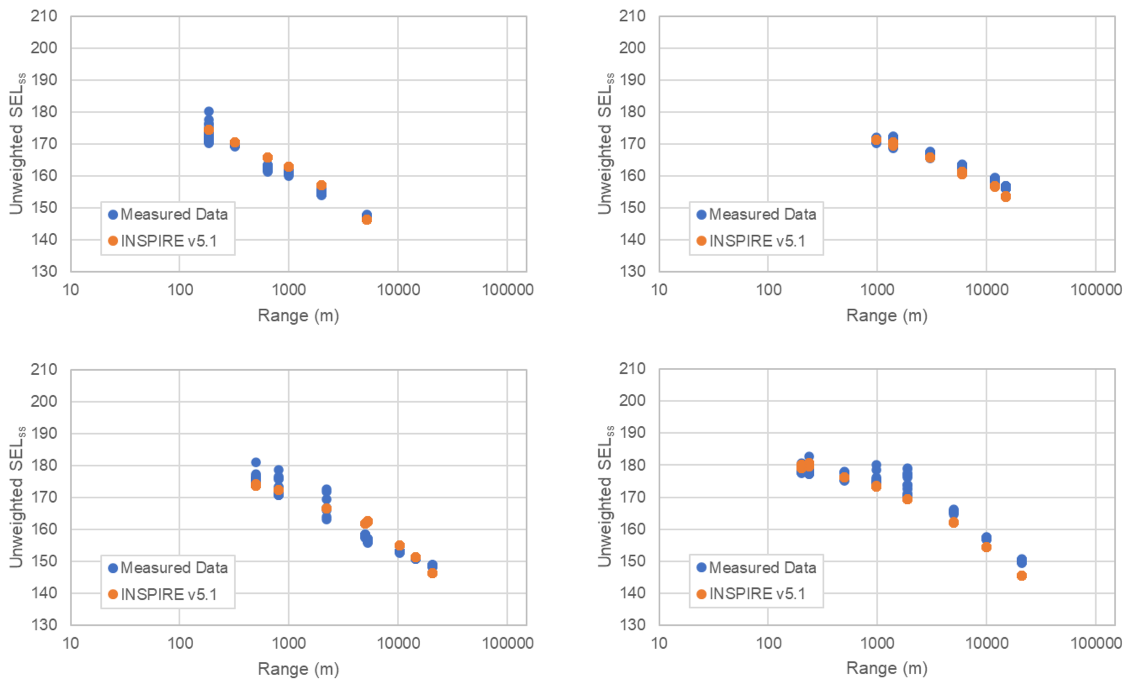

Figure 3-2 Comparison between example measured unweighted SEL_{ss} impact piling data (blue points) and modelled data using INSPIRE version 5.1 (orange points) Top Left: 1.8 m pile, 260 kJ maximum hammer energy, Irish Sea, 2010; Top Right: 9.5 m pile, 1,600 kJ maximum hammer energy, North Sea, 2020; Bottom Left: 6.1 m pile, 1,060 kJ maximum hammer energy, Southern North Sea, 2009; Bottom Right: 6 m pile, 1,100 kJ maximum hammer energy, Southern North Sea, 2009.

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

3.1.1 Noise modelling verification

It is expected that, as per typical requirements in the UK, the underwater noise generated during the installation of a selection of the foundation pile installations will be sampled on site using hydrophones. By nature, these will be measurements of a specific piling event undertaken at a location and hammer energy profile which may or may not have been modelled previously.

The purpose of the monitoring is to determine the actual underwater noise levels on site for comparison with the modelled levels presented in this report and used as the basis of the impacts predicted in the Environmental Statement, which are themselves intended to represent a worst case. The measurements taken during installation will be constrained by the piling plan and site limitations and a direct (like-for-like) comparison with a modelled scenario is unlikely to be possible. Such comparisons usually take the form of "level vs. range" (LvR) plots for a given transect and blow energy profile.

The underlying calculations summarised in this report effectively comprise of thousands of LvR plots and as such, these have not been reproduced in full. Samples are provided in section 3.2.5, but due to the complexity of surrounding conditions and variation in blow energies, they are unlikely to be and should not be considered representative of other transects that may be monitored directly in the future.

3.2 Modelling parameters

3.2.1 Modelling locations

Modelling for WTG/OSP foundation impact piling has been undertaken at three representative locations covering the extents, and various water depths, within the Morecambe windfarm site.

- North West (NW) – situated along the north western edge of the windfarm site, showing propagation into the wider Irish Sea;
- East (E) – situated at the eastern edge of the windfarm site situated in shallower waters closest to the shore at Blackpool; and
- South West (SW) – situated in the deepest water inside the boundary, along the southwestern edge of the site.

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

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

Modelling locations	North West (NW)	East (E)	South West (SW)
Latitude	53.8211°N	53.8058°N	53.7667°N
Longitude	003.6269°W	003.4983°W	003.6359°W
Water depth	28.5 m	25.2 m	37.2 m

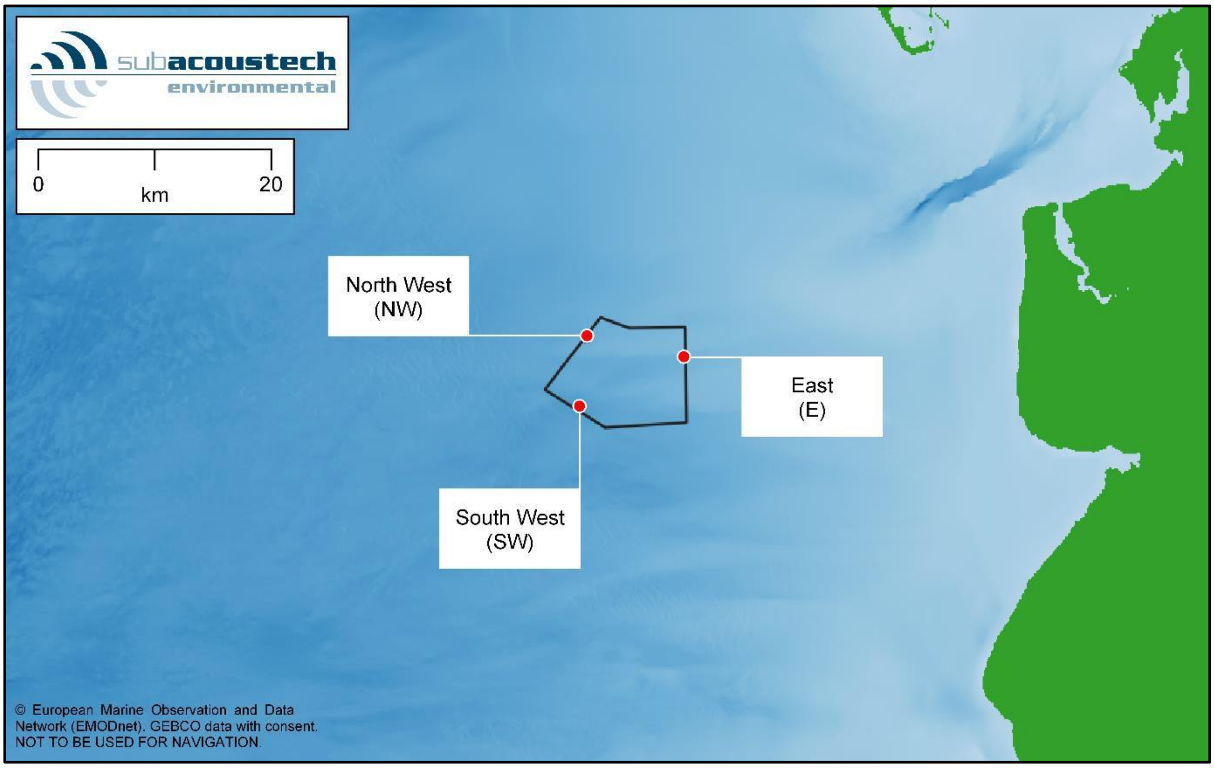

Figure 3-3 Approximate positions of the modelling locations at Morecambe OWF

3.2.2 <u>WTG/OSP foundation and impact piling parameters</u>

Two foundation scenarios have been considered for this study. These were:

- A worst-case monopile scenario, installing a 14 m diameter pile (it is noted that the pile diameter is marginally larger than that now in the Project design envelope (12m), however results encompass the worst case) with a maximum blow energy of 6,600 kJ; and
- A worst-case pin pile (jacket) scenario, installing 5 m pile (it is noted that the pile diameter is marginally larger than that now in the Project design envelope (3m), however results encompass the worst case) diameter piles with a maximum blow energy of 2,500 kJ.

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

In a 24-hour period it is expected that up to three monopile foundations or four pin piles can be driven. Scenarios covering single pile installations for monopiles and pin piles, as well as three sequential monopile foundations and four sequential pin pile installations have been considered for this study.

Table 3-2 Summary of the soft start and ramp up scenario used for the worst-case monopile modelling

Monopile worst-case	**1,056 kJ**	**2,112 kJ**	**3,168 kJ**	**4,224 kJ**	**5,280 kJ**	**6,600 kJ**
Number of strikes	200	150	150	150	150	7,350
Duration	20 mins	10 mins	10 mins	10 mins	10 mins	3 hours 30 mins
Strike rate	10 blows/min	15 blows/min				35 blows/min
1 pile: 8,150 strikes, 4 hours 30 minutes duration 3 piles: 24,450 strikes, 13 hours 30 minutes duration						

Table 3-3 Summary of the soft start and ramp up scenario used for the worst-case pin pile modelling

Pin pile worst-case	**400 kJ**	**800 kJ**	**1,200 kJ**	**1,600 kJ**	**2,000 kJ**	**2,500 kJ**
Number of strikes	200	150	150	150	150	7,350
Duration	20 mins	10 mins	10 mins	10 mins	10 mins	3 hours 30 mins
Strike rate	10 blows/min	15 blows/min				35 blows/min
1 pile: 8,150 strikes, 4 hours 30 minutes duration 4 piles: 32,600 strikes, 18 hours duration						

Additionally, a maximum strike rate scenario has been modelled, the results of this are presented in Section 4.4, which is considered the worst case in terms of cumulative (multiple strikes) impact ranges.

3.2.3 Apparent source levels

Noise modelling requires knowledge of a source level, which is the theoretical noise level at one metre from the noise source. It is worth noting that the 'source level' technically does not exist in the context of many shallow water (< 100 m) noise sources (Heaney *et al*., 2020). The noise level at one metre from the pile will be highly complex and vary up and down the water column by the pile, rather than being one simple noise level. In practice, for underwater noise modelling such as this, it is effectively an 'apparent source level' that is used, essentially a value that can be used to produce correct noise levels at range (for a specific model), as required in impact assessments.

The INSPIRE model requires an apparent source level, which is estimated based on the pile diameter and the blow energy imparted on the pile by the hammer. This is adjusted depending on the water depth at the modelling location to allow for the length of 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.

The unweighted, single strike SPL_{peak} and SEL_{ss} apparent source levels estimated for this study are provided in Table 3-4. These figures have been presented in accordance with typical requirements by regulatory authorities, although as indicated above they were not necessarily compatible or comparable with any other model or predicted apparent source level. In each case, the differences in apparent source level for each location within a scenario were minimal.

Table 3-4 Summary of the unweighted apparent source levels used for modelling

Apparent source levels	Location	**Monopile worst-case** 14 m / 6,600 kJ	**Pin pile worst-case** 5 m / 2,500 kJ
SPL_{peak}	NW	243.1 dB re 1 µPa @ 1 m	241.5 dB re 1 µPa @ 1 m
	E	243.1 dB re 1 µPa @ 1 m	241.5 dB re 1 µPa @ 1 m
	SW	243.1 dB re 1 µPa @ 1 m	241.5 dB re 1 µPa @ 1 m
SEL_{ss}	NW	224.3 dB re 1 µPa^{2}s @ 1 m	222.4 dB re 1 µPa^{2}s @ 1 m
	E	224.3 dB re 1 µPa^{2}s @ 1 m	222.4 dB re 1 µPa^{2}s @ 1 m
	SW	224.3 dB re 1 µPa^{2}s @ 1 m	222.4 dB re 1 µPa^{2}s @ 1 m

3.2.4 Environmental conditions

With the inclusion of measured noise propagation data for similar offshore piling operations in UK waters, the INSPIRE model intrinsically accounts for various environmental conditions. This includes the differences that can occur with the temperature and salinity of the water, as well as the sediment type surrounding the site. Data from the British Geological Survey showed that the seabed in and around Morecambe OWF was generally made up of sand. This has not been included as a direct input into the model, as the model accounts for the 'average' seabed type in the aggregation of measured data around the UK. Variations in seabed type have not been found to lead to a significant effect on the transmission of noise levels from piling.

Additional information on baseline ambient noise has been provided in **Appendix B**.

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

3.2.5 Level vs Range Plots

The following charts provide the underwater noise propagation loss for the two SPL_{peak} and SEL_{ss} transects that represented the minimum loss (maximum transmission) and maximum loss (minimum transmission). These were from the SW location (heading west) and E location (heading ENE), respectively. These assumed monopile piling operations at the maximum hammer energy.

As noted in section 3.1.1, these were samples of thousands of possible location, transect, pile, and hammer energy combinations that existed and should not necessarily be considered to be representative of any condition other than the one described.

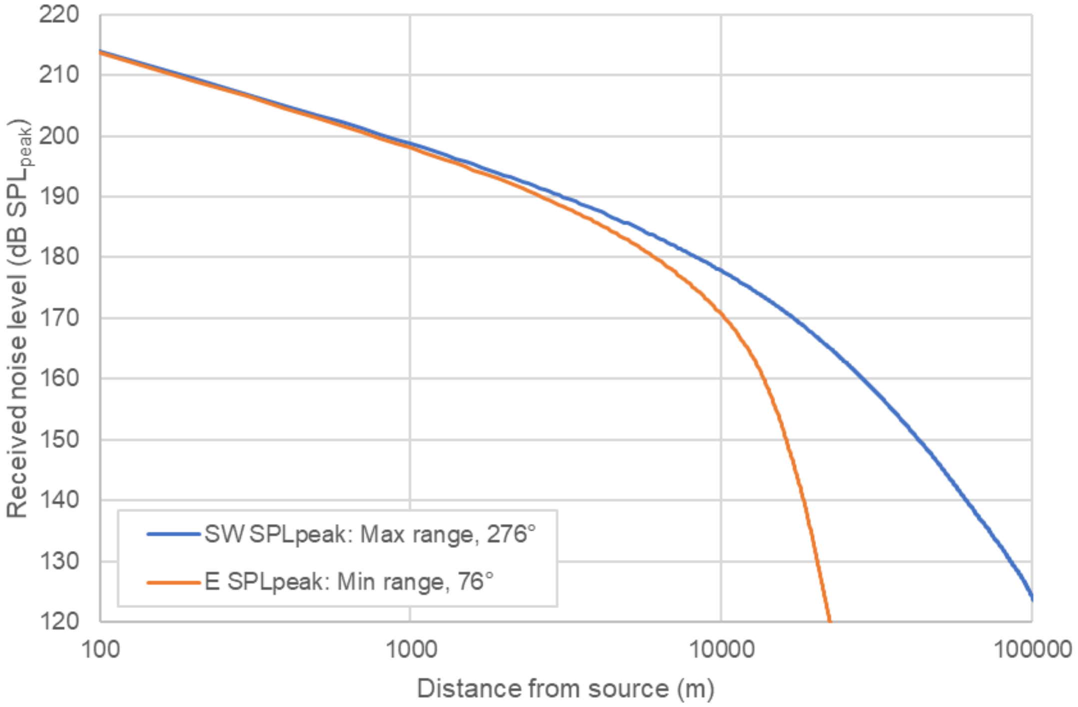

Figure 3-4 Example level vs. range plot for SPL_{peak} metrics, based on the maximum (SW) and minimum (E) noise transmission over distance

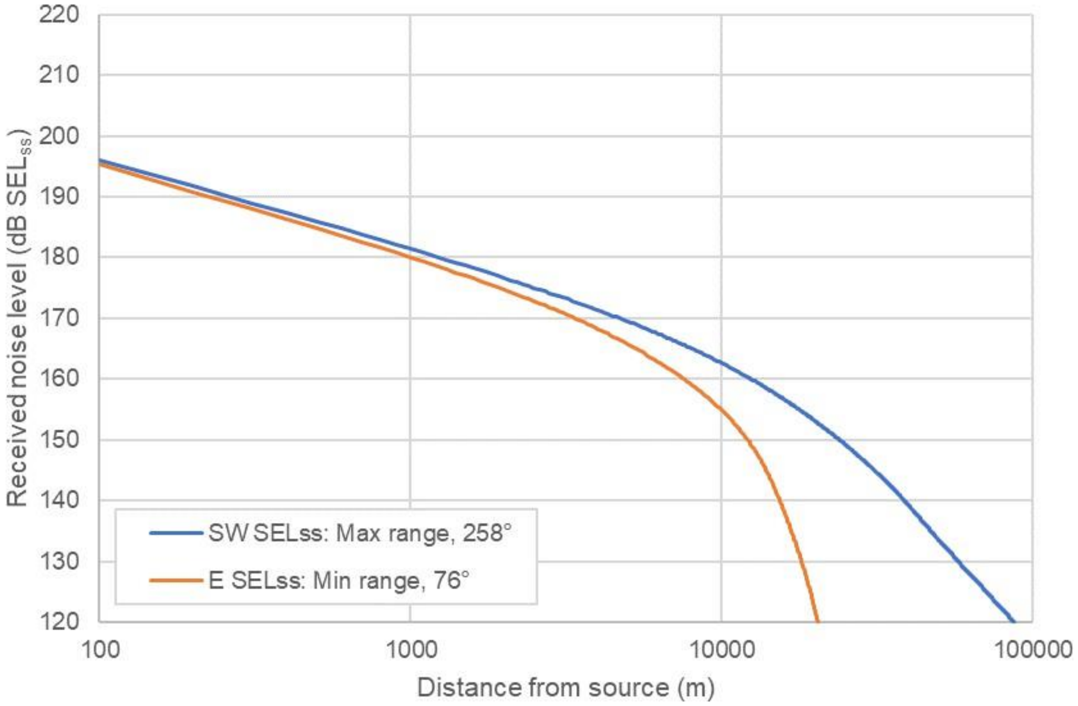

Figure 3-5 Example level vs. range plot for SPL_{SS} metrics, based on the maximum (SW) and minimum (E) noise transmission over distance

3.3 Cumulative SELs and fleeing receptors

Expanding on the information in Section 2.2 regarding SEL_{cum} and the fleeing animal model 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 commencement of piling) for the fleeing animal receptor. For example, if a receptor began to flee in a straight line away 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.

To help explain this, it is helpful to examine how the multiple pulse SEL_{cum} ranges are calculated. As explained in Section 2.1.4, the SEL_{cum} is a measure of the total received noise over a whole operation: in the cases of the Southall *et al*. (2019) and Popper *et al*. (2014) criteria this covers noise in a 24-hour period unless otherwise specified.

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 pulse 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} 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 3-6 and Figure 3-7 show the difference in the received SELs by a stationary receptor and a fleeing receptor travelling at a constant speed of 1.5 ms^{-1}, using the worst-case monopile scenario at the NW location for a single pile installation.

The received SEL_{ss} from the stationary receptor, as illustrated in Figure 3-6, showed the noise level gradually increasing as the blow energy increased throughout the piling operation. These step changes were also visible for the fleeing receptor, but as the receptor was further from the source by the time the levels increased, the total received exposure reduced, resulting in progressively lower received noise levels. As an example, for the first 20 minutes of the piling scenario, during soft start, at a rate of 1.5 ms^{-1}, the fleeing receptor will have moved 1.8 km away. After the full piling duration of 4 hours 30 minutes, the receptor will be over 24 km from the pile.

Figure 3-7 shows the effect these different received levels have when calculating the SEL_{cum}. It clearly shows the difference in cumulative effect of the receptor remaining still, as opposed to fleeing. To use an extreme example, starting at a range of 1 m, the first strike would result in a received level of 219.4 dB re 1 μPa^2s. If the receptor were to remain stationary throughout the piling operation it would receive a cumulative level of 263.3 dB re 1 μPa^2s, whereas when fleeing at 1.5 ms^{-1} over the same scenario would result in a cumulative received level of just 219.9 dB re 1 μPa^2s for the receptor.

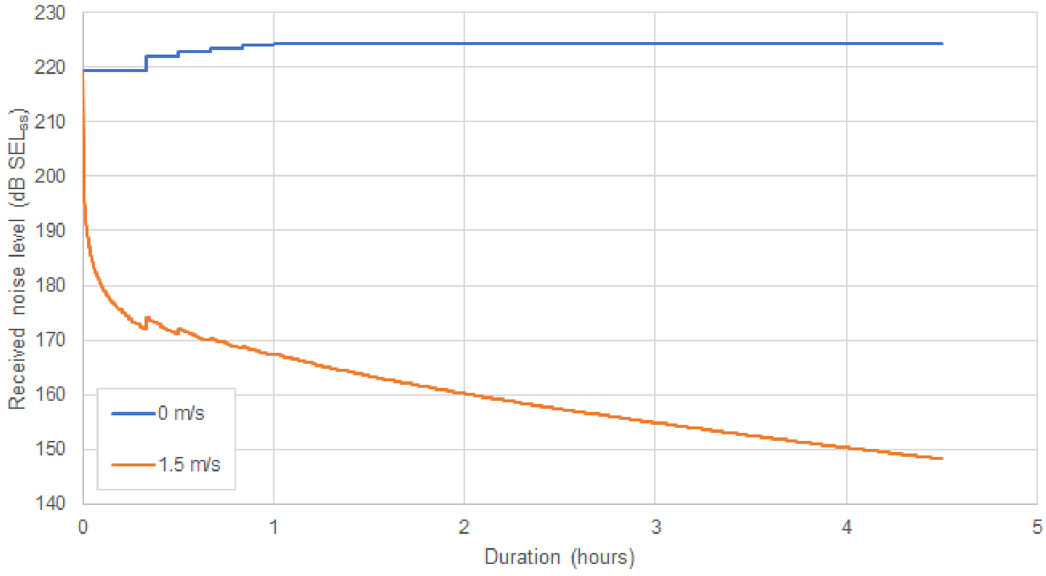

Figure 3-6 Received single-strike noise levels (SEL_{ss}) for receptors during the worst-case monopile foundation parameters at the NW location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source

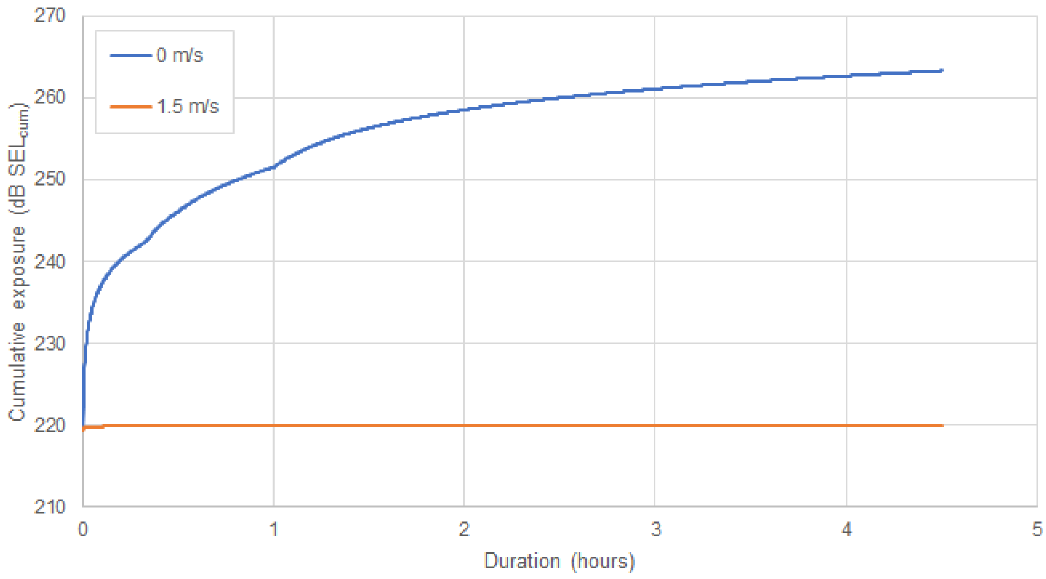

Figure 3-7 Cumulative received noise levels (SEL_{cum}) for receptors during worst-case monopile foundation parameters at the NW location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source

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 3-8.

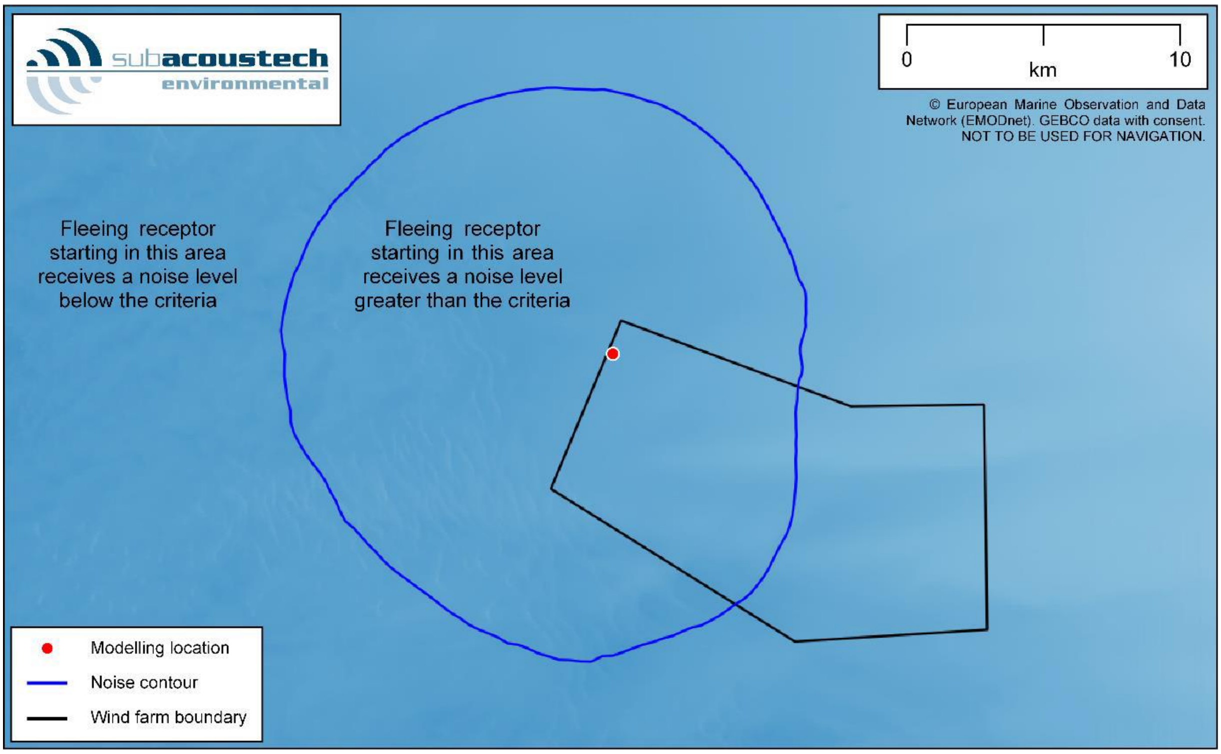

Figure 3-8 Example plot showing a fleeing animal SEL_{cum} criteria contour and the areas where the cumulative noise exposure will exceed the particular impact criteria

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

3.3.1 <u>The effects of input parameters on cumulative SELs and fleeing receptors</u>

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

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

4 Modelling results

This section presents the modelled impact ranges for impact piling noise following the parameters detailed in Section 3.2, covering the Southall *et al*. (2019) marine mammal criteria (Section 2.2.1) and the Popper *et al*. (2014) fish criteria (Section 2.2.2). To aid navigation, Table 4-1 contains a list of the impact range tables in this section. The biggest modelled ranges were predicted for the worst-case monopile scenario at the SW modelling location.

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

For the results presented throughout this report any predicted ranges smaller than 50 m and areas less than 0.01 km² for single strike criteria and ranges smaller than 100 m and areas less than 0.1 km² for cumulative criteria, have not been presented. At ranges this close to the noise source, the modelling processes were unable to model to a sufficient level of accuracy due to complex acoustic effects present near the pile. These ranges have been 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 (p24)	NW (4.2.1)	Monopile worst case (4.1)	Southall *et al*. (2019)	Unweighted SPL_{peak}
Table 4-4 (p24)				Weighted SEL_{cum} (Impulsive)
Table 4-5 (p24)			Popper *et al*. (2014)	Unweighted SPL_{peak}
Table 4-6 (p25)				Unweighted SEL_{cum} (Pile driving)
Table 4-7 (p25)			Hawkins *et al*. (2014)	Unweighted SEL_{ss}
Table 4-8 (p25)	E (4.2.2)		Southall *et al*. (2019)	Unweighted SPL_{peak}
Table 4-9 (p25)				Weighted SEL_{cum} (Impulsive)
Table 4-10 (p26)			Popper *et al*. (2014)	Unweighted SPL_{peak}
Table 4-11 (p26)				Unweighted SEL_{cum} (Pile driving)
Table 4-12 (p26)			Hawkins *et al*. (2014)	Unweighted SEL_{ss}
Table 4-13 (p26)	SW (4.2.3)		Southall *et al*. (2019)	Unweighted SPL_{peak}
Table 4-14 (p27)				Weighted SEL_{cum} (Impulsive)
Table 4-15 (p27)			Popper *et al*. (2014)	Unweighted SPL_{peak}
Table 4-16 (p27)				Unweighted SEL_{cum} (Pile driving)
Table 4-17 (p27)			Hawkins *et al*. (2014)	Unweighted SEL_{ss}
Table 4-18 (p28)	NW (4.2.4.1)	Multiple sequential monopile worst case (4.2.4)	Southall *et al*. (2019)	Weighted SEL_{cum} (Impulsive)
Table 4-19 (p28)			Popper *et al*. (2014)	Unweighted SEL_{cum} (Pile driving)
Table 4-20 (p28)	E (4.2.4.2)		Southall *et al*. (2019)	Weighted SEL_{cum} (Impulsive)
Table 4-21 (p29)			Popper *et al*. (2014)	Unweighted SEL_{cum} (Pile driving)
Table 4-22 (p29)	SW (4.2.4.3)		Southall *et al*. (2019)	Weighted SEL_{cum} (Impulsive)
Table 4-23 (p29)			Popper *et al*. (2014)	Unweighted SEL_{cum} (Pile driving)
Table 4-24 (p30)	NW (4.3.1)	Pin pile worst case (4.3)	Southall *et al*. (2019)	Unweighted SPL_{peak}
Table 4-25 (p30)				Weighted SEL_{cum} (Impulsive)
Table 4-26 (p30)			Popper *et al*. (2014)	Unweighted SPL_{peak}
Table 4-27 (p31)				Unweighted SEL_{cum} (Pile driving)

Table (page)	Parameters (section)		Criteria	
Table 4-28 (p31)			Hawkins *et al*. (2014)	Unweighted SEL_{ss}
Table 4-29 (p31)	E (4.3.2)		Southall *et al*. (2019)	Unweighted SPL_{peak}
Table 4-30 (p31)				Weighted SEL_{cum} (Impulsive)
Table 4-31 (p32)			Popper *et al*. (2014)	Unweighted SPL_{peak}
Table 4-32 (p32)				Unweighted SEL_{cum} (Pile driving)
Table 4-33 (p32)			Hawkins *et al*. (2014)	Unweighted SEL_{ss}
Table 4-34 (p32)	SW (4.3.3)		Southall *et al*. (2019)	Unweighted SPL_{peak}
Table 4-35 (p33)				Weighted SEL_{cum} (Impulsive)
Table 4-36 (p33)			Popper *et al*. (2014)	Unweighted SPL_{peak}
Table 4-37 (p33)				Unweighted SEL_{cum} (Pile driving)
Table 4-38 (p33)			Hawkins *et al*. (2014)	Unweighted SEL_{ss}
Table 4-39 (p34)	NW (4.3.4.1)	Multiple sequential pin pile worst case (4.3.4)	Southall *et al*. (2019)	Weighted SEL_{cum} (Impulsive)
Table 4-40 (p34)			Popper *et al*. (2014)	Unweighted SEL_{cum} (Pile driving)
Table 4-41 (p34)	E (4.3.4.2)		Southall *et al*. (2019)	Weighted SEL_{cum} (Impulsive)
Table 4-42 (p35)			Popper *et al*. (2014)	Unweighted SEL_{cum} (Pile driving)
Table 4-43 (p35)	SW (4.3.4.3)		Southall *et al*. (2019)	Weighted SEL_{cum} (Impulsive)
Table 4-44 (p35)			Popper *et al*. (2014)	Unweighted SEL_{cum} (Pile driving)
Table 4-45 (p37)	SW (4.4)	Summary of the maximum strike rate scenario parameters for monopile modelling (worst case)		
Table 4-46 (p37)		Summary of the maximum strike rate scenario parameters for pin pile modelling (worst case)		
Table 4-47 (p38)	SW (4.4.1)	Monopile worst case (4.4.1)	Southall *et al*. (2019)	Weighted SEL_{cum} (Impulsive)
Table 4-48 (p38)			Southall *et al*. (2019)	Weighted SEL_{cum} (Non-impulsive)
Table 4-49 (p38)			Popper *et al*. (2014)	Unweighted SEL_{cum} (Pile driving)
Table 4-50 (p39)	SW (4.4.2)	Multiple sequential monopile worst case (4.4.2)	Southall *et al*. (2019)	Weighted SEL_{cum} (Impulsive)
Table 4-51 (p39)			Southall *et al*. (2019)	Weighted SEL_{cum} (Non-impulsive)
Table 4-52 (p39)			Popper *et al*. (2014)	Unweighted SEL_{cum} (Pile driving)
Table 4-53 (p40)	SW (4.4.3)	Pin pile worst case (4.4.3)	Southall *et al*. (2019)	Weighted SEL_{cum} (Impulsive)
Table 4-54 (p40)			Southall *et al*. (2019)	Weighted SEL_{cum} (Non-impulsive)
Table 4-55 (p40)			Popper *et al*. (2014)	Unweighted SEL_{cum} (Pile driving)
Table 4-56 (p41)	SW (4.4.4)	Multiple sequential pin pile worst case (4.4.4)	Southall *et al*. (2019)	Weighted SEL_{cum} (Impulsive)
Table 4-57 (p41)			Southall *et al*. (2019)	Weighted SEL_{cum} (Non-impulsive)
Table 4-58 (p41)			Popper *et al*. (2014)	Unweighted SEL_{cum} (Pile driving)

4.1 Predicted noise levels at 750 m from the noise source

In addition to the apparent source levels given 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 although not a requirement in the UK sector, is a common consideration for underwater noise studies at offshore wind farms. It has the added advantage of being comparable with other modelling or on-site 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 transmission at each location while piling at maximum hammer energy.

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 maximum hammer blow energy

Predicted level at 750 m range	**Location**	**Monopile worst-case** 14 m / 6,600 kJ	**Pin pile worst-case** 5 m / 2,500 kJ
SPL_{peak}	NW	201.7 dB re 1 µPa	200.5 dB re 1 µPa
	E	201.3 dB re 1 µPa	199.7 dB re 1 µPa
	SW	202.4 dB re 1 µPa	200.8 dB re 1 µPa
SEL_{ss}	NW	183.6 dB re 1 µPa²s	181.6 dB re 1 µPa²s
	E	183.2 dB re 1 µPa²s	181.2 dB re 1 µPa²s
	SW	184.3 dB re 1 µPa²s	182.3 dB re 1 µPa²s

4.2 Monopile foundations

Table 4-3 to Table 4-17 present the modelling results for the worst case monopile foundation modelling scenarios in terms of the Southall *et al*. (2019) marine mammal criteria (Section 2.2.1) and the Popper *et al*. (2014) fish criteria (Section 2.2.2). These results show the impacts from installing a single monopile installation; results for modelling of three sequential pin pile installations are given in Section 4.2.4.

The largest marine mammal impact ranges for monopiles were predicted at the SW modelling location. Maximum PTS injury ranges were predicted for LF cetaceans using the SEL_{cum} criteria, with ranges of up to 5.0 km; VHF cetaceans showed maximum PTS ranges of up to 3.2 km for the same scenario.

For fish, the largest recoverable injury ranges (203 dB SEL_{cum} threshold) for monopiles were predicted to be 7.0 km assuming a stationary receptor at the SW modelling location; if a fleeing receptor is assumed, the impact ranges were reduced to less than 100 m. Maximum TTS ranges (186 dB SEL_{cum} threshold) were predicted up to 25 km for a stationary animal, reducing to 13 km for a fleeing animal.

4.2.1 NW location

Table 4-3 Summary of the unweighted SPL_{peak} impact ranges using the Southall et al. (2019) impulsive criteria for the monopile worst case modelling scenario at the NW location

Southall *et al.* (2019) Unweighted SPL_{peak}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	620 m	620 m
	PCW (218 dB)	0.01 km²	50 m	50 m	50 m
TTS	LF (213 dB)	0.04 km²	120 m	120 m	120 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	6.4 km²	1.5 km	1.4 km	1.4 km
	PCW (212 dB)	0.06 km²	140 m	140 m	140 m

Table 4-4 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) impulsive criteria for the monopile worst case modelling scenario at the NW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	18 km²	3.2 km	1.3 km	2.3 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	10 km²	2.2 km	1.2 km	1.8 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	810 km²	22 km	8.5 km	15 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	680 km²	18 km	8.9 km	14 km
	PCW (170 dB)	76 km²	6.0 km	3.1 km	4.8 km

Table 4-5 Summary of the unweighted SPL_{peak} impact ranges using the Popper et al. (2014) pile driving criteria for the monopile worst case modelling scenario at the NW location

Popper *et al.* (2014) Unweighted SPL_{peak}	**Area**	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.04 km²	120 m	120 m	120 m
207 dB	0.27 km²	300 m	290 m	290 m

Table 4-6 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the monopile worst case modelling scenario at the NW location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	250 km²	11 km	5.4 km	8.7 km
Stationary	219 dB	1.9 km²	800 m	750 m	770 m
	216 dB	4.4 km²	1.2 km	1.2 km	1.2 km
	210 dB	21 km²	2.7 km	2.5 km	2.6 km
	207 dB	43 km²	3.9 km	3.5 km	3.7 km
	203 dB	100 km²	6.0 km	5.2 km	5.7 km
	186 dB	1,200 km²	23 km	15 km	20 km

Table 4-7 Summary of the unweighted SEL_{ss} ranges using the Hawkins et al. (2014) levels for the monopile worst case modelling scenario at the NW location

Hawkins *et al.* (2014) Unweighted SEL_{ss}	**Area**	**Maximum range**	**Minimum range**	**Mean range**
135 dB	4,100 km²	46 km	21 km	35 km

4.2.2 E location

Table 4-8 Summary of the unweighted SPL_{peak} impact ranges using the Southall et al. (2019) impulsive criteria for the monopile worst case modelling scenario at the E location

Southall *et al.* (2019) Unweighted SPL_{peak}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (219 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.1 km²	590 m	570 m	580 m
	PCW (218 dB)	0.01 km²	50 m	50 m	50 m
TTS	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)	5.3 km²	1.4 km	1.3 km	1.3 km
	PCW (212 dB)	0.05 km²	130 m	130 m	130 m

Table 4-9 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) impulsive criteria for the monopile worst case modelling scenario at the E location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	3.0 km²	1.4 km	780 m	970 m
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	3.7 km²	1.8 km	680 m	1.0 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	290 km²	14 km	6.0 km	9.3 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	420 km²	17 km	6.3 km	11 km
	PCW (170 dB)	32 km²	5.0 km	1.9 km	3.0 km

Table 4-10 Summary of the unweighted SPL_{peak} impact ranges using the Popper et al. (2014) pile driving criteria for the monopile worst case modelling scenario at the E location

Popper *et al.* (2014) Unweighted SPL_{peak}	**Area**	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.04 km²	110 m	110 m	110 m
207 dB	0.24 km²	280 m	280 m	280 m

Table 4-11 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the monopile worst case modelling scenario at the E location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	120 km²	9.7 km	3.4 km	6.0 km
Stationary	219 dB	1.7 km²	750 m	700 m	730 m
	216 dB	3.7 km²	1.1 km	1.1 km	1.1 km
	210 dB	17 km²	2.5 km	2.2 km	2.3 km
	207 dB	33 km²	3.5 km	3.0 km	3.2 km
	203 dB	72 km²	5.5 km	4.5 km	4.8 km
	186 dB	830 km²	21 km	12 km	16 km

Table 4-12 Summary of the unweighted SEL_{ss} ranges using the Hawkins et al. (2014) levels for the monopile worst case modelling scenario at the E location

Hawkins *et al.* (2014) Unweighted SEL_{ss}	**Area**	**Maximum range**	**Minimum range**	**Mean range**
135 dB	2,900 km²	42 km	17 km	29 km

4.2.3 SW location

Table 4-13 Summary of the unweighted SPL_{peak} impact ranges using the Southall et al. (2019) impulsive criteria for the monopile worst case modelling scenario at the SW location

Southall *et al.* (2019) Unweighted SPL_{peak}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	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)	1.5 km²	690 m	680 m	690 m
	PCW (218 dB)	0.01 km²	60 m	60 m	60 m
TTS	LF (213 dB)	0.05 km²	130 m	130 m	130 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	8.3 km²	1.6 km	1.6 km	1.6 km
	PCW (212 dB)	0.07 km²	150 m	150 m	150 m

Table 4-14 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) impulsive criteria for the monopile worst case modelling scenario at the SW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	39 km²	5.0 km	2.0 km	3.4 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	20 km²	3.2 km	1.7 km	2.5 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	1,000 km²	24 km	10 km	17 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	820 km²	20 km	11 km	16 km
	PCW (170 dB)	120 km²	7.8 km	4.2 km	6.1 km

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

Popper *et al.* (2014) Unweighted SPL_{peak}	**Area**	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.05 km²	130 m	130 m	130 m
207 dB	0.32 km²	320 m	320 m	320 m

Table 4-16 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the monopile worst case modelling scenario at the SW location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	350 km²	13 km	6.9 km	10 km
Stationary	219 dB	2.3 km²	880 m	850 m	860 m
	216 dB	5.6 km²	1.4 km	1.3 km	1.3 km
	210 dB	28 km²	3.1 km	2.9 km	3.0 km
	207 dB	57 km²	4.5 km	4.1 km	4.3 km
	203 dB	130 km²	7.0 km	6.1 km	6.5 km
	186 dB	1,400 km²	25 km	17 km	21 km

Table 4-17 Summary of the unweighted SEL_{ss} ranges using the Hawkins et al. (2014) levels for the monopile worst case modelling scenario at the SW location

Hawkins *et al.* (2014) Unweighted SEL_{ss}	**Area**	**Maximum range**	**Minimum range**	**Mean range**
135 dB	4,500 km²	48 km	24 km	37 km

4.2.4 Multiple sequential monopiles

Table 4-18 to Table 4-23 present the modelling results for the worst case pin pile foundation modelling scenarios when considering three sequential installations in terms of the Southall *et al*. (2019) marine mammal criteria (Section 2.2.1) and the Popper *et al*. (2014) fish criteria (Section 2.2.2).

When comparing the impact ranges for single pile and sequential pile installations, the overall increases were minimal, as by the time the subsequent piles were installed, the fleeing receptor would be at such a distance that the additional exposure was minimal; the largest increases seen for these scenarios were only a few hundred metres. When considering a stationary animal, the ranges were significantly increased as the receptor would be essentially receiving noise from quadruple the number of pile strikes.

4.2.4.1 NW location

Table 4-18 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) impulsive criteria for the multiple sequential monopile worst case modelling scenario at the NW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	18 km²	3.2 km	1.3 km	2.3 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	11 km²	2.3 km	1.2 km	1.8 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	810 km²	22 km²	8.5 km	1.5 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	690 km²	19 km	8.9 km	14 km
	PCW (170 dB)	77 km²	6.1 km	3.1 km	4.9 km

Table 4-19 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the multiple sequential monopile worst case modelling scenario at the NW location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
Fleeing	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	250 km²	11 km	5.4 km	8.8 km
Stationary	219 dB	7.1 km	1.6 km	1.5 km	1.5 km
	216 dB	15 km²	2.3 km	2.2 km	2.2 km
	210 dB	63 km²	4.7 km	4.2 km	4.5 km
	207 dB	120 km²	6.5 km	5.6 km	6.1 km
	203 dB	240 km²	9.4 km	7.9 km	8.8 km
	186 dB	1,900 km²	29 km	17 km	24 km

4.2.4.2 E location

Table 4-20 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) impulsive criteria for the multiple sequential monopile worst case modelling scenario at the E location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	3.0 km²	1.4 km	780 m	970 m
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	3.8 km²	1.8 km	680 m	1.0 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	290 km²	14 km	6.0 km	9.3 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	420 km²	17 km	6.3 km	11 km
	PCW (170 dB)	32 km²	5.0 km	1.9 km	3.1 km

Table 4-21 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the multiple sequential monopile worst case modelling scenario at the E location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	120 km²	9.8 km	3.4 km	6.0 km
Stationary	219 dB	5.9 km²	1.4 km	1.3 km	1.4 km
	216 dB	13 km²	2.1 km	1.9 km	2.0 km
	210 dB	47 km²	4.3 km	3.6 km	3.9 km
	207 dB	83 km²	5.9 km	4.8 km	5.2 km
	203 dB	170 km²	8.6 km	6.5 km	7.3 km
	186 dB	1,300 km²	27 km	13 km	20 km

4.2.4.3 SW location

Table 4-22 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) impulsive criteria for the multiple sequential monopile worst case modelling scenario at the SW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	39 km²	5.0 km	2.0 km	3.4 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	20 km²	3.3 km	1.7 km	2.5 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	1,000 km²	24 km	10 km	17 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	830 km²	21 km	11 km	16 km
	PCW (170 dB)	120 km²	7.9 km	4.2 km	6.2 km

Table 4-23 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the multiple sequential monopile worst case modelling scenario at the SW location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	350 km²	14 km	6.9 km	10 km
Stationary	219 dB	9.1 km²	1.8 km	1.7 km	1.7 km
	216 dB	20 km²	2.6 km	2.5 km	2.6 km
	210 dB	85 km²	5.5 km	5.0 km	5.2 km
	207 dB	160 km²	7.5 km	6.5 km	7.0 km
	203 dB	310 km²	11 km	8.9 km	10 km
	186 dB	2,200 km²	32 km	19 km	26 km

4.3 Pin pile foundations

Table 4-24 to Table 4-38 present the modelling results for the worst case pin pile foundation modelling scenarios in terms of the Southall *et al*. (2019) marine mammal criteria (Section 2.2.1) and the Popper *et al*. (2014) fish criteria (Section 2.2.2). These results show the impacts from installing a single pin pile; results for modelling of four sequential pin pile installations are given in Section 4.3.4.

The largest marine mammal impact ranges for a single pin pile installation were predicted at the SW modelling location; maximum PTS injury ranges were predicted for LF cetaceans using the SEL_{cum} criteria, with ranges of up to 2.5 km. VHF cetaceans showed maximum PTS ranges of up to 1.5 km for the same location.

For fish, the largest recoverable injury ranges (203 dB SEL_{cum} threshold) for a single pin pile installation was predicted to be 5.6 km assuming a stationary receptor at the SW modelling location; if a fleeing receptor is assumed, the impact ranges were reduced to less than 100 m. Maximum TTS ranges (186 dB SEL_{cum} threshold) were predicted up to 22 km for a stationary animal, reducing to 11 km for a fleeing animal.

4.3.1 NW location

Table 4-24 Summary of the unweighted SPL_{peak} impact ranges using the Southall et al. (2019) impulsive criteria for the pin pile worst case modelling scenario at the NW location

Southall *et al.* (2019) Unweighted SPL_{peak}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	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)	0.74 km²	490 m	490 m	490 m
	PCW (218 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.03 km²	90 m	90 m	90 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	4.1 km²	1.2 km	1.1 km	1.1 km
	PCW (212 dB)	0.04 km²	110 m	110 m	110 m

Table 4-25 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) impulsive criteria for the pin pile worst case modelling scenario at the NW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	1.7 km²	1.1 km	280 m	690 m
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	1.2 km²	800 m	300 m	590 m
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	570 km²	19 km	6.5 km	13 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	500 km²	16 km	7.6 km	12 km
	PCW (170 dB)	50 km²	5.0 km	2.3 km	3.9 km

Table 4-26 Summary of the unweighted SPL_{peak} impact ranges using the Popper et al. (2014) pile driving criteria for the pin pile worst case modelling scenario at the NW location

Popper *et al.* (2014) Unweighted SPL_{peak}	**Area**	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.03 km²	90 m	90 m	90 m
207 dB	0.16 km²	230 m	230 m	230 m

Table 4-27 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the pin pile worst case modelling scenario at the NW location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	150 km²	8.7 km	4.0 km	6.7 km
Stationary	219 dB	1.1 km²	600 m	580 m	590 m
	216 dB	2.5 km²	900 m	880 m	890 m
	210 dB	13 km²	2.1 km	2.0 km	2.0 km
	207 dB	27 km²	3.0 km	2.8 km	2.9 km
	203 dB	66 km²	4.8 km	4.3 km	4.6 km
	186 dB	980 km²	20 km	14 km	18 km

Table 4-28 Summary of the unweighted SEL_{ss} ranges using the Hawkins et al. (2014) levels for the pin pile worst case modelling scenario at the NW location

Hawkins *et al.* (2014) Unweighted SEL_{ss}	**Area**	**Maximum range**	**Minimum range**	**Mean range**
135 dB	3,600 km²	42 km	21 km	33 km

4.3.2 E location

Table 4-29 Summary of the unweighted SPL_{peak} impact ranges using the Southall et al. (2019) impulsive criteria for the pin pile worst case modelling scenario at the E location

Southall *et al.* (2019) Unweighted SPL_{peak}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	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)	0.66 km²	460 m	450 m	460 m
	PCW (218 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
TTS	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)	3.5 km²	1.1 km	1.0 km	1.1 km
	PCW (212 dB)	0.03 km²	100 m	100 m	100 m

Table 4-30 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) impulsive criteria for the pin pile worst case modelling scenario at the E location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	0.3 km²	630 m	180 m	290 m
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	0.3 km²	550 m	150 m	270 m
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	290 km²	16 km	4.3 km	8.9 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	290 km²	14 km	5.2 km	9.2 km
	PCW (170 dB)	18 km²	4.0 km	1.2 km	2.2 km

Table 4-31 Summary of the unweighted SPL_{peak} impact ranges using the Popper et al. (2014) pile driving criteria for the pin pile worst case modelling scenario at the E location

Popper *et al.* (2014) Unweighted SPL_{peak}	**Area**	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.02 km²	90 m	90 m	90 m
207 dB	0.15 km²	220 m	220 m	220 m

Table 4-32 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the pin pile worst case modelling scenario at the E location assuming both a fleeing and stationary animal

Popper *et al.* (2019) Unweighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	64 km²	7.3 km	2.2 km	4.3 km
Stationary	219 dB	0.9 km²	580 m	530 m	540 m
	216 dB	2.2 km²	850 m	800 m	830 m
	210 dB	10 km²	1.9 km	1.7 km	1.8 km
	207 dB	21 km²	2.8 km	2.5 km	2.6 km
	203 dB	49 km²	4.4 km	3.7 km	4.0 km
	186 dB	670 km²	19 km	11 km	14 km

Table 4-33 Summary of the unweighted SEL_{ss} ranges using the Hawkins et al. (2014) levels for the pin pile worst case modelling scenario at the E location

Hawkins *et al.* (2014) Unweighted SEL_{ss}	**Area**	**Maximum range**	**Minimum range**	**Mean range**
135 dB	2500 km²	39 km	16 km	27 km

4.3.3 SW location

Table 4-34 Summary of the unweighted SPL_{peak} impact ranges using the Southall et al. (2019) impulsive criteria for the pin pile worst case modelling scenario at the SW location

Southall *et al.* (2019) Unweighted SPL_{peak}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	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)	0.9 km²	540 m	540 m	540 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.03 km²	100 m	100 m	100 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	5.3 km²	1.3 km	1.3 km	1.3 km
	PCW (212 dB)	0.04 km²	110 m	110 m	110 m

Table 4-35 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) impulsive criteria for the pin pile worst case modelling scenario at the SW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	7.1 km²	2.5 km	550 m	1.4 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	3.7 km²	1.5 km	600 m	1.1 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	740 km²	21 km	8.3 km	15 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	610 km²	18 km	9.1 km	14 km
	PCW (170 dB)	86 km²	6.7 km	3.4 km	5.1 km

Table 4-36 Summary of the unweighted SPL_{peak} impact ranges using the Popper et al. (2014) pile driving criteria for the pin pile worst case modelling scenario at the SW location

Popper *et al.* (2014) Unweighted SPL_{peak}	**Area**	**Maximum range**	**Minimum range**	**Mean range**
213 dB	0.03 km²	100 m	100 m	100 m
207 dB	0.19 km²	250 m	250 m	250 m

Table 4-37 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the pin pile worst case modelling scenario at the SW location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	220 km²	11 km	5.4 km	8.3 km
Stationary	219 dB	1.3 km²	650 m	630 m	640 m
	216 dB	3.1 km²	1.0 km	980 m	1.0 km
	210 dB	17 km²	2.4 km	2.3 km	2.3 km
	207 dB	36 km²	3.5 km	3.3 km	3.4 km
	203 dB	89 km²	5.6 km	5.1 km	5.3 km
	186 dB	1200 km²	22 km	15 km	19 km

Table 4-38 Summary of the unweighted SEL_{ss} ranges using the Hawkins et al. (2014) levels for the pin pile worst case modelling scenario at the SW location

Hawkins *et al.* (2014) Unweighted SEL_{ss}	**Area**	**Maximum range**	**Minimum range**	**Mean range**
135 dB	4000 km²	44 km	23 km	35 km

4.3.4 Multiple sequential pin piles

Table 4-39 to Table 4-44 present the modelling results for the worst case pin pile foundation modelling scenarios for four sequential installations in terms of the Southall *et al*. (2019) marine mammal criteria (Section 2.2.1) and the Popper *et al*. (2014) fish criteria (Section 2.2.2).

As with the monopile results, when comparing the impact ranges for single pile and sequential pile installations, the overall increases were minimal, as by the time the subsequent piles were installed, the fleeing receptor would be at such a distance that the additional exposure was minimal. The largest increases seen for these scenarios were only a few hundred metres. When considering a stationary animal, the ranges increased by considerably more as the receptor would be essentially receiving noise from quadruple the number of pile strikes.

4.3.4.1 NW location

Table 4-39 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) impulsive criteria for the multiple sequential pin pile worst case modelling scenario at the NW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	1.7 km	1.1 km	280 m	690 m
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	1.2 km²	830 m	300 m	600 m
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	570 km²	19 km	6.5 km	13 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	500 km²	16 km	7.6 km	12 km
	PCW (170 dB)	51 km²	5.0 km	2.3 km	3.9 km

Table 4-40 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the multiple sequential pin pile worst case modelling scenario at the NW location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	150 km²	8.8 km	4.0 km	6.7 km
Stationary	219 dB	5.7 km²	1.4 km	1.4 km	1.4 km
	216 dB	13 km²	2.1 km	2.0 km	2.0 km
	210 dB	54 km²	4.3 km	3.9 km	4.1 km
	207 dB	100 km²	6.0 km	5.2 km	5.7 km
	203 dB	210 km²	8.8 km	7.2 km	8.2 km
	186 dB	1,800 km²	28 km	17 km	24 km

4.3.4.2 E location

Table 4-41 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) impulsive criteria for the multiple sequential pin pile worst case modelling scenario at the E location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	0.3 km²	630 m	180 m	290 m
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	0.3 km²	550 m	150 m	280 m
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	290 km²	16 km	4.3 km	8.9 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	300 km²	14 km	5.2 km	9.3 km
	PCW (170 dB)	18 km²	4.0 km	1.2 km	2.3 km

Table 4-42 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the multiple sequential pin pile worst case modelling scenario at the E location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	65 km²	7.4 km	2.2 km	4.3 km
Stationary	219 dB	4.9 km²	1.3 km	1.2 km	1.2 km
	216 dB	10 km²	1.9 km	1.7 km	1.8 km
	210 dB	40 km²	4.0 km	3.3 km	3.6 km
	207 dB	72 km²	5.5 km	4.5 km	4.8 km
	203 dB	150 km²	8.1 km	6.2 km	6.8 km
	186 dB	1200 km²	26 km	13 km	19 km

4.3.4.3 SW location

Table 4-43 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) impulsive criteria for the multiple sequential pin pile worst case modelling scenario at the SW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	7.1 km²	2.5 km	550 m	1.4 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	3.8 km²	1.6 km	600 m	1.1 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	740 km²	21 km	8.3 km	15 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	620 km²	18 km	9.1 km	14 km
	PCW (170 dB)	88 km²	6.8 km	3.4 km	5.2 km

Table 4-44 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the multiple sequential pin pile worst case modelling scenario at the SW location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	220 km²	11 km	5.4 km	8.3 km
Stationary	219 dB	7.4 km²	1.6 km	1.5 km	1.5 km
	216 dB	17 km²	2.4 km	2.3 km	2.3 km
	210 dB	72 km²	5.0 km	4.6 km	4.8 km
	207 dB	130 km²	7.0 km	6.1 km	6.6 km
	203 dB	280 km²	10 km	8.5 km	9.4 km
	186 dB	2100 km²	31 km	19 km	25 km

4.4 Maximum strike rate scenario (worst case)

Additional underwater noise modelling has been undertaken considering further potential impact piling parameters at Morecambe OWF. Following the impact piling modelling presented in Sections 4.1 to 4.3, further investigation into scenarios using higher strike rates were identified for the monopile and pin pile scenarios. A piling hammer is capable of more rapid strikes at lower blow energies. To show the differences between the maximum strike rate scenario and the results presented in Sections 4.1 to 4.3 of the report, additional modelling has been completed for the South West (SW) location and presented here as the worst case.

The maximum strike rate scenario retained the same pile diameter and maximum blow energies but included a slow start, as well as a greater total number of pile strikes over a shorter duration resulting in faster strike rates. All other parameters for modelling have been kept consistent with the modelling in the main report.

A summary of the maximum strike rate scenario parameters is given in Table 4-45 and Table 4-46 below.

Table 4-45 Summary of the soft start and ramp up scenario used for the worst-case monopile modelling

Monopile Maximum strike rate	550 kJ		1,375 kJ	2,750 kJ	4,125 kJ	5,225 kJ	6,600 kJ
Number of strikes	10	1,067	1,601	710	551	2,012	3,405
Duration	20 minutes	10.7 minutes	18.6 minutes	9.8 minutes	9.5 minutes	45.7 minutes	113.5 minutes
Strike rate	0.5 bl/min	100 bl/min	86 bl/min	72 bl/min	58 bl/min	44 bl/min	30 bl/min
1 pile: 9,356 strikes, 3 hours 47 minutes 48 seconds duration 3 piles: 28,068 strikes, 11 hours 23 minutes 24 seconds duration							

Table 4-46 Summary of the soft start and ramp up scenario used for the worst-case pin pile modelling

Pin pile Maximum strike rate	250 kJ		625 kJ	1,250 kJ	1,875 kJ	2,375 kJ	2,500 kJ
Number of strikes	10	1,067	1,601	710	551	500	3,405
Duration	20 minutes	10.7 minutes	18.6 minutes	9.8 minutes	9.5 minutes	11.3 minutes	113.5 minutes
Strike rate	0.5 bl/min	100 bl/min	86 bl/min	72 bl/min	58 bl/min	44 bl/min	30 bl/min
1 pile: 7,844 strikes, 3 hours 13 minutes 24 seconds duration 4 piles: 31,376 strikes, 12 hours 53 minutes 36 seconds duration							

The following sections present the impact ranges for the maximum strike rate scenario at the SW location, the deepest location, as a sensitivity test. As the modelling location, pile diameters and maximum blow energies remained the same as the main report, only the results for the SEL_{cum} criteria have been presented, as the single strike results will also remain the same.

The modelled results show an increase in all ranges compared to the main modelling, most noticeably for the fleeing animal scenarios where, due to the maximum strike rate parameters, more pile strikes occurred while a receptor was closer to the pile at the start of the impact piling operations. This was also why there were only minimal increases for fleeing animals when multiple sequential piles were considered.

4.4.1 Monopile foundations

Table 4-47 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) impulsive criteria for the monopile maximum strike rate modelling scenario at the SW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	330 km^2	13 km	6.5 km	10 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	150 km^2	8.1 km	5.6 km	6.9 km
	PCW (185 dB)	1.9 km^2	950 m	600 m	770 m
TTS	LF (168 dB)	2,100 km^2	34 km	15 km	25 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	1,400 km^2	26 km	15 km	21 km
	PCW (170 dB)	500 km^2	15 km	9.6 km	13 km

Table 4-48 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) non-impulsive criteria for the monopile maximum strike rate modelling scenario at the SW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	630 km^2	18 km	8.9 km	14 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	230 km^2	10 km	6.8 km	8.6 km
	PCW (181 dB)	30 km^2	3.5 km	2.6 km	3.1 km

Table 4-49 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the monopile maximum strike rate modelling scenario at the SW location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing	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	6.0 km^2	1.7 km	1.1 km	1.4 km
	186 dB	780 km^2	19 km	11 km	16 km
Stationary	219 dB	2.9 km^2	980 m	950 m	960 m
	216 dB	7.0 km^2	1.5 km	1.5 km	1.5 km
	210 dB	34 km^2	3.4 km	3.2 km	3.3 km
	207 dB	68 km^2	4.9 km	4.5 km	4.7 km
	203 dB	160 km^2	7.6 km	6.5 km	7.1 km
	186 dB	1,600 km^2	26 km	17 km	22 km

4.4.2 Multiple sequential monopiles

Table 4-50 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) impulsive criteria for the maximum strike rate scenario for multiple sequential monopiles at the SW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	330 km²	13 km²	6.5 km	10 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	150 km²	8.2 km	5.6 km	7.0 km
	PCW (185 dB)	2.0 km²	980 m	600 m	780 m
TTS	LF (168 dB)	2,100 km²	34 km	15 km	25 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	1,500 km²	27 km	15 km	21 km
	PCW (170 dB)	510 km²	15 km	9.6 km	13 km

Table 4-51 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) non-impulsive criteria for the maximum strike rate scenario for multiple sequential monopiles at the SW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	LF (179 dB)	630 km²	18 km	8.9 km	14 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	240 km²	10 km	6.8 km	8.6 km
	PCW (181 dB)	30 km²	3.6 km	2.6 km	3.1 km

Table 4-52 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the maximum strike rate scenario for multiple sequential monopiles at the SW location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	6.2 km²	1.7 km	1.1 km	1.4 km
	186 dB	790 km²	19 km	11 km	16 km
Stationary	219 dB	11 km²	2.0 km	1.9 km	1.9 km
	216 dB	25 km²	2.9 km	2.8 km	2.8 km
	210 dB	100 km²	6.0 km	5.4 km	5.6 km
	207 dB	180 km²	8.2 km	7.0 km	7.6 km
	203 dB	360 km²	12 km	9.4 km	11 km
	186 dB	2,400 km²	33 km	20 km	27 km

4.4.3 Pin pile foundations

Table 4-53 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) impulsive criteria for the pin pile maximum strike rate modelling scenario at the SW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	150 km^2	8.9 km	4.1 km	6.7 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	60 km^2	5.1 km	3.6 km	4.4 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	1,500 km^2	29 km	6.4 km	10 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	1,000 km^2	22 km	13 km	18 km
	PCW (170 dB)	330 km^2	12 km	7.9 km	10 km

Table 4-54 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) non-impulsive criteria for the pin pile maximum strike rate modelling scenario at the SW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	350 km^2	14 km	6.4 km	10 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	110 km^2	6.8 km	4.7 km	5.8 km
	PCW (181 dB)	6.9 km^2	1.8 km	1.2 km	1.5 km

Table 4-55 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the pin pile maximum strike rate modelling scenario at the SW location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing	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	470 km^2	15 km	9.0 km	12 km
Stationary	219 dB	1.0 km^2	580 m	550 m	560 m
	216 dB	2.5 km^2	900 m	880 m	890 m
	210 dB	14 km	2.1 km	2.0 km	2.1 km
	207 dB	29 km	3.2 km	3.0 km	3.1 km
	203 dB	75 km^2	5.1 km	4.7 km	4.9 km
	186 dB	1,100 km	21 km	15 km	19 km

4.4.4 Multiple sequential pin piles

Table 4-56 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) impulsive criteria for the maximum strike rate scenario for multiple sequential pin piles at the SW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (183 dB)	150 km²	8.9 km	4.1 km	6.7 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	61 km²	5.2 km	3.6 km	4.4 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	1,500 km²	29 km	13 km	21 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	1,000 km²	22 km	13 km	18 km
	PCW (170 dB)	340 km²	12 km	7.9 km	10 km

Table 4-57 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) non-impulsive criteria for the maximum strike rate scenario for multiple sequential pin piles at the SW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	LF (179 dB)	350 km²	14 km	6.4 km	10 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	110 km²	6.9 km	4.7 km	5.9 km
	PCW (181 dB)	7.2 km²	1.8 km	1.2 km	1.5 km

Table 4-58 Summary of the unweighted SEL_{cum} impact ranges using the Popper et al. (2014) pile driving criteria for the maximum strike rate scenario for multiple sequential pin piles at the SW location assuming both a fleeing and stationary animal

Popper *et al.* (2014) Unweighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
Fleeing	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m
	186 dB	480 km²	15 km	9.0 km	12 km
Stationary	219 dB	5.9 km²	1.4 km	1.4 km	1.4 km
	216 dB	14 km²	2.1 km	2.1 km	2.1 km
	210 dB	60 km²	4.6 km	4.2 km	4.4 km
	207 dB	110 km²	6.4 km	5.7 km	6.1 km
	203 dB	240 km²	9.6 km	8.0 km	8.8 km
	186 dB	1,900 km²	30 km	19 km	25 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 have 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 Morecambe OWF.

Table 5-1 Summary of the possible noise making activities at Morecambe OWF 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.
Trenching	Plough trenching may be required during offshore cable installation.
Rock placement	Potentially required on site for installation of offshore cables (cable crossings and cable protection) and scour protection around foundation structures.
Vibro-piling	There is the potential for a vibratory hammer to be used to install foundation piles or sheet piles for coffer dams, etc.
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 guard duties, 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 12 and 24 MW.
UXO clearance	There is a possibility that Unexploded Ordnance (UXO) may exist within the boundaries of Morecambe OWF, which would need to be cleared before construction can begin.

The NPL Good Practice Guide 133 for underwater noise measurements (Robinson *et al*., 2014) indicated 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 large operation WTG noise or UXO detonation). The high-level overview of modelling that has been presented here was considered sufficient and there would be little benefit in using a more detailed model at this stage. The limitations of this approach have been noted, including the lack of frequency or bathymetric dependence.

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.

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 was based on an empirical analysis of the noise measurements taken along transects around these sources by Subacoustech Environmental. The predictions used 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 apparent 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 used 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 noted that this modelling approach did not take bathymetry or any other environmental conditions into account, and as such could be applied to any location at, or surrounding Morecambe OWF.

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

Source	Estimated unweighted apparent source level	Approximate transmission loss	Comments
Cable laying	171 dB re 1 µPa @ 1 m (RMS)	$13\log_{10} R$ (no absorption)	Based on 11 datasets from a pipe laying vessel measuring 300 m in length; this was considered a worst-case noise source for cable laying operations
Suction dredging	186 dB re 1 µPa @ 1 m (RMS)	$19\log_{10} R + 0.0009R$	Based on five datasets from suction and cutter suction dredgers
Trenching	172 dB re 1 µPa @ 1 m (RMS)	$13\log_{10} R + 0.0004R$	Based on three datasets of measurements from trenching vessels more than 100 m in length
Rock placement	172 dB re 1 µPa @ 1 m (RMS)	$12\log_{10} R + 0.0005R$	Based on four datasets from rock placement vessel '*Rollingstone'*
Vibropiling	193 dB re 1 µPa @ 1 m (RMS)	$18\log_{10} R$ (no absorption)	Based on four datasets from vibro-piling installation of sheet piles and tubular piles
Vessel noise (large)	168 dB re 1 µPa @ 1 m (RMS)	$12\log_{10} R + 0.0021R$	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)	$12\log_{10} R + 0.0021R$	Based on three datasets of moderate sized vessels less than 100 m in length. Vessel speed assumed as 10 knots

For SEL_{cum} calculations, the duration the noise 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.

To account for the weightings required for modelling using the Southall *et al*. (2019) criteria (see section 2.2.1), reductions in apparent source level have been applied to the various noise sources. Figure 5-1 shows the representative noise measurements used, which have been adjusted for the apparent source levels given in Table 5-2. Table 5-3 presents details of the reductions in apparent source levels for each of the weightings used for modelling.

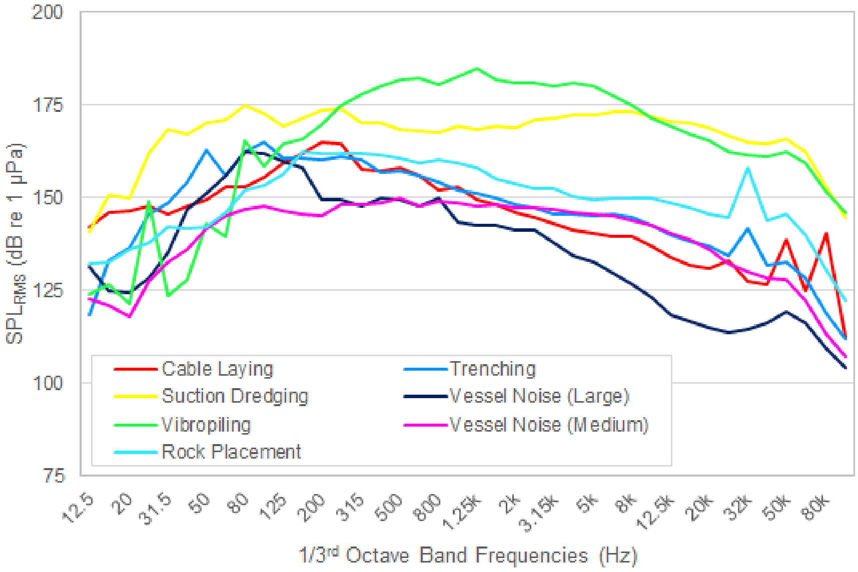

Figure 5-1 Summary of the 1/3rd octave frequency bands to which the Southall et al. (2019) weightings were applied in the simple modelling

Table 5-3 Reductions in apparent source level for the different construction noise sources considered when the Southall et al. (2019) weightings were 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
Suction Dredging	2.5 dB	7.9 dB	9.6 dB	4.2 dB
Trenching	4.1 dB	23.0 dB	25.0 dB	13.7 dB
Rock placement	1.6 dB	11.9 dB	12.5 dB	8.2 dB
Vibropiling	2.4 dB	16.0 dB	20.8 dB	4.4 dB
Vessel noise	5.5 dB	34.4 dB	38.6 dB	17.4 dB

Table 5-4 and Table 5-5 summarise the predicted impact range for these noise sources. All the sources in this section have been considered non-impulsive or continuous.

Given the modelled impact ranges, any marine mammal would have to be closer than 100 m from the continuous noise source at the start of the activity in most cases to acquire the necessary exposure to induce PTS as per Southall *et al*. (2019). The exposure calculation assumed 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 reached the 'onset' stage at these ranges, which was 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 were low enough that there would be a minimal risk.

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

All sources presented here resulted in much quieter levels than those presented for impact piling in Section 4.

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

Southall *et al.* (2019) Weighted SEL_{cum}		**Cable laying**	**Suction dredging**	**Trench-ing**	**Rock place-ment**	**Vibro piling**	**Vessels (large)**	**Vessels (medium)**
PTS	199 dB (LF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	198 dB (HF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	173 dB (VHF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	201 dB (PCW)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
TTS	179 dB (LF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	178 dB (HF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	153 dB (VHF)	< 100 m	230 m	< 100 m	990 m	210 m	< 100 m	< 100 m
	181 dB (PCW)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-5 Summary of the impact ranges for fish from Popper et al. (2014) for shipping and continuous noise, covering the different construction noise sources

Popper *et al.* (2014) Unweighted SPL_{RMS}	**Cable laying**	**Suction dredging**	**Trench-ing**	**Rock place-ment**	**Vibro piling**	**Vessels (large)**	**Vessels (medium)**
Recoverable injury 170 dB (48 hours)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
TTS 158 dB (12 hours)	< 50 m	< 50 m	< 50 m	< 50 m	90 m	< 50 m	< 50 m

5.2 Operational WTG noise

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

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

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

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

WTGs measuring between 12 and 24 MW have been modelled to give the greatest range of impacts, noting the size of the wind turbines for Morecambe would be determined post-consent.

The maximum turbine sizes considered at Morecambe OWF are much larger than those used for the estimation above, so caution must be used when considering the results presented in this section. Figure 5-2 presents a level against range plot for the two turbine sizes using the Tougaard *et al*. (2020) calculation, assuming an average 6 ms^{-1} wind speed. Although wind speeds (and thus operational noise levels) may be greater than this, this will not represent the typical condition. It is also worth noting that the background noise level will also naturally increase, somewhat offsetting any additional impact this may have.

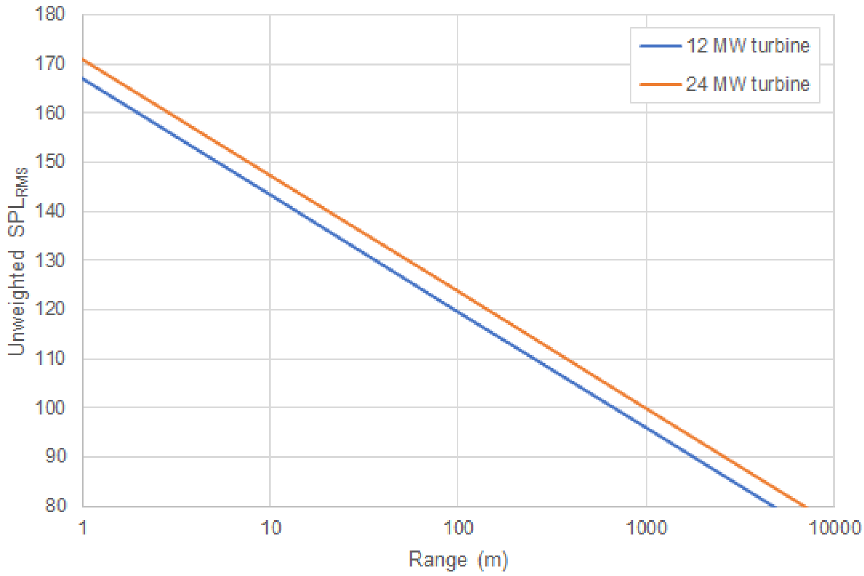

Figure 5-2 Predicted unweighted SPL_{RMS} from operational WTGs with power outputs of 12 MW and 24 MW using the calculation from Tougaard et al. (2020)

Using this data, a summary of the predicted impact ranges has been produced, shown in Table 5-6 and Table 5-7. 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 was considered a non-impulsive or continuous source. For SEL_{cum} calculations it has been assumed that the operational WTG noise would be present 24 hours a day.

Table 5-6 Summary of the operational WTG noise impact ranges using the non-impulsive noise criteria from Southall et al. (2019) for marine mammals

Southall *et al*. (2019) Weighted SEL_{cum}		**Operational WTG (12 MW)**	**Operational WTG (24 MW)**
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 5-7 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 (12 MW)**	**Operational WTG (24 MW)**
Recoverable injury 170 dB (48 hours) Unweighted SPL_{RMS}	< 50 m	< 50 m
TTS 158 dB (12 hours) Unweighted SPL_{RMS}	< 50 m	< 50 m

These results show that, for operational WTGs, injury risk would be minimal. Increasing the wind speed would not lead to significant increases in the impact ranges. 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 would result in much greater noise levels and impact ranges, and hence should be considered the activity which has the potential to have the greatest effect during the construction and lifecycle of Morecambe OWF.

5.3 UXO clearance

It is possible that UXO devices with a range of charge weights (or quantity of contained explosive) are present within the boundaries of Morecambe OWF. These may 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 detonates with the clearance.

5.3.1 Estimation of underwater noise levels

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 has been based on the equivalent weight of TNT (the Net Explosive Quantity, NEQ). 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.

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

The potential UXO devices within the windfarm site are given in Table 5-8 based on desk studies.

Table 5-8 UXO devices potentially present at the Morecambe OWF site

UXO item	**Ferrous Mass**	**NEQ**
18” Mark XVII Torpedo (5,268 mm x 450 mm)	578.0 kg	353.6 kg
18” Mark XV Torpedo (5,251 mm x 450 mm	570.0 kg	321.1 kg
18” Mark XII Torpedo (4,953 mm x 450 mm)	526.0 kg	176.0 kg
3” Rocket Projectile (554 mm x 152 mm)	21.8 kg	5.45 kg
250 lb Mark XI Depth Charge (940 mm x 279 mm)	40.8 kg	103.2 kg
250 lb Mark VIII Depth Charge (969 mm x 279 mm)	40.8 kg	72.6 kg

In each case an additional donor weight of 0.5 kg has been included to initiate detonation. Low-order deflagration has also been assessed, which assumes that the donor or shaped charge (charge weight of 0.5 kg) detonates fully to initiate a burnout of the explosive but without the follow-up detonation of the UXO. No mitigation has been considered for this modelling.

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 followed Arons (1954) and the Marine Technical Directorate Ltd (MTD) (1996).

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 North Sea and Irish Sea. This uses standard frequency-based absorption coefficients for the seawater conditions expected in the region.

Despite this attenuation correction, the resulting noise levels still need to be considered carefully. For example, SPL_{peak} noise levels over larger distances are difficult to predict accurately (von Benda-Beckmann *et al*., 2015). Soloway and Dahl (2014) only verify results from the equation above for small charges at ranges of less than 1 km, although the results were 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 has been 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 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 (NEQ)	0.5kg	5.45kg + donor	72.6kg + donor	103.2kg + donor	176.0kg + donor	321.1kg + donor	353.6kg + donor
SPL_{peak} source level (dB re 1 µPa @ 1 m)	272.1	280.2	288.4	289.5	291.2	293.2	293.5
SEL_{ss} source level (dB re 1 µPa²s @ 1 m)	217.1	223.9	230.9	231.9	233.3	235.0	235.3

5.3.3 Impact ranges

Table 5-10 to Table 5-13 present the impact ranges for UXO detonation, considering various charge weights and impact criteria. It should be noted that Popper *et al*. (2014) gave specific impact criteria for explosions (Table 2-6). A UXO detonation source is defined as a single pulse, and as such the SEL_{cum} criteria from Southall *et al*. (2019) have been given as SEL_{ss} in the tables below. Thus, fleeing animal assumptions do not apply. As with the previous sections, ranges smaller than 50 m have not been presented.

Although the impact ranges presented in Table 5-10 to Table 5-13 were large, the duration the noise would be 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}		0.5kg	5.45kg + donor	72.6kg + donor	103.2kg + donor	176.0kg + donor	321.1kg + donor	353.6kg + donor
PTS	219 dB (LF)	220 m	500 m	1.1 km	1.3 km	1.5 km	1.9 km	1.9 km
	230 dB (HF)	70 m	160 m	380 m	420 m	510 m	620 m	640 m
	202 dB (VHF)	1.2 km	2.8 km	6.6 km	7.4 km	8.8 km	10 km	11 km
	218 dB (PCW)	240 m	560 m	1.2 km	1.4 km	1.7 km	2.1 km	2.1 km
TTS	213 dB (LF)	410 m	930 m	2.1 km	2.4 km	2.8 km	3.5 km	3.6 km
	230 dB (HF)	130 m	300 m	700 m	790 m	940 m	1.1 km	1.1 km
	196 dB (VHF)	2.3 km	5.2 km	12 km	13 km	16 km	19 km	20 km
	212 dB (PCW)	450 m	1.0 km	2.3 km	2.6 km	3.2 km	3.9km	4.0 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}		0.5kg	5.45kg + donor	72.6kg + donor	103.2kg + donor	176.0kg + donor	321.1kg + donor	353.6kg + donor
PTS	183 dB (LF)	320 m	1.0 km	3.6 km	4.3 km	5.6 km	7.5 km	7.9 km
	185 dB (HF)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
	155 dB (VHF)	110 m	320 m	820 m	910 m	1.0 km	1.2 km	1.3 km
	185 dB (PCW)	60 m	190 m	650 m	770 m	1.0 km	1.3 km	1.4 km
TTS	168 dB (LF)	4.5 km	14 km	46 km	53 km	67 km	85 km	89 km
	170 dB (HF)	< 50 m	80 m	240 m	280 m	350 m	440 m	460 m
	140 dB (VHF)	930 m	1.8 km	2.9 km	3.1 km	3.4 km	3.7 km	3.7 km
	170 dB (PCW)	800 m	2.6 km	8.5 km	9.9 km	12 km	16 km	16 km

Table 5-12 Summary of the PTS and TTS impact ranges for UXO detonation using the non-impulsive, weighted SEL_{ss} noise criteria from Southall et al. (2019) for marine mammals

Southall *et al.* (2019) Weighted SEL_{ss}		**0.5kg**	**5.45kg + donor**	**72.6kg + donor**	**103.2kg + donor**	**176.0kg + donor**	**321.1kg + donor**	**353.6kg + donor**
PTS	199 dB (LF)	< 50 m	60 m	210 m	260 m	330 m	450 m	470 m
	198 dB (HF)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 50 m	< 50 m	60 m	70 m	80 m	110 m	110 m
	201 dB (PCW)	< 50 m	< 50 m	< 50 m	< 50 m	60 m	80 m	80 m
TTS	179 dB (LF)	650 m	2.1 km	7.4 km	8.7 km	11 km	14 km	15 km
	178 dB (HF)	< 50 m	< 50 m	70 m	80 m	100 m	130 m	130 m
	153 dB (VHF)	150 m	430 m	1.0 km	1.1 km	1.3 km	1.5 km	1.5 km
	181 dB (PCW)	110 m	380 m	1.3 km	1.5 km	2.0 km	2.6 km	2.8 km

Table 5-13 Summary of the impact ranges for UXO detonation using the unweighted SPL_{peak} explosion noise criteria from Popper et al. (2014) for all species of fish

Popper *et al.* (2014) Unweighted SPL_{peak}		**0.5kg**	**5.45kg + donor**	**72.6kg + donor**	**103.2kg + donor**	**176.0kg + donor**	**321.1kg + donor**	**353.6kg + donor**
Mortality & potential mortal injury	234 dB	< 50 m	110 m	250 m	280 m	340 m	410 m	430 m
	229 dB	80 m	180 m	420 m	470 m	560 m	690 m	710 m

5.3.4 Summary

The maximum PTS range calculated for UXO was 11 km for the VHF cetacean category, when considering the unweighted SPL_{peak} criteria. For SEL_{ss} criteria, the largest PTS range was calculated for LF cetaceans with a predicted impact of 7.9 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 was very precautionary. Although an assumption of non-pulse could under-estimate the potential impact (Martin *et al*. 2020) (the equivalent range based on LF cetacean non-pulse criteria was 470 m), it is likely that the long-range smoothing of the pulse peak would reduce its potential harm and the maximum 'impulsive' range for all species was very precautionary.

6 Summary and conclusions

Subacoustech Environmental have undertaken a study on behalf of Royal HaskoningDHV UK Ltd. to assess the potential underwater noise and its effects during construction and operation of the generation assets of the proposed Morecambe OWF, located in the east Irish Sea.

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

Three representative modelling locations were chosen to give spatial variation as well as account for changes in water depth around the site. At each location two modelling scenarios were considered:

- A worst-case monopile scenario, with a maximum blow energy of 6,600 kJ; and
- A worst-case pin pile scenario, with a maximum blow energy of 2,500 kJ.

Up to three monopiles or four pin piles could be installed in a 24-hour period.

The loudest levels of noise and greatest impact ranges have been predicted for the worst case monopile scenario at the SW location.

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

For marine mammals, maximum PTS ranges were predicted for LF cetaceans, with ranges of up to 5.0 km based on the worst case monopile scenario. For fish, the largest recoverable injury ranges were predicted to be less than 100 m for a fleeing receptor, increasing to 10.0 km for a stationary receptor, continuously exposed to piling for its whole duration without moving.

When comparing impact ranges for a single pile installation and sequential pile installations the overall increases were minimal when considering a fleeing animal.

Noise sources other than piling were considered using a high-level, simple modelling approach, including cable laying, trenching, rock placement, drilling, dredging, vessel noise and operational WTG noise. The predicted noise levels for the other construction noise sources and during WTG operation were well below those predicted for impact piling noise. The risk of any potentially injurious effects to fish or marine mammals from these sources were 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 Morecambe OWF site, and for the expected UXO clearance noise, there was a risk of PTS out to 11 km for the largest UXO device considered, using the unweighted SPL_{peak} criteria for VHF cetaceans. However, this is likely to be precautionary as the impact range has been 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, including the worst case for cumulative (multiple strikes) impacts (Appendix B) have been used to inform analysis of the impacts of underwater noise on marine mammals and fish in their respective reports.

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Appendix A Additional modelling results (non-impulsive)

Following from the Southall *et al*. (2019) modelled impact piling ranges presented in Section 4 of the main report, the modelling results for non-impulsive criteria from impact piling noise at Morecambe OWF, as discussed in Section 2.2.1, are presented below. The predicted ranges here fall well below the impulsive criteria presented in the main report.

Table A 1 to Table A 12 present the modelling results considering the non-impulsive Southall *et al*. (2019) criteria.

Table A 1 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) non-impulsive criteria for the monopile worst case modelling scenario at the NW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	LF (179 dB)	91 km²	7.2 km	2.9 km	5.2 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	30 km²	3.7 km	2.0 km	3.0 km
	PCW (181 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m

Table A 2 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) non-impulsive criteria for the monopile worst case modelling scenario at the E location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	LF (179 dB)	19 km²	3.5 km	1.8 km	2.4 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	12 km²	3.1 km	1.2 km	1.9 km
	PCW (181 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m

Table A 3 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) non-impulsive criteria for the monopile worst case modelling scenario at the SW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	LF (179 dB)	150 km²	9.4 km	4.0 km	6.7 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	48 km²	4.9 km	2.7 km	3.9 km
	PCW (181 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m

Table A 4 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) non-impulsive criteria for the multiple sequential monopile worst case modelling scenario at the NW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	91 km^2	7.2 km	2.9 km	5.2 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	30 km^2	3.8 km	2.0 km	3.0 km
	PCW (181 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m

Table A 5 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) non-impulsive criteria for the multiple sequential monopile worst case modelling scenario at the E location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	19 km^2	3.5 km	1.8 km	2.4 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	12 km^2	3.1 km	1.2 km	1.9 km
	PCW (181 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m

Table A 6 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) non-impulsive criteria for the multiple sequential monopile worst case modelling scenario at the SW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	150 km^2	9.4 km	4.0 km	6.7 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	49 km^2	5.0 km	2.7 km	3.9 km
	PCW (181 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m

Table A 7 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) non-impulsive criteria for the pin pile worst case modelling scenario at the NW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	LF (179 dB)	32 km²	4.5 km	1.3 km	3.0 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	7.8 km²	2.0 km	830 m	1.5 km
	PCW (181 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m

Table A 8 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) non-impulsive criteria for the pin pile worst case modelling scenario at the E location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	LF (179 dB)	8.2 km²	3.3 km	630 m	1.4 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	2.1 km²	1.5 km	400 m	760 m
	PCW (181 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m

Table A 9 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) non-impulsive criteria for the pin pile worst case modelling scenario at the SW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	LF (179 dB)	64 km²	6.6 km	2.1 km	4.3 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	17 km²	3.0 km	1.5 km	2.3 km
	PCW (181 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m

Table A 10 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) non-impulsive criteria for the multiple sequential pin pile worst case modelling scenario at the NW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	LF (179 dB)	32 km²	4.5 km	1.3 km	3.0 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	8.0 km²	2.0 km	830 m	1.5 km
	PCW (181 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m

Table A 11 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) non-impulsive criteria for the multiple sequential pin pile worst case modelling scenario at the E location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	LF (179 dB)	8.2 km²	3.3 km	630 m	1.4 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	2.2 km²	1.5 km	400 m	760 m
	PCW (181 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m

Table A 12 Summary of the weighted SEL_{cum} impact ranges using the Southall et al. (2019) non-impulsive criteria for the multiple sequential pin pile worst case modelling scenario at the SW location assuming a fleeing animal

Southall *et al.* (2019) Weighted SEL_{cum}		**Area**	**Maximum range**	**Minimum range**	**Mean range**
PTS	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	LF (179 dB)	64 km²	6.6 km	2.1 km	4.3 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	17 km²	3.1 km	1.5 km	2.3 km
	PCW (181 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m

Appendix B Baseline ambient noise

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

Outside of the naturally occurring ambient noise, anthropogenic noise dominates the background. The Irish Sea is heavily shipped by fishing, cargo, and passenger vessels, which contribute to the ambient noise in the water. The larger vessels are not only louder, but the noise tends to have a lower frequency, which travels more readily, especially in the deeper open water. Other vessels such as dredgers and small fishing boats have a lower overall contribution. There are no known dredging areas, active dredge zones, or dredging application options or prospective dredging areas within the windfarm site, with the nearest aggregate production area being 9.7km away (Liverpool Bay aggregate production area (Area 457)).

Other sources of anthropogenic noise include oil and gas platforms, other drilling activity and military exercises and operational windfarms. Drilling, including oil and gas drilling, may contribute some low frequency noise at the region around the windfarm site, although due to its low-level nature, this is unlikely to contribute to the overall ambient noise. Little information is available on the scope and timing of military exercises, but they are not expected to last for an extended period and so would make little contribution to the long-term ambient noise in the area. Operational windfarms have a very localised disturbance effect and are not generally audible outside the array area Holme *et al*. (2023); therefore, they are unlikely to contribute to the overall ambient noise.

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

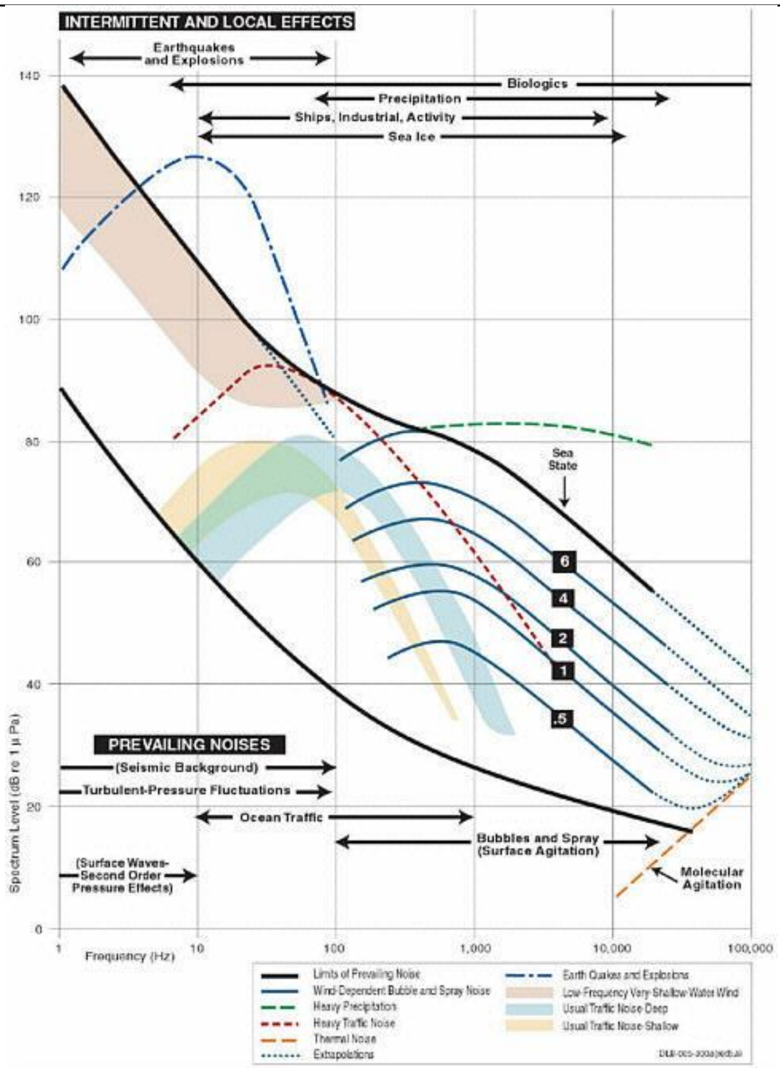

Figure B-1 Ambient underwater noise following Wenz (1962) showing frequency dependency from different noise sources

Searching Subacoustech's underwater noise measurement database showed a comprehensive baseline noise survey was undertaken in the Irish Sea using an underwater noise monitoring station installed in the middle of the Burbo Bank Extension Offshore Wind Farm (OWF) (approximately 29km from the Project), which continuously monitored the ambient noise levels between 23rd March 2016 and 25th April 2016. The measurements taken during this survey identified the main contributing sources of noise that make up the ambient noise environment in the vicinity. Although this survey was undertaken in 2016, it is expected to represent a reasonable approximation of the subsea noise levels in the Irish Sea regions.

The overview of the entire monitoring period in Figure B-2 below shows that the range of underwater noise levels typically lay, with isolated exceptions, between 95 dB and 130 Decibel (dB) re 1 µPa Sound Pressure Level Root Mean Squared (SPL_{RMS}) (displayed as 10-minute averages). Although there were clear instances of times when the noise levels reached or approached the upper and lower extremes on most days, a trend can be identified when looking at this timeframe. The logarithmic average noise level over this period was 120.4 dB re 1 µPa SPL_{RMS}.

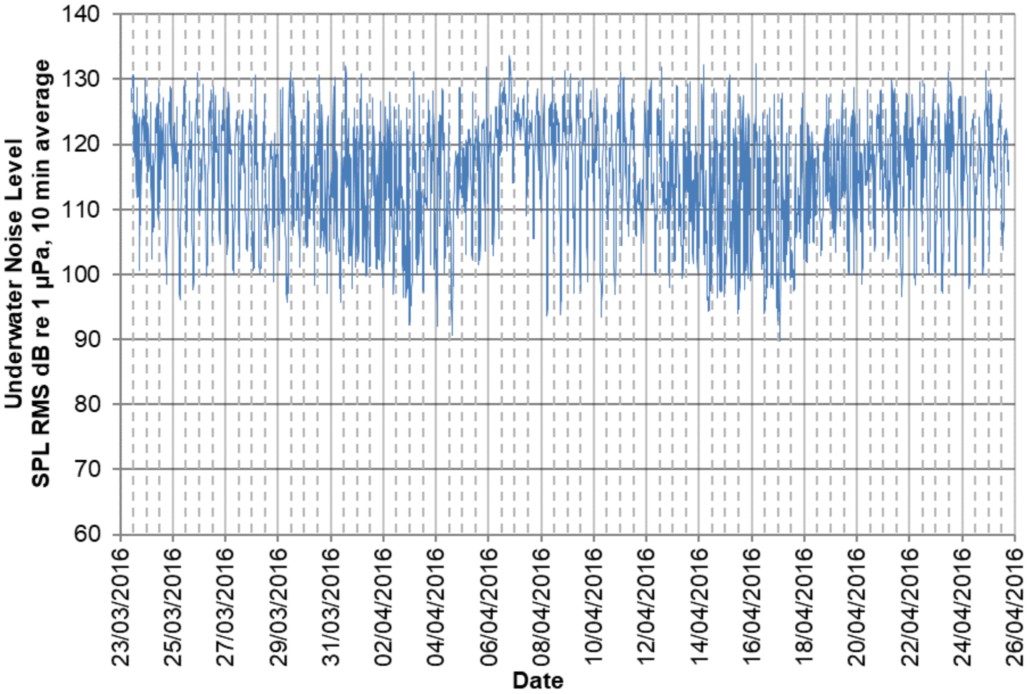

Figure B-2 Overall sampled underwater noise levels at Burbo Bank Extension site, March-April 2016

Two primary sources influenced the noise levels in the Irish Sea: flow-related noise associated with tides moving material on the seabed and vessel noise. The highest noise levels recorded above were produced at times of greatest currents and the passing of vessels, whereas the quietest noise levels were at slack water with no significant anthropogenic influence.

Another underwater noise dataset was recorded at Gwynt y Môr OWF (approximately 29km from the Project) over four days in August 2012 during construction of the OWF, but in the absence of, and away from any specific construction activity in the vicinity. Noise levels were measured on a survey vessel and were 88 – 132 dB SPL_{RMS} with mean daily noise levels of 92 – 119 dB SPL_{RMS}. This was lower than that measured at the Burbo Bank Extension site, although benefited from being measured while drifting on the vessel, which minimised any flow noise on the hydrophone.

In principle, when noise introduced by anthropogenic sources propagates far enough it will reduce to the level of ambient noise, at which point it can be considered negligible. In practice, as the underwater noise thresholds defined by Southall *et al.* (2019) and Popper *et al.* (2014) were all considerably above the level of background noise, any noise baseline would not influence an assessment to these criteria.

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P318R0100	02	23/06/2022	Initial writing and internal review
P318R0101	-	19/07/2022	Corrected minor formatting error
P318R0102	01	20/07/2022	Updates following client comments
P318R0103	02	06/12/2022	Updates to modelling parameters
P318R0104	-	21/06/2023	Issue to client
P318R0105	-	22/06/2023	Addition of section 3.2.5
P318R0106	-	22/11/2023	Updates following stakeholder comments and maximum strike rate scenario results added as Appendix B.
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