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Awel y Môr Offshore Wind Farm: 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 micropascal (µPa). The dB symbol is followed by a second symbol identifying the specific reference value (e.g., re 1 µPa).
Peak pressure	The highest pressure above or below ambient that is associated with a sound wave.
Peak-to-peak pressure	The sum of the highest positive and negative pressures that are associated with a sound wave.
Permanent Threshold Shift (PTS)	A permanent total or partial loss of hearing caused by acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the air, and thus a permanent reduction of hearing acuity.
Root Mean Square (RMS)	The square root of the arithmetic average of a set of squared instantaneous values. Used for presentation of an average sound pressure level.
Sound Exposure Level (SEL)	The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.
Sound Exposure Level, cumulative (SEL_{cum})	Single value for the collected, combined total of sound exposure over a specified time or multiple instances of a noise source.
Sound Exposure Level, single strike (SEL_{ss})	Calculation of the sound exposure level representative of a single noise impulse, typically a pile strike.
Sound Pressure Level (SPL)	The sound pressure level is an expression of sound pressure using the decibel (dB) scale; the standard frequency pressures of which are 1 µPa for water and 20 µPa for air.
Sound Pressure Level Peak (SPL_{peak})	The highest (zero-peak) positive or negative sound pressure, in decibels.
Temporary Threshold Shift (TTS)	Temporary reduction of hearing acuity because of exposure to sound over time. Exposure to high levels of sound over relatively short time periods could cause the same amount of TTS as exposure to lower levels of sound over longer time periods. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory cells. The duration of TTS varies depending on the nature of the stimulus.
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

The Awel y Môr Offshore Wind Farm (AyM) is a sister project to the existing Gwynt y Môr Offshore Wind Farm (GyM) located off the north coast of Wales in the southern Irish Sea. As part of the Environmental Impact Assessment (EIA) process, Subacoustech Environmental Ltd. have undertaken detailed underwater noise modelling and analysis in relation to marine mammals and fish at the AyM site.

AyM is situated 10.6 km form the Welsh coast at its closest point and is located to the west of the existing GyM site and has a proposed capacity of greater than 100 MW. The location of AyM is shown in Figure 1.

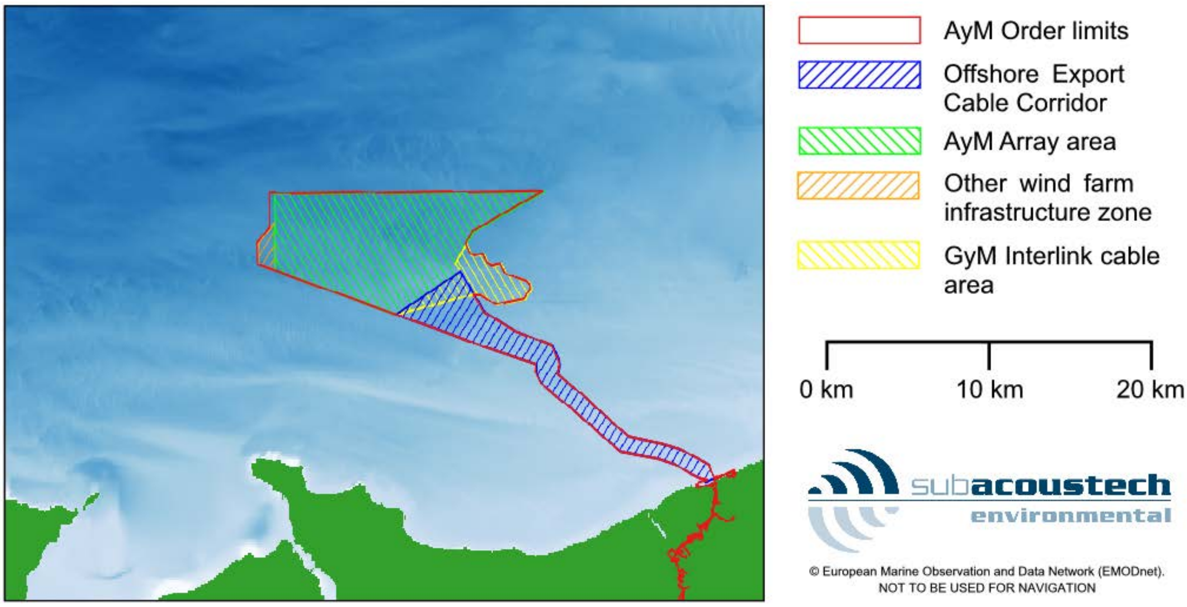

Figure 1: Overview map showing the AyM site boundary, the offshore export cable corridor, and the surrounding bathymetry

This report presents a detailed assessment of the potential underwater noise during the construction and operation of AyM and its effects, and covers the following:

- A review of background information of 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);
- A brief description of baseline ambient noise (Section 3);
- Discussion of the approach, input parameters and assumptions for the detailed noise modelling undertaken (Section 4);
- Presentation and interpretation of the detailed subsea noise modelling for impact piling with regards to the effects in marine mammals and fish using various metrics and criteria (Section 5);
- Noise modelling of the other noise sources expected around construction and operation of AyM including cable laying, rock placement, dredging, trenching, vessel activity, operational Wind Turbine Generator (WTG) noise, and Unexploded Ordnance (UXO) detonation (Section 6); and
- Summary and conclusions (Section 7).

Further modelling of the non-impulsive criteria for impact piling are provide in Appendix A of this report.

2 Background to underwater noise metrics

2.1 Underwater noise

Sound travels much faster in water (approximately 1,500 m/s) than in air (340 m/s). 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 having an equal increase in effect, typically each doubling of sound level will cause a roughly equal increase of "loudness."

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

The fundamental definition of the dB scale is given by:

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

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

The dB scale represents a ratio, 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.

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

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).

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 and Southall *et al*., 2019).

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 the sound in seconds, and t is the 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}.

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 at the AyM area.

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

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

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

2.2.1 Marine mammals

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

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

Table 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 kH	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)

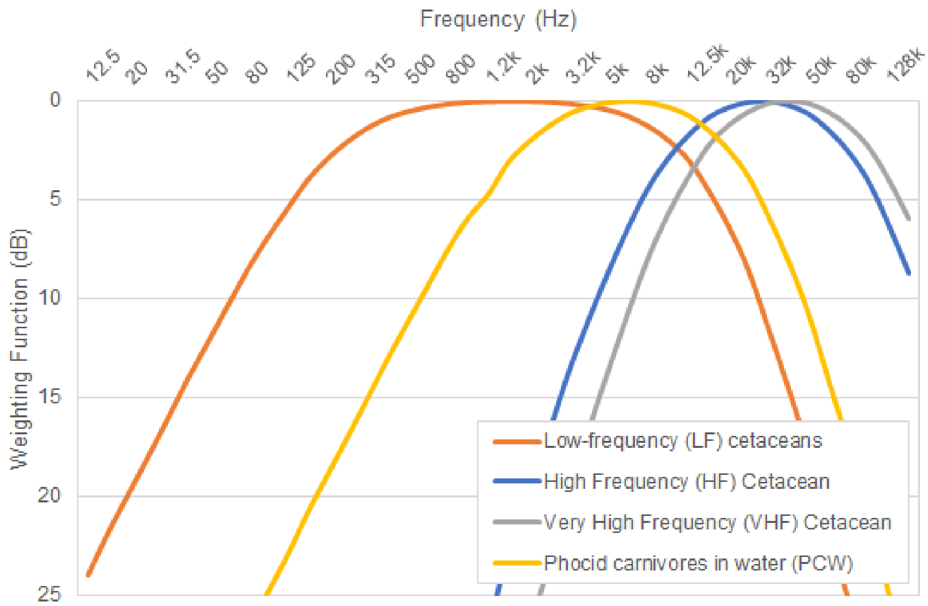

Figure 2: Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al., 2019)

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

Southall *et al*. (2019) presents single strike, unweighted peak criteria (SPL_{peak}) and cumulative (i.e., more than a single sound impulse) weighted sound exposure criteria (SEL_{cum}) for both permanent threshold shift (PTS), where unrecoverable hearing damage may occur, and temporary threshold shift (TTS), where a temporary reduction in hearing sensitivity may occur in individual receptors.

As sound pulses propagate through the environment and dissipate, they also lose their most injurious characteristics (e.g., rapid pulse rise time and high peak sound pressure) and become more like a "non-pulse" at greater distances; Southall *et al*. (2019) briefly discusses this. Active research is currently underway into the identification of the distance at which the pulse can be considered effectively non-impulsive, and Hastie *et al*. (2019) have analysed a series of impulsive data to investigate this. Although the situation is complex, the paper reported that most of the signals crossed their threshold for rapid rise time and high peak sound pressure characteristics associated with impulsive noise at around 3.5 km from the source. However, research by Martin *et al*. (2020) casts doubt on these findings, showing that noise in this category should be considered impulsive as long as it is above effective quiet. To provide as much detail as possible, both impulsive and non-impulsive criteria from Southall *et al.* (2019) have been included in this study, with the non-impulsive criteria presented in Appendix A.

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

Table 2: Single string 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 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} are required, a fleeing animal model has been used for marine mammals. This assumes that a receptor, when exposed to high noise levels, will swim away from the noise source. For this, a constant fleeing speed of 3.25 m/s has been assumed for the low-frequency cetaceans (LF) group (Blix and Folkow, 1995), based on data for minke whale, and for other receptors, a constant rate of 1.5 m/s has been assumed for fleeing, which is a cruising speed for a harbour porpoise (Otani *et al*., 2000). These are considered worst case assumptions as marine mammals are recognised as being able to sustain swim speeds greater than these, and swim much faster under stress conditions. The fleeing animal model and the assumptions related to it are discussed in more detail in section 4.3.

It is worth noting that, with regards to the criteria from NMFS (2018), although numerically identical to Southall *et al.* (2019), the guidance applies different names to the marine mammal groups and weightings. For example, what Southall *et al*. (2019) calls high-frequency cetaceans (HF), NMFS (2018) calls mid-frequency cetaceans (MF), and what Southall *et al*. (2019) calls very high-frequency cetaceans (VHF), NMFS (2018) refers to as high-frequency cetaceans (HF). As such, care should be taken when comparing results using the Southall *et al*. (2019) and NMFS (2018) criteria, especially as the "HF" groupings and criteria describe different species depending on which study is being used.

2.2.2 Fish

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

The Popper *et al*. (2014) study groups species of fish by whether they possess a swim bladder, and whether it is involved in its hearing; a group for fish eggs and larvae is also included. The guidance also gives 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 4 to Table 6.

Table 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 7	See Table 7
Eggs and larvae	> 210 dB SEL_{cum} > 207 dB peak	See Table 7	See Table 7

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

Table 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 4	See Table 4	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing	See Table 4	See Table 4	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder involved in hearing	See Table 4	See Table 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 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 5	See Table 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 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 is recognised that there is limited evidence for fish fleeing from high level noise sources in the wild, and it would reasonably be expected that the reaction would differ between species. Most species are likely to move away from a sound that is loud enough to cause harm (Dahl *et al*., 2015; Popper *et al*., 2014), some may seek protection in the sediment and others may dive deeper in the water column. For those species that flee, the speed chosen for this study of 1.5 m/s is relatively slow in relation to data from Hirata (1999) and thus is considered somewhat conservative.

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

Stationary animal modelling has been included in this study, based on research from Hawkins *et al*. (2014) and other modelling for similar 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.

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 species of fish, as well as invertebrates, actually detect particle motion rather than 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 most sensitive species, are sensitive to sound pressure.

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

The primary reason for the continuing use of sound pressure as the criteria, despite particle motion appearing to be the physical measure to which the fish react or sense, is 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 *et al.,* 2019).

3 Baseline ambient noise

The baseline noise level in open water, in the absence of any 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 mammals and fish vocalisation, as well as an element from invertebrates.

Outside of the naturally occurring ambient noise, man-made 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 aggregate dredgers and small fishing boats have a lower overall contribution. There are no known dredging areas, active dredge zones, or dredging application option and prospecting areas within or in close proximity to AyM.

Other sources of anthropogenic noise include oil and gas platforms and other drilling activity and military exercises. Drilling, including oil and gas drilling, may contribute some low frequency noise at the region around AyM, although due to its low-level nature (see Section 6), 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 have little contribution to the long-term ambient noise in the area.

Typical underwater noise levels show a frequency dependency in relation to different noise sources: the classic curves for this are given in Wenz (1962) and are reproduced in Figure 3. These show that any unweighted, overall (i.e., single-figure, non-frequency-dependent) noise level is typically dependent on the very low-frequency (< 100 Hz) 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 level in the 100 Hz to 1 kHz region, but to a lesser extent, will also extend into higher and lower frequencies.

The best source of baseline noise data available in the region is underwater noise monitoring undertaken from a station installed in the middle of the Burbo Bank Extension, 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 of AyM. Although this survey was undertaken in 2016, it is expected to represent a reasonable approximation of the subsea noise levels in the North Wales and Liverpool Bay regions prior to installation of WTGs.

The overview of the entire monitoring period in Figure 4 below shows that the range of underwater noise levels typically lie, with isolated exceptions, between 95 dB and 130 dB re 1 µPa SPL_{RMS} (displayed as 10-minute averages). Although there are clear instances of times when the noise levels reach or approach 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 SPL_{RMS}.

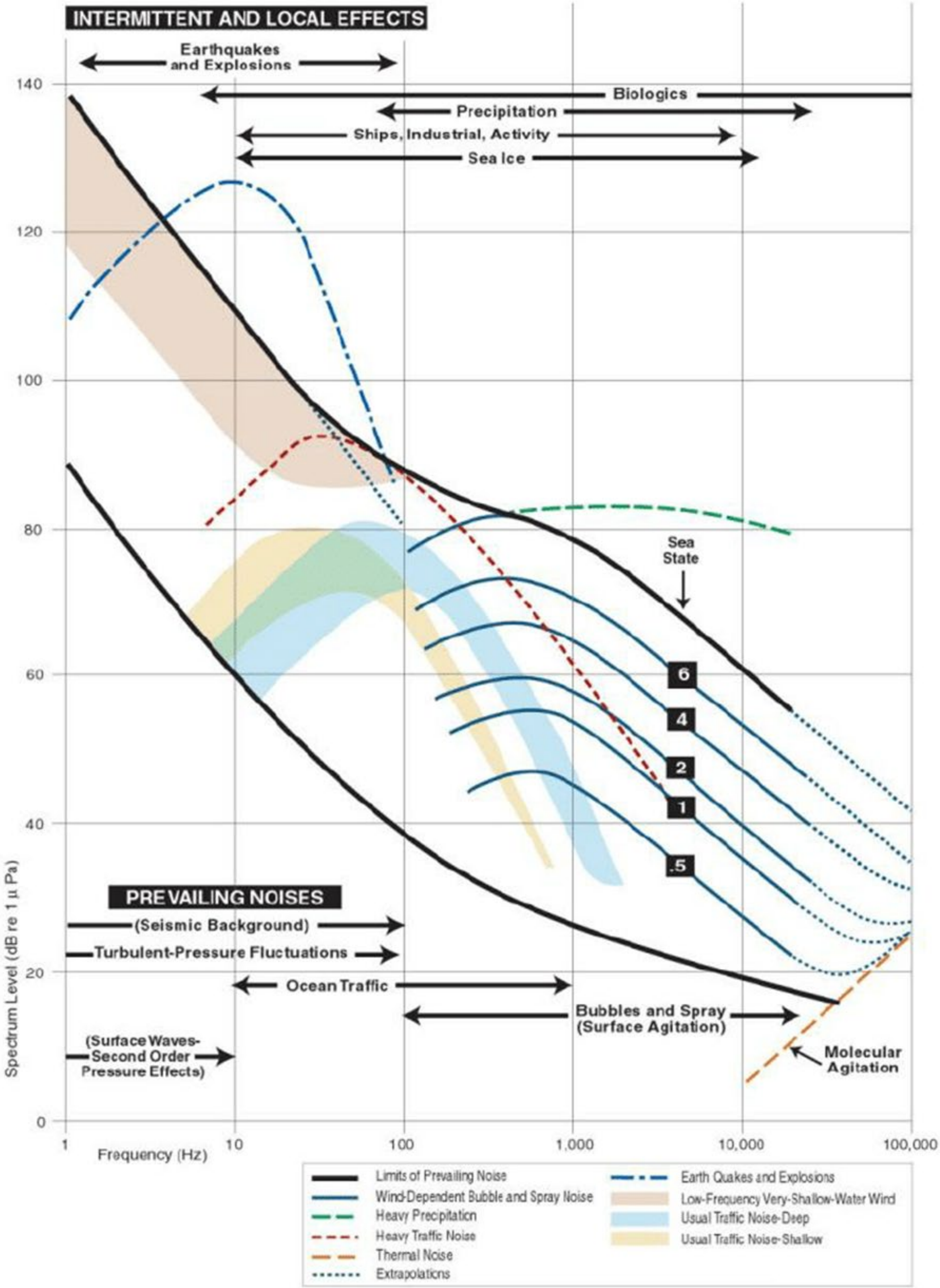

Figure 3: Ambient underwater noise, following Wenz (1962), showing frequency dependency from different noise sources

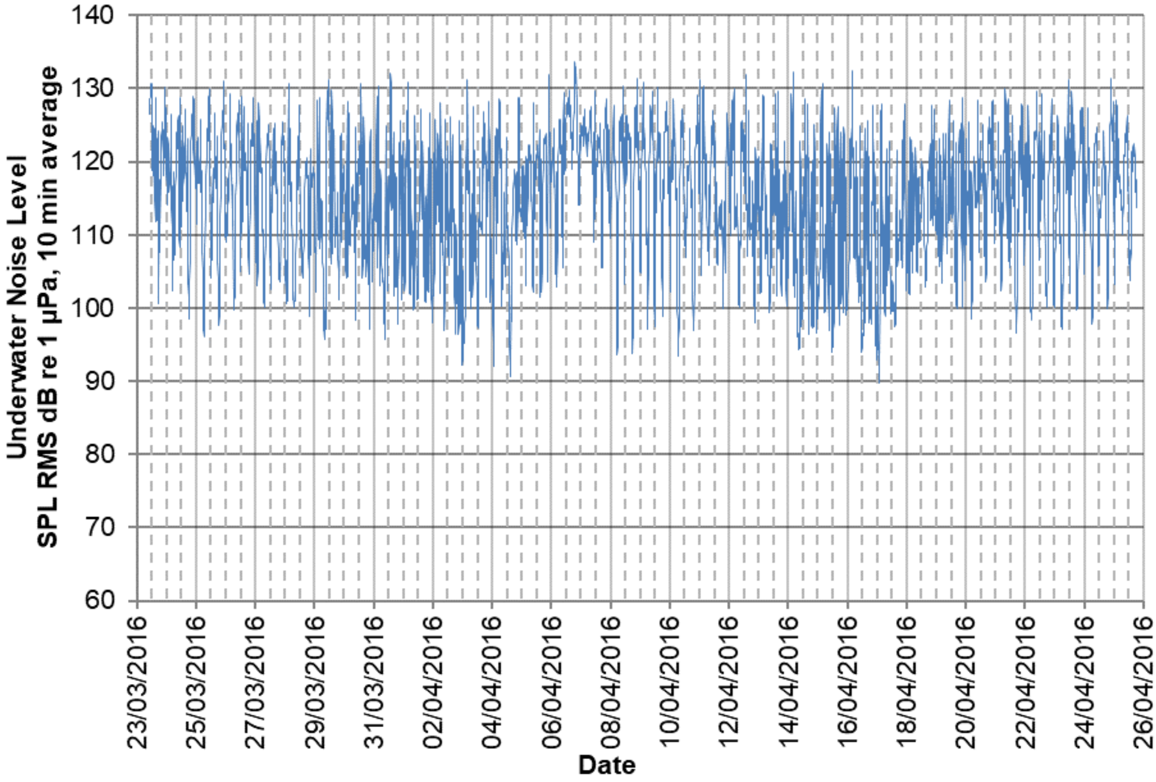

Figure 4: Overall sampled underwater noise levels at Burbo Bank Extension site, March-April 2016

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

The lowest noise levels were sampled in the absence of vessel movements and at slack water.

Another underwater noise dataset was sampled at the GyM over four days in August 2012, during construction of the offshore wind farm (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 is 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 natural ambient noise, at which point it can be considered negligible. In practice, as the underwater noise thresholds defined in section 2.2 are all considerably above the level of background noise, any noise baseline would not feature in an assessment to these criteria.

4 Modelling methodology

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

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 is 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 AyM. 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 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 AyM, and these are discussed in section 6.

4.1 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 is 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 is used.

In addition, INSPIRE is also validated by comparing the noise levels outputted from the model with measurements and modelling undertaken by third parties, 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 impact piling. 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 5. 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 5 presents a small selection of measured impact piling noise data plotted against outputs from INSPIRE. The plots show data points from measured data (in blue) plotted alongside modelled data (in orange) using INSPIRE 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.

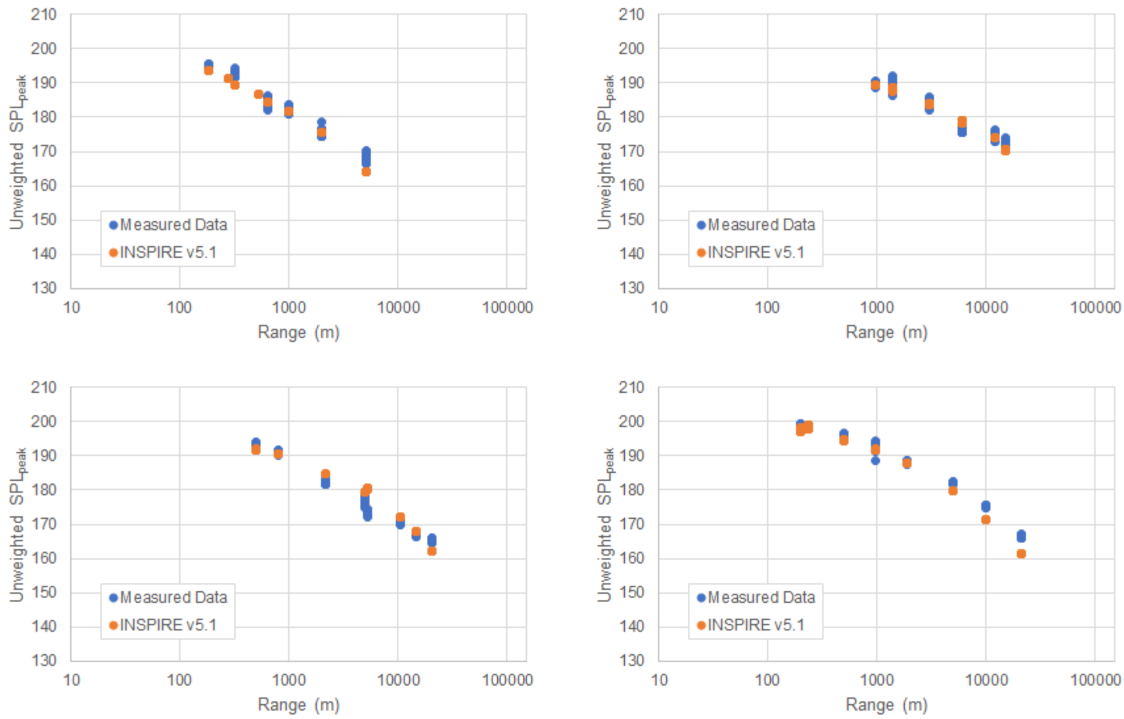

Figure 5: Comparison between example measured impact piling data (blue points) and modelled data using INSPIRE version 5.1 (orange points)

Top Left: 1.8 m pile, Irish Sea, 2010; Top Right: 9.5 m pile, North Sea, 2020; Bottom Left: 6.1 m pile, Southern North Sea, 2009; Bottom Right: 6 m pile, Southern North Sea, 2009.

4.2 Modelling parameters

4.2.1 Modelling locations

Modelling for WTG foundation impact piling has been undertaken at two representative AyM locations, covering the extents and various water depths at the site, and as agreed as agreed with Natural Resources Wales via the EIA Evidence Plan Process (Document Ref: 8.2).

- The north-west (NW) location was chosen as it is in deep water, likely to produce the largest impact ranges; and

- The south-east (SE) location is in shallower water towards the coast, closest to the Dee Estuary, which is an area of interest.

A third location near landfall has been included for installation of sheet piles for a cofferdam using impact piling. The parameters for this sheet piling modelling are covered in section 4.2.5 and the results are presented in section 5.4.

These locations are summarised in Table 10 and illustrated in Figure 6.

Table 10 Summary of the underwater noise modelling locations at AyM

Modelling locations	NW location	SE location	Cofferdam
Latitude	53.48706° N	53.44283° N	53.34446° N
Longitude	3.8587° W	3.69781° W	3.46645° W
Water depth (mean tide)	32.4 m	19.2 m	8.1 m

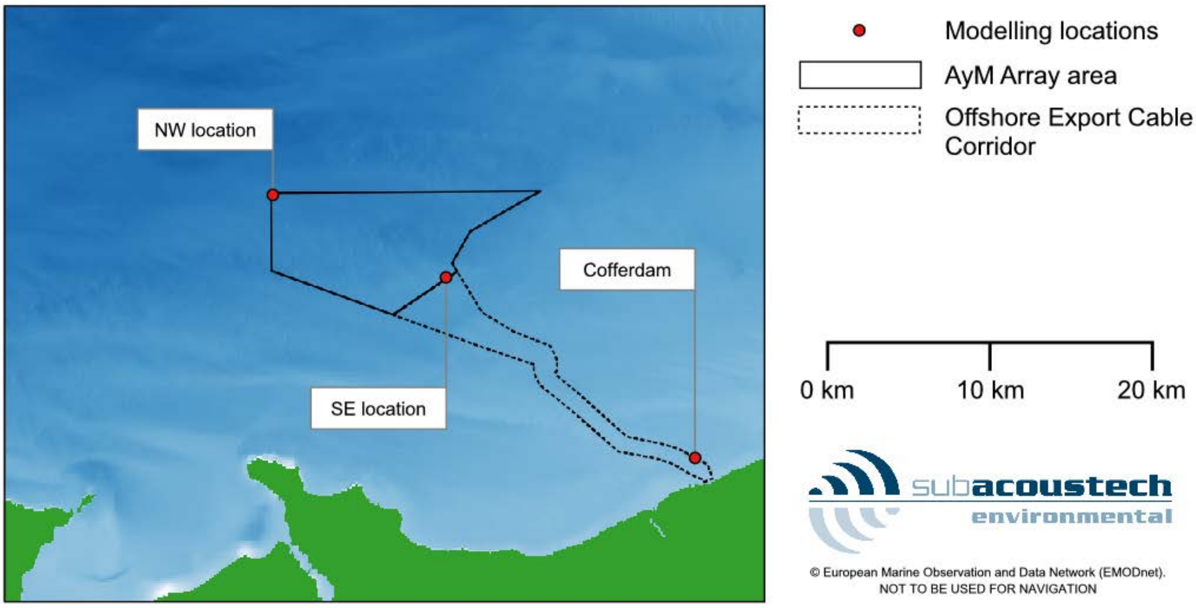

Figure 6: Approximate positions of the modelling locations at AyM

4.2.2 WTG foundation impact piling parameters

Two piling scenarios cover the worst-case monopile and multi-leg pile foundations for WTGs. The modelled scenarios are as follows:

- Worst-case monopile foundations – up to 15 m in diameter, installed using a maximum blow energy of 5,000 kJ, with a maximum of two foundations installed in a 24-hour period; and
- Worst-case multi-leg foundations – up to 3.5 m in diameter, installed using a maximum blow energy of 3,000 kJ, with a maximum of four foundations installed in a 24-hour period.

These worst-case scenarios consider the maximum possible piling durations and blow energies at the end of ramp up, which may prove to be highly unrealistic due to hammer capacity or pile fatigue, or other on-site practicalities.

For SEL_{cum}, the soft start and ramp up of blow energies along with the total duration and strike rate must also be considered; these are summarised in Table 11 and Table 12. The modelled scenarios contain a total of 8,768 strikes over 272 minutes (per pile) for the worst-case monopile foundation scenario and 7,340 strikes over 230 minutes (per pile) for the worst-case multi-leg foundation scenario.

In a 24-hour period it is expected that up to two monopile foundations or four multi-leg foundation piles can be installed. This is included as part of the modelling, assuming that the foundation piles are installed consecutively. This increases the overall upper limit of piling durations in a 24-hour period for monopile foundations to just over nine hours and for multi-leg foundations to 15 hours 20 minutes.

In addition, there is a possibility that two instances of multi-leg piling may occur simultaneously for the same foundation. No simultaneous piling for monopiles is proposed.

Table 11: Summary of the worst-case soft start and ramp-up scenario used for calculating SEL_{cum} for monopile foundations

Worst-case monopile foundations	**750 kJ**	**1,000 kJ**	**2,000 kJ**	**3,000 kJ**	**4,000 kJ**	**5,000 kJ**
Number of strikes	100	100	340	680	1020	6,528
Duration	10 mins	10 mins	10 mins	20 mins	30 mins	192 mins
Strike rate	10 str/min		34 str/min			

Table 12: Summary of the worst-case soft start and ramp-up scenario used for calculating SEL_{cum} for multi-leg foundations

Worst-case multi-leg foundations	**450 kJ**	**600 kJ**	**1,200 kJ**	**1,800 kJ**	**2,400 kJ**	**3,000 kJ**
Number of strikes	100	100	340	680	1020	5,100
Duration	10 mins	10 mins	10 mins	20 mins	30 mins	150 min
Strike rate	10 str/min		34 str/min			

4.2.3 Source levels

Noise modelling requires knowledge of the source level, which is the theoretical noise level at one metre from the noise source. The INSPIRE model assumes that the noise source – the hammer striking the pile – acts as an effective single point, as it will appear at a distance. The source level 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 in contact with the water, which can affect the amount of noise that is transmitted from the pile into its surroundings.

It is worth noting that the 'source level' technically does not exist in the context of many shallow water noise sources (Heaney *et al*. 2020). In practice, in underwater noise modelling such as this, it is effectively an 'apparent source level' and simply a value that can be used to produce correct noise levels at range (for a specific model), as required in impact assessments.

The unweighted, single strike SPL_{peak} and SEL_{ss} source levels estimated for this study are provided in Table 13. These figures are presented in accordance with typical requests by regulatory authorities, although as indicated above they are not necessarily compatible or comparable with any other model or predicted source levels. The differences in source level for each location are small to negligible.

Table 13: Summary of the unweighted source levels used for modelling

Worst-case parameters	Location	**Monopile foundations** 15 m / 5,000 kJ	**Multi-leg foundations** 3.5 m / 3,000 kJ
SPL_{peak} source levels	NW	242.8 dB re 1 µPa @ 1 m	241.6 dB re 1 µPa @ 1 m
	SE	242.8 dB re 1 µPa @ 1 m	241.4 dB re 1 µPa @ 1 m
SEL_{ss} source levels	NW	223.9 dB re 1 µPa^{2}s @ 1 m	222.3 dB re 1 µPa^{2}s @ 1 m
	SE	223.9 dB re 1 µPa^{2}s @ 1 m	222.0 dB re 1 µPa^{2}s @ 1 m

4.2.4 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 show that the seabed surrounding the AyM site is generally made up of various combinations of sand and gravelly sand.

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

4.2.5 Cofferdam sheet piling parameters

There is the potential for a cofferdam to be built near landfall as part of export cable construction, which will involve the installation of sheet piles using impact piling. A representative location has been chosen for this sheet piling modelling, at the deepest location at which the cofferdam is expected to be installed. This location is shown in Table 10 and Figure 6.

Due to the shallow, tidal area where the cofferdam is expected to be installed, the variation in the tide has also been considered. Noise levels are predicted during both Mean High Water Springs (MHWS) and Mean Low Water Springs (MLWS). At the modelling location these tides are:

- MHWS is 8.0 m above the Lowest Astronomical Tide (LAT), which is 11.8 m at the modelling location; and
- MLWS is 0.6 m above LAT, which is 4.4 m at the modelling location.

The modelling assumes sheet piles measuring 0.75 m in width will be installed. Each pile takes one hour to install and a maximum of eight sheet piles are to be installed in a day. The maximum blow energy of the piling hammer is expected to be 300 kJ. The soft start and ramp-up parameters are summarised in Table 14.

Table 14: Summary of the soft start and ramp-up scenario used for calculating SEL_{cum} for the cofferdam sheet piling

Cofferdam sheet piling	**60 kJ**	**Gradual ramp-up**	**300 kJ**
Number of strikes	1050	175	875
Duration	30 mins	5 mins	25 mins
Strike rate	35 str/min		

The results of this modelling have been presented for Southall *et al*. (2019) and Popper *et al*. (2014) criteria in section 5.4.

4.3 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 starting at the position denoted on a modelled PTS contour began to flee, in a straight line away from the noise source, 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 the whole piling operation: in the case of the Southall *et al*. (2019) and Popper *et al*. (2014) criteria this covers any piling in a 24-hour period.

When considering a stationary receptor, i.e., one that stays at the same position throughout piling, calculating the SEL_{cum} is relatively straightforward: all the noise levels produced during the piling event and received at a single point along the 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 the 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 then the received noise level for each pile strike while the receptor is fleeing is noted. For example, if a pile strike occurs every six seconds and an animal is fleeing at a rate of 1.5 m/s, it is 9 m further from the source after each subsequent pile strike, resulting in a slightly reduced received noise level with each strike. These values are then aggregated into an SEL_{cum} over the entire piling period. The faster an animal is fleeing the greater the distance travelled between each pile strike. The impact range outputted by the model for this situation is the distance the receptor must be at the start of piling to exactly meet the exposure threshold.

The graphs in Figure 7 and Figure 8 show the difference in the SELs received by a stationary receptor and a fleeing receptor travelling at a constant speed of 1.5 m/s, using the worst case monopile foundation parameters (Table 11). This was carried out at the NW location for a single monopile installation as an example.

The received SEL_{ss} from the stationary receptor, as illustrated in Figure 7 shows the noise level gradually increasing as the blow energy increases throughout the piling operation. These step changes are also visible for the fleeing receptor, but as the receptor is further from the source by the time the levels increase, the total received exposure is reduced, resulting in progressively lower received noise levels. For example, after the first 10 minutes where the blow energy is 750 kJ, the fleeing receptor will have already moved 900 m away. After the full piling duration of 272 minutes, the receptor will be over 24 km from the pile.

Figure 8 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 results in a received level of 217.9 dB re 1 $\mu Pa^2 s$. If the receptor individual were to remain stationary throughout the 272 minutes of piling it would receive a cumulative received level of 263.1 dB re 1 $\mu Pa^2 s$, whereas fleeing at 1.5 m/s over the same piling scenario would result in a cumulative received level of just 218.6 dB re 1 $\mu Pa^2 s$ for the receptor.

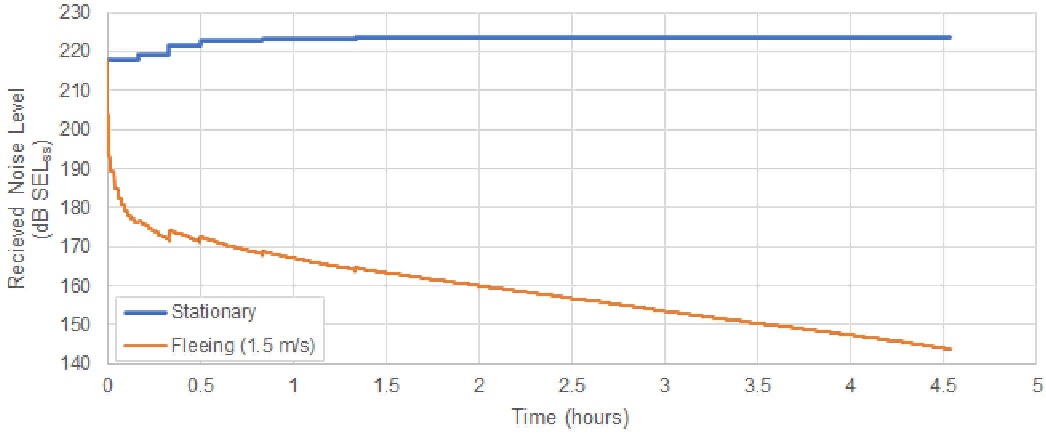

Figure 7: Received single-strike noise levels (SEL_{ss}) for receptors during the worst-case monopile foundation parameters at the NW location, assuming both a stationary and a fleeing receptor starting at a location 1 m from the noise source

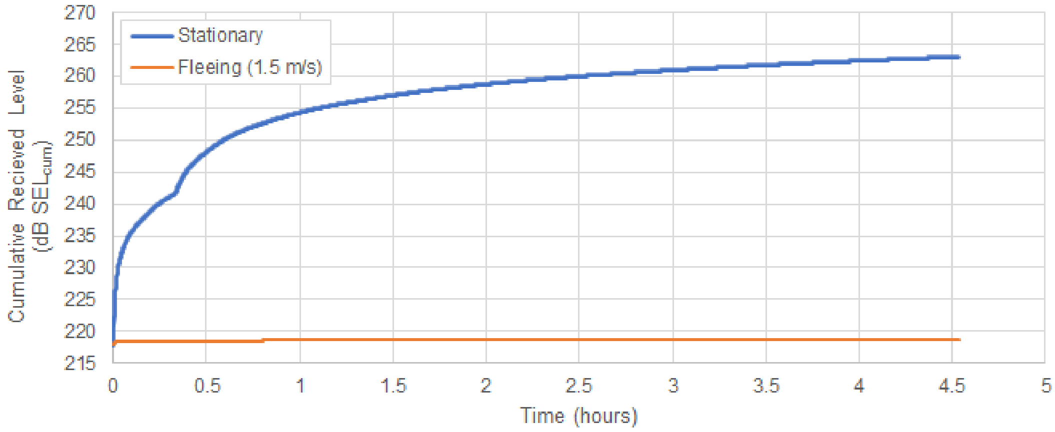

Figure 8: Cumulative received noise levels (SEL_{cum}) for receptors during the worst-case monopile foundation parameters at the NW location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source

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 9.

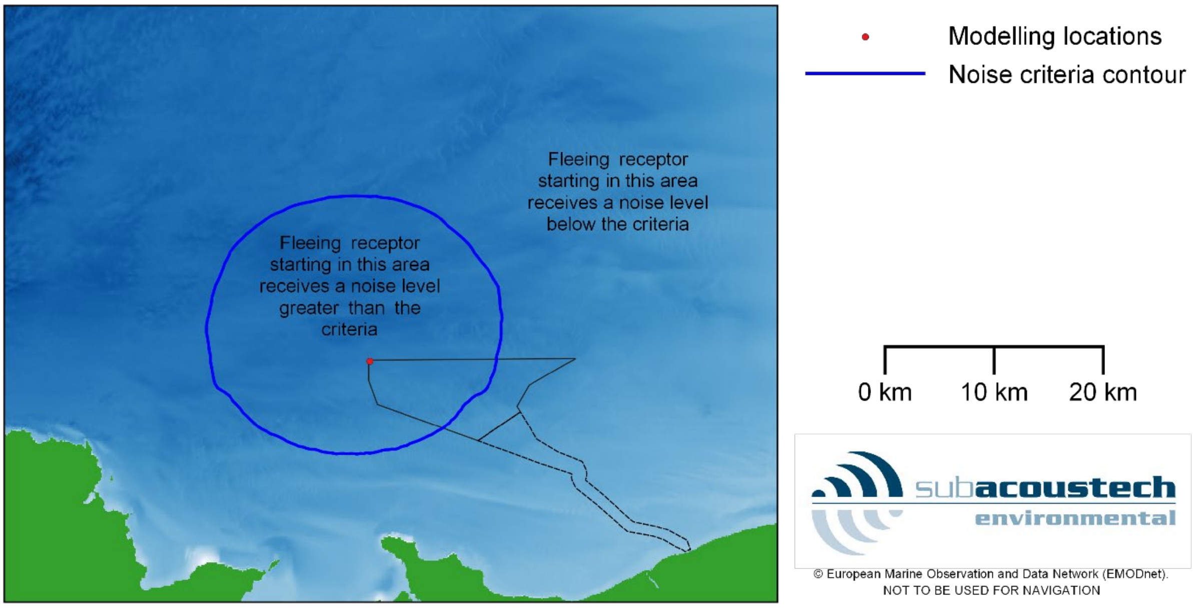

Figure 9: Plot showing a fleeing animal SEL_{cum} criteria contour and the areas where the cumulative received noise level will excess the impact criteria. Boundary used for explanation purposes only.

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's modelling approach does not include this, but 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 1.5 m/s, 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 negligible.

4.3.1 The effects of input parameters on cumulative SELs and fleeing receptors

As discussed in section 4.2.2, parameters such as water depth, 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.

Figure 10 summarises the hammer blow energy ramp up for the four modelled cumulative scenarios, showing how the monopile scenarios reach a higher blow energy over a greater total duration, as well as the effect of multiple consecutive piling operations. For a precautionary modelling prediction, it is assumed that subsequent piles follow on directly from the previous with no pause.

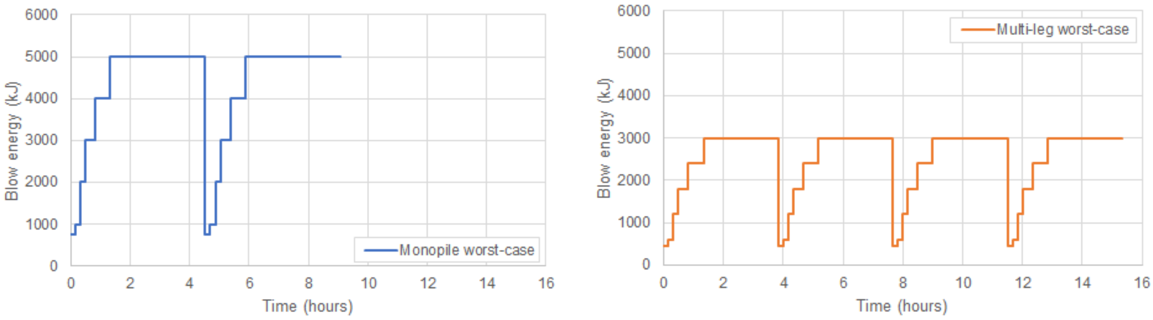

Figure 10: Graphical representation of the blow energy for the modelled ramp up scenarios

Linked to the effect of the ramp up is the strike rate, as the more 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. Figure 11 shows the strike rate against time for the monopile and jacket foundation modelled scenarios.

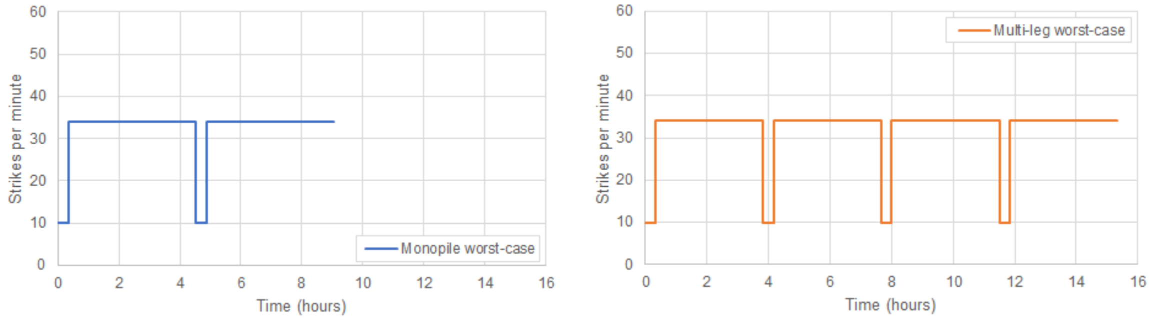

Figure 11: Graphical representation of the strike rate for the modelled ramp up scenarios

5 Modelling results

The following sections present the modelled impact ranges for impact piling noise following the parameters details in section 4.2, split into the Southall *et al*. (2019) marine mammal criteria (section 5.1) and the Popper *et al*. (2014) fish criteria (section 5.2), with subsections covering the monopile and multi-leg foundations. To aid navigation Table 15 contains a list of all the impact range tables in this section.

Additional modelling for simultaneous piling at separate locations is presented in section 5.3, and the cofferdam sheet piling modelling results are presented in section 5.4. Further modelling has also been completed for the Southall *et al*. (2019) non-impulsive noise criteria, and these are presented in Appendix A.

For the results presented throughout this section, any predicted ranges smaller than 50 m and areas less than 0.01 km^2 for single strike criteria, and ranges smaller than 100 m and areas less than 0.1 km^2 for cumulative criteria, have not been presented. At ranges this close to the noise source, the modelling processes are unable to model to a sufficient level of accuracy due to acoustic effects near the pile. Ranges are given as "less than" this limit.

The largest ranges are predicted for the worst-case monopile foundation parameters at the NW location.

Table 15: Summary of the results tables presented in sections 5.1 and 5.2

Table (page)	Location	Parameters	Criteria	
Table 16 (p24)	NW	Worst-case monopile foundations	Southall *et al*. (2019)	Unweighted SPL_{peak}
Table 17 (p24)	SE			
Table 18 (p24)	NW			Weighted SEL_{cum} (Impulsive)
Table 19 (p25)	SE			
Table 20 (p25)	NW	Worst-case multi-leg foundations		Unweighted SPL_{peak}
Table 21 (p25)	SE			
Table 22 (p26)	NW			Weighted SEL_{cum} (Impulsive)
Table 23 (p26)	SE			
Table 24 (p26)	NW	Worst-case monopile foundations	Popper *et al*. (2014)	Unweighted SPL_{peak}
Table 25 (p27)	SE			
Table 26 (p27)	NW			Unweighted SEL_{cum} (Pile driving)
Table 27 (p27)	SE			
Table 28 (p28)	NW	Worst-case multi-leg foundations		Unweighted SPL_{peak}
Table 29 (p28)	SE			
Table 30 (p28)	NW			Unweighted SEL_{cum} (Pile driving)
Table 31 (p28)	SE			

5.1 Marine mammal criteria

Table 16 to Table 23 present the modelling results in terms of the Southall *et al*. (2019) marine mammal criteria, covering the worst-case monopile and multi-leg foundation parameters as described in section 4.2.

The largest marine mammal impact ranges are predicted for the worst-case monopile foundations at the NW location, due in part to the water depths at and surrounding the modelling location. Maximum PTS injury ranges are predicted in fleeing LF cetaceans with ranges of up to 8.5 km (a reduction from 9.2km as presented within the PEIR, as a result of the reduction in the array boundary). Fleeing VHF cetaceans show maximum PTS ranges of up to 4.7 km (a reduction from 5.1km as presented within the PEIR, as a result of the reduction in the array boundary). Smaller ranges are predicted for the SE location due to the shallower water depths and proximity to the coastline, and these have not changed from those presented within the PEIR.

Additional Southall *et al.* (2019) criteria covering the non-impulsive impacts in marine mammals are presented in Appendix A.

5.1.1 Worst-case monopile foundations

Table 16: Summary of the impact ranges from the worst-case monopile foundation modelling at the NW location using the impulsive Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al*. (2019) Unweighted SPL_{peak}		Worst-case monopile foundations – NW location			
		Area	**Max range**	**Min 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	630 m	620 m	630 m
	PCW (218 dB)	0.01 km²	50 m	50 m	50 m
TTS	**LF** (213 dB)	0.04 km²	50 m	50 m	50 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	6.9 km²	1.5 km	1.5 km	1.5 km
	PCW (212 dB)	0.06 km²	140 m	130 m	140 m

Table 17: Summary of the impact ranges from the worst-case monopile foundation modelling at the SE location using the impulsive Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al*. (2019) Unweighted SPL_{peak}		Worst-case monopile foundations – SE location			
		Area	**Max range**	**Min 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)	0.71 km²	490 m	470 m	480 m
	PCW (218 dB)	< 0.01 km²	50 m	< 50 m	50 m
TTS	**LF** (213 dB)	0.03 km²	100 m	90 m	100 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	3.7 km²	1.1 km	1.0 km	1.1 km
	PCW (212 dB)	0.04 km²	110 m	110 m	110 m

Table 18: Summary of the impact ranges from the worst-case monopile foundation modelling at the NW location using the impulsive Southall et al. (2019) weighted SEL_{cum} impulsive criteria for marine mammals assuming a fleeing receptor

Southall *et al*. (2019) Weighted SEL_{cum}		Worst-case monopile foundations – NW location			
		Area	**Max range**	**Min range**	**Mean range**
PTS	**LF** (183 dB)	120 km²	8.5 km	3.8 km	6.1 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	48 km²	4.7 km	3.0 km	3.9 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	**LF** (168 dB)	1400 km²	30 km	10 km	20 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	960 km²	23 km	11 km	17 km
	PCW (170 dB)	210 km²	10 km	5.7 km	8.0 km

Table 19: Summary of the impact ranges from the worst-case monopile foundation modelling at the SE location using the impulsive Southall et al. (2019) weighted SEL_{cum} impulsive criteria for marine mammals assuming a fleeing receptor

Southall *et al*. (2019) Weighted SEL_{cum}		Worst-case monopile foundations – SE location			
		Area	**Max range**	**Min range**	**Mean range**
PTS	**LF** (183 dB)	19 km^2	4.2 km	800 m	2.2 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	13 km^2	2.9 km	1.2 km	2.0 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	**LF** (168 dB)	590 km^2	23 km	5.2 km	12 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	470 km^2	19 km	6.1 km	12 km
	PCW (170 dB)	60 km^2	6.3 km	2.5 km	4.2 km

5.1.2 Worst-case multi-leg foundations

Table 20: Summary of the impact ranges from the worst-case multi-leg foundation modelling at the NW location using the impulsive Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al*. (2019) Unweighted SPL_{peak}		Worst-case multi-leg foundations – NW location			
		Area	**Max range**	**Min range**	**Mean range**
PTS	**LF** (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.9 km^2	520 m	520 m	520 m
	PCW (218 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	**LF** (213 dB)	0.03 km^2	100 m	100 m	100 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	4.9 km^2	1.3 km	1.2 km	1.3 km
	PCW (212 dB)	0.04 km^2	110 m	110 m	110 m

Table 21: Summary of the impact ranges from the worst-case multi-leg foundation modelling at the SE location using the impulsive Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al*. (2019) Unweighted SPL_{peak}		Worst-case multi-leg foundations – SE location			
		Area	**Max range**	**Min range**	**Mean range**
PTS	**LF** (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	0.48 km^2	400 m	390 m	390 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	**LF** (213 dB)	0.02 km^2	80 m	80 m	80 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	2.6 km^2	940 m	880 m	910 m
	PCW (212 dB)	0.03 km^2	90 m	90 m	90 m

Table 22: Summary of the impact ranges from the worst-case multi-leg foundation modelling at the NW location using the impulsive Southall et al. (2019) weighted SEL_{cum} impulsive criteria for marine mammals assuming a fleeing receptor

Southall *et al*. (2019) Weighted SEL_{cum}		Worst-case multi-leg foundations – NW location			
		Area	**Max range**	**Min range**	**Mean range**
PTS	**LF** (183 dB)	70 km^2	6.5 km	2.7 km	4.6 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	28 km^2	3.6 km	2.3 km	2.9 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	**LF** (168 dB)	1100 km^2	27 km	9.7 km	18 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	820 km^2	21 km	10 km	16 km
	PCW (170 dB)	170 km^2	9.2 km	5.2 km	7.2 km

Table 23: Summary of the impact ranges from the worst-case multi-leg foundation modelling at the SE location using the impulsive Southall et al. (2019) weighted SEL_{cum} impulsive criteria for marine mammals assuming a fleeing receptor

Southall *et al*. (2019) Weighted SEL_{cum}		Worst-case multi-leg foundations – SE location			
		Area	**Max range**	**Min range**	**Mean range**
PTS	**LF** (183 dB)	5.9 km^2	2.6 km	280 m	1.1 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	5.8 km^2	2.0 km	750 m	1.3 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	**LF** (168 dB)	460 km^2	20 km	4.5 km	11 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	390 km^2	17 km	5.6 km	11 km
	PCW (170 dB)	44 km^2	5.5 km	2.1 km	3.6 km

5.2 Fish criteria

Table 25 to Table 31 present the impact ranges for the fish criteria for pile driving from Popper *et al*. (2014) covering the worst-case monopile and multi-leg foundation parameters as described in section 4.2.

The largest recoverable injury ranges (203 dB SEL_{cum} threshold) in species of fish are 11 km at the NW position for the worst-case monopile parameters, assuming a stationary receptor; if a fleeing receptor is assumed all the impact ranges a reduced to below 100 m. Maximum TTS ranges (186 dB SEL_{cum} threshold) are predicted of up to 16 km for the worst-case monopile foundations at the NW locations assuming a fleeing animal model; this increases to 30 km when considering a stationary animal.

5.2.1 Worst-case monopile foundations

Table 24: Summary of the impact ranges from the worst-case monopile foundation modelling at the NW location using the Popper et al. (2014) unweighted SPL_{peak} pile driving criteria for fish

Popper *et al*. (2014) Unweighted SPL_{peak}	Worst-case monopile foundations – NW location			
	Area	**Max range**	**Min range**	**Mean range**
213 dB	0.04 km^2	120 m	120 m	120 m
207 dB	0.3 km^2	290 m	290 m	290 m

Table 25: Summary of the impact ranges from the worst-case monopile foundation modelling at the SE location using the Popper et al. (2014) unweighted SPL_{peak} pile driving criteria for fish

Popper *et al*. (2014) Unweighted SPL_{peak}	Worst-case monopile foundations – SE location			
	Area	**Max range**	**Min range**	**Mean range**
213 dB	0.03 km^2	100 m	90 m	100 m
207 dB	0.17 km^2	240 m	230 m	230 m

Table 26: Summary of the impact ranges from the worst-case monopile foundation modelling at the NW location using the Popper et al. (2014) unweighted SEL_{cum} pile driving criteria for both fleeing and stationary fish

Popper *et al*. (2014) Unweighted SEL_{cum}		Worst-case monopile foundations – NW location			
		Area	**Max range**	**Min range**	**Mean range**
Fleeing (1.5 m/s)	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	450 km^2	16 km	7.8 km	12 km
Stationary	219 dB	4.8 km^2	1.3 km	1.2 km	1.2 km
	216 dB	11 km^2	1.9 km	1.9 km	1.9 km
	210 dB	51 km^2	4.2 km	3.9 km	4.0 km
	207 dB	100 km^2	6.0 km	5.4 km	5.7 km
	203 dB	220 km^2	9.1 km	7.6 km	8.4 km
	186 dB	1800 km^2	30 km	16 km	24 km

Table 27: Summary of the impact ranges from the worst-case monopile foundation modelling at the SE location using the Popper et al. (2014) unweighted SEL_{cum} pile driving criteria for both fleeing and stationary fish

Popper *et al*. (2014) Unweighted SEL_{cum}		Worst-case monopile foundations – SE location			
		Area	**Max range**	**Min range**	**Mean range**
Fleeing (1.5 m/s)	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	150 km^2	10 km	3.7 km	6.6 km
Stationary	219 dB	2.6 km^2	950 m	880 m	920 m
	216 dB	5.8 km^2	1.4 km	1.3 km	1.4 km
	210 dB	25 km^2	3.1 km	2.7 km	2.8 km
	207 dB	48 km^2	4.4 km	3.6 km	3.9 km
	203 dB	100 km^2	6.6 km	4.9 km	5.7 km
	186 dB	960 km^2	24 km	10 km	17 km

5.2.2 Worst-case multi-leg foundations

Table 28: Summary of the impact ranges from the worst-case multi-leg foundation modelling at the NW location using the Popper et al. (2014) unweighted SPL_{peak} pile driving criteria for fish

Popper *et al*. (2014) Unweighted SPL_{peak}	Worst-case multi-leg foundations – NW location			
	Area	**Max range**	**Min range**	**Mean range**
213 dB	0.03 km^2	100 m	100 m	100 m
207 dB	0.2 km^2	240 m	240 m	240 m

Table 29: Summary of the impact ranges from the worst-case multi-leg foundation modelling at the SE location using the Popper et al. (2014) unweighted SPL_{peak} pile driving criteria for fish

Popper *et al*. (2014) Unweighted SPL_{peak}	Worst-case multi-leg foundations – SE location			
	Area	**Max range**	**Min range**	**Mean range**
213 dB	0.02 km^2	80 m	80 m	80 m
207 dB	0.11 km^2	190 m	190 m	190 m

Table 30: Summary of the impact ranges from the worst-case multi-leg foundation modelling at the NW location using the Popper et al. (2014) unweighted SEL_{cum} pile driving criteria for both fleeing and stationary fish

Popper *et al*. (2014) Unweighted SEL_{cum}		Worst-case multi-leg foundations – NW location			
		Area	**Max range**	**Min range**	**Mean range**
Fleeing (1.5 m/s)	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	320 km^2	13 km	6.7 km	9.9 km
Stationary	219 dB	5.5 km^2	1.3 km	1.3 km	1.3 km
	216 dB	13 km^2	2.0 km	2.0 km	2.0 km
	210 dB	57 km^2	4.5 km	4.1 km	4.3 km
	207 dB	110 km^2	6.3 km	5.6 km	6.0 km
	203 dB	240 km^2	9.5 km	7.9 km	8.7 km
	186 dB	1900 km^2	31 km	16 km	24 km

Table 31: Summary of the impact ranges from the worst-case multi-leg foundation modelling at the SE location using the Popper et al. (2014) unweighted SEL_{cum} pile driving criteria for both fleeing and stationary fish

Popper *et al*. (2014) Unweighted SEL_{cum}		Worst-case multi-leg foundations – SE location			
		Area	**Max range**	**Min range**	**Mean range**
Fleeing (1.5 m/s)	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	92 km^2	8.1 km	2.8 km	5.1 km
Stationary	219 dB	2.8 km^2	980 m	930 m	940 m
	216 dB	6.1 km^2	1.5 km	1.4 km	1.4 km
	210 dB	27 km^2	3.2 km	2.7 km	2.9 km
	207 dB	51 km^2	4.5 km	3.7 km	4.0 km
	203 dB	110 km^2	6.8 km	5.0 km	5.9 km
	186 dB	980 km^2	25 km	10 km	17 km

5.3 Simultaneous modelling

Additional modelling has been carried out to investigate the potential impacts of two multi-leg piling installations occurring simultaneously at the same foundation. This is a change to the proposed design envelope from that presented in the PEIR, which assumed two distant concurrent piling events for either monopile or multi-pin operations. Using the worst-case multi-leg scenario from section 4.2, modelling has been carried out for two simultaneous piling installations at the NW and SE modelling locations. All modelling in this section assumes that the two piling operations start at the same time, to represent a worst-case scenario. No simultaneous piling is proposed for monopiles.

As the maximum blow energies are not changing for these scenarios only SEL_{cum} results have been presented below. Comparing these results to those from the previous section, increases in impact range can be seen, especially for fleeing receptors as the number of strikes while close to the source have essentially been doubled.

Table 32 to Table 35 present summaries of the modelled simultaneous impact ranges along with the areas from the previous section for a single foundation installation for ease of comparison.

5.3.1 *Marine mammal criteria*

Table 32: Summary of the impact ranges from simultaneous installation of two of the worst-case multi-leg foundation modelling at the NW location using the impulsive Southall et al. (2019) weighted SEL_{cum} impulsive criteria for marine mammals assuming a fleeing receptor

Southall *et al*. (2019) Weighted SEL_{cum}		Simultaneous worst-case multi-leg foundations NW location				Single foundation area for comparison
		Area	**Max range**	**Min range**	**Mean range**	
PTS	**LF** (183 dB)	170 km²	10 km	4.3 km	7.1 km	70 km²
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²
	VHF (155 dB)	83 km²	6.3 km	3.8 km	5.1 km	28 km²
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²
TTS	**LF** (168 dB)	1500 km²	33 km	11 km	21 km	1100 km²
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²
	VHF (140 dB)	1200 km²	26 km	11 km	19 km	820 km²
	PCW (170 dB)	330 km²	13 km	7.0 km	10 km	170 km²

Table 33: Summary of the impact ranges from simultaneous installation of two of the worst-case multi-leg foundation modelling at the SE location using the impulsive Southall et al. (2019) weighted SEL_{cum} impulsive criteria for marine mammals assuming a fleeing receptor

Southall *et al*. (2019) Weighted SEL_{cum}		Simultaneous worst-case multi-leg foundations SE location				Single foundation area for comparison
		Area	**Max range**	**Min range**	**Mean range**	
PTS	**LF** (183 dB)	29 km²	5.2 km	900 m	2.7 km	5.9 km²
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²
	VHF (155 dB)	25 km²	4.0 km	1.7 km	2.7 km	5.8 km²
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²
TTS	**LF** (168 dB)	670 km²	24 km	5.3 km	13 km	460 km²
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 0.1 km²
	VHF (140 dB)	590 km²	21 km	6.5 km	13 km	390 km²
	PCW (170 dB)	110 km²	8.5 km	3.2 km	5.5 km	44 km²

5.3.2 Fish criteria

Table 34: Summary of the impact ranges from simultaneous installation of two of the worst-case multi-leg foundation modelling at the NW location using the Popper et al. (2014) unweighted SEL_{cum} pile driving criteria for both fleeing and stationary fish

Popper *et al*. (2014) Unweighted SEL_{cum}		Simultaneous worst-case multi-leg foundations NW location				Single foundation area for comparison
		Area	Max range	Min range	Mean range	
Fleeing (1.5 m/s)	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 100 m
	186 dB	540 km²	17 km	8.3 km	13 km	9.9 km
Stationary	219 dB	13 km²	2.0 km	2.0 km	2.0 km	1.3 km
	216 dB	28 km²	3.0 km	3.0 km	3.0 km	2.0 km
	210 dB	110 km²	6.3 km	5.6 km	6.0 km	4.3 km
	207 dB	200 km²	8.6 km	7.3 km	8.0 km	6.0 km
	203 dB	390 km²	12 km	9.7 km	11 km	8.7 km
	186 dB	2400 km²	36 km	16 km	27 km	24 km

Table 35: Summary of the impact ranges from simultaneous installation of two of the worst-case multi-leg foundation modelling at the SE location using the Popper et al. (2014) unweighted SEL_{cum} pile driving criteria for both fleeing and stationary fish

Popper *et al*. (2014) Unweighted SEL_{cum}		Simultaneous worst-case multi-leg foundations SE location				Single foundation area for comparison
		Area	Max range	Min range	Mean range	
Fleeing (1.5 m/s)	219 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km²	< 100 m	< 100 m	< 100 m	< 100 m
	186 dB	180 km²	11 km	3.9 km	7.2 km	5.1 km
Stationary	219 dB	6.1 km²	1.5 km	1.4 km	1.4 km	940 m
	216 dB	13 km²	2.2 km	2.0 km	2.0 km	1.4 km
	210 dB	51 km²	4.5 km	3.7 km	4.0 km	2.9 km
	207 dB	91 km²	6.2 km	4.7 km	5.4 km	4.0 km
	203 dB	180 km²	9.0 km	6.2 km	7.5 km	5.9 km
	186 dB	1300 km²	29 km	11 km	19 km	17 km

5.4 Cofferdam sheet piling

Table 36 to Table 43 show the noise modelling results for the cofferdam sheet pile installation near landfall, as discussed in section 4.2.5. Results are given for marine mammals using the Southall *et al*. (2019) criteria.

The results show that, due to the small piles, low blow energies and shallow water most impact ranges predicted for cofferdam installation using impact piling are expected to be negligible, especially when compared to impact piling for WTG foundations (sections 5.1 and 5.2). For marine mammals all SEL_{cum} PTS ranges are predicted to be less than 100 m and maximum TTS ranges for VHF cetaceans are predicted out to 480 m during the worst-case MHWS scenario.

For species of fish all SEL_{cum} injury criteria are predicted to be less than 160 m using the worst-case stationary animal results during MHWS; TTS ranges are predicted out to a maximum 1.3 km.

5.4.1 Marine mammal criteria

Table 36: Summary of the impact ranges from cofferdam sheet piling modelling using the impulsive Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals at MHWS

Southall *et al*. (2019) Unweighted SPL_{peak}		Worst-case multi-leg foundations – NW location			
		Area	**Max range**	**Min 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)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	PCW (218 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
TTS	**LF** (213 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	0.02 km²	70 m	70 m	70 m
	PCW (212 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m

Table 37: Summary of the impact ranges from cofferdam sheet piling modelling using the impulsive Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals at MLWS

Southall *et al*. (2019) Unweighted SPL_{peak}		**Worst-case multi-leg foundations – SE location**			
		Area	**Max range**	**Min range**	**Mean range**
PTS	**LF** (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (218 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	**LF** (213 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	PCW (212 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table 38: Summary of the impact ranges from cofferdam sheet piling modelling using the impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing receptor at MHWS

Southall *et al*. (2019) Weighted SEL_{cum}		**Worst-case multi-leg foundations – NW location**			
		Area	**Max range**	**Min range**	**Mean range**
PTS	**LF** (183 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	**LF** (168 dB)	0.1 km^2	210 m	180 m	200 m
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	0.4 km^2	480 m	230 m	340 m
	PCW (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m

Table 39: Summary of the impact ranges from cofferdam sheet piling modelling using the impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing receptor at MLWS

Southall *et al*. (2019) Weighted SEL_{cum}		**Worst-case multi-leg foundations – SE location**			
		Area	**Max range**	**Min range**	**Mean range**
PTS	**LF** (183 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	**LF** (168 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	< 0.1 km^2	100 m	< 100 m	< 100 m
	PCW (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m

5.4.2 Fish criteria

Table 40: Summary of the impact ranges from cofferdam sheet piling modelling using the Popper et al. (2014) unweighted SPL_{peak} pile driving criteria for fish at MHWS

Popper *et al.* (2014) Unweighted SPL_{peak}	Cofferdam sheet piling - MHWS			
	Area	**Max range**	**Min range**	**Mean range**
213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table 41: Summary of the impact ranges from cofferdam sheet piling modelling using the Popper et al. (2014) unweighted SPL_{peak} pile driving criteria for fish at MLWS

Popper *et al.* (2014) Unweighted SPL_{peak}	Cofferdam sheet piling - MLWS			
	Area	**Max range**	**Min range**	**Mean range**
213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
207 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table 42: Summary of the impact ranges from cofferdam sheet piling modelling using the Popper et al. (2014) unweighted SEL_{cum} pile driving criteria for fish assuming both a fleeing and stationary receptor at MHWS

Popper *et al.* (2014) Unweighted SEL_{cum}		Cofferdam sheet piling - MHWS			
		Area	**Max range**	**Min range**	**Mean range**
Fleeing (1.5 m/s)	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	< 0.1 km^2	< 100 m	< 100 m	< 100 m
Stationary	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	160 m	150 m	150 m
	186 dB	5.0 km^2	1.3 km	1.2 km	1.3 km

Table 43: Summary of the impact ranges from cofferdam sheet piling modelling using the Popper et al. (2014) unweighted SEL_{cum} pile driving criteria for fish assuming both a fleeing and stationary receptor at MLWS

Popper *et al.* (2014) Unweighted SEL_{cum}		Cofferdam sheet piling - MLWS			
		Area	**Max range**	**Min range**	**Mean range**
Fleeing (1.5 m/s)	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	< 0.1 km^2	< 100 m	< 100 m	< 100 m
Stationary	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	0.6 km^2	440 m	410 m	430 m

6 Other noise sources

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

Table 44 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 AyM.

Table 44: Summary of the possible noise making activities at AyM 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.
Vessel noise	Jack-up barges for piling substructure and WTG installation. Other large and medium sized vessels to carry out other construction tasks and anchor handling. Other small vessels for crew transport and maintenance on site.
Operational WTG	Noise transmitted through the water from operational WTG. The project design envelope gives WTGs with rotor diameters of up to 300 m.
UXO detonation	There is a possibility that Unexploded Ordnance (UXO) may exist within the boundaries of AyM, which would need to be cleared before construction can begin.

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

Most of these activities are considered in section 6.1, with turbine operational noise and UXO clearance assessed in sections 6.2 and 6.3 respectively.

6.1 Noise making activities

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

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

Predicted source levels and propagation calculations for the construction activities are presented in Table 45 along with a summary of the number of datasets used in each case. As previously, all SEL_{cum} criteria use the same assumptions as presented in section 2.2, and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. It should be noted that this modelling approach does not take bathymetry or any other environmental conditions into account, and as such can be applied to any location in the AyM area.

Table 45: Summary of the estimated unweighted source levels and transmission losses for the different construction noise sources considered

Source	Estimated unweighted 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 is 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*'
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 is present also needs to be considered, with all sources operating for a worst-case 12 hours in any given 24-hour period apart from vessel noise which is assumed to be present for 24 hours a day.

To account for the weightings required for modelling using the Southall *et al*. (2019) criteria (section 2.2.1), reductions in source level have been applied to the various noise sources. Figure 12 shows the representative noise measurements used, adjusted for the source levels given in Table 45. Table 46 presents details of the reductions in source levels for each of the weightings used for modelling.

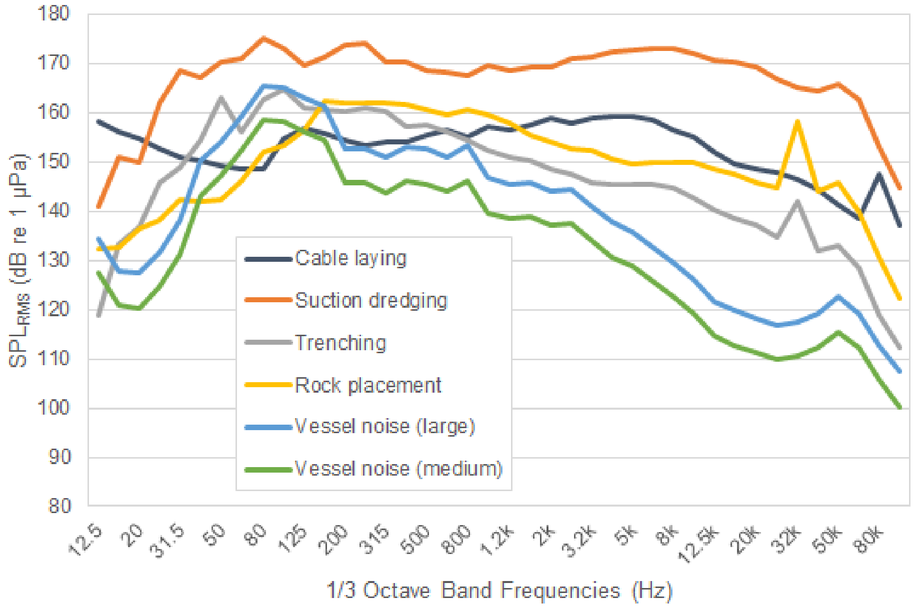

Figure 12: Summary of the 1/3rd octave frequency bands used as a basis for the Southall et al. (2019) weightings used in the simple modelling

Table 46: Reductions in source level for the different construction noise sources considered when the Southall et al. (2019) weightings are applied

Source	Reduction in source level from the unweighted level			
	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
Vessel noise	5.5 dB	34.4 dB	38.6 dB	17.4 dB

Table 47 and Table 48 summarise the predicted impact ranges for these noise sources. It is worth noting that Southall *et al*. (2019) and Popper *et al*. (2014) both give alternative criteria for non-impulsive or continuous noise sources compared to impulsive noise (see section 2.2); all sources in this section are considered non-pulses 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 assumes the same receptor swim speed as the impact piling modelling in section 5. As explained in section 4.3, it should also be noted that this would only mean that the receptor reaches the 'onset' stage, which is the minimum exposure that could potentially lead to the start of an effect and may only be marginal. In most hearing groups, the noise levels are low enough that there is negligible risk.

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

All sources presented here are much quieter than those presented for impact piling in section 5.

Table 47: 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**	**Trenching**	**Rock placement**	**Vessels (large)**	**Vessels (medium)**
PTS	199 dB (LF)	< 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
	173 dB (VHF)	< 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
TTS	179 dB (LF)	< 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
	153 dB (VHF)	< 100 m	200 m	< 100 m	1.0 km	200 m	< 100 m
	181 dB (PCW)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m

Table 48: 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**	**Trenching**	**Rock placement**	**Vessels (large)**	**Vessels (medium)**
Recoverable injury 170 dB (48 hours)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
TTS 158 dB (12 hours)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m

6.2 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.

Operational noise is commonly assessed in terms of the nominal power output of the proposed turbine. At the time of assessment, the project design envelope for AyM does not give a fixed upper power output, although there is a maximum potential WTG rotor diameter of 300 m, which will be used as an alternative metric for the representative size of the turbine. A summary of sites where operational WTG measurements have been collected by Subacoustech is given in Table 49.

Table 49: Characteristics of measured operational WTGs used as a basis for modelling

Wind farm	**Lynn**	**Inner Dowsing**	**Gunfleet Sands 1 & 2**	**Gunfleet Sands 3**
Type of WTG used	Siemens SWT-3.6-107	Siemens SWT-3.6-107	Siemens SWT-3.6-107	Siemens SWT-6.0-120
Number of WTGs	27	27	48	2
Power rating	3.6 MW	3.6 MW	3.6 MW	6 MW
Rotor diameter	107 m	107 m	107 m	120 m
Water depths	6 to 8 m	6 to 14 m	0 to 15 m	5 to 12 m
Representative sediment type	Sandy gravel / muddy sandy gravel	Sandy gravel / muddy sandy gravel	Sand / muddy sand / muddy sandy gravel	Sand / muddy sand / muddy sandy gravel
WTG separation	500 m	500 m	890 m	435 m

Tougaard *et al.* (2020) and Stöber and Thomsen (2021) both produced similar studies of underwater noise measurements at operational wind turbines, but none were above 6 MW. However, their results will be referenced below.

The estimation of the effects of operational WTG noise in these situations has two features that make it harder to predict compared with noise sources such as impact piling. Primarily, the problem is one of sufficient noise level; noise measurements made at many operational OWFs have demonstrated that the operational noise produced was at such a low level that it was difficult to measure relative to background noise at distances of a few hundred metres or more (Cheesman, 2016). Secondly, the multiple WTGs of an offshore wind farm could be considered as an extended, distributed noise source, as opposed to a "point source," for example as would be appropriate for piling driving at a single location. The measurement techniques used at the sites above have dealt with these issues by considering the operational WTG noise spectra in terms of levels within and on the edge of the wind farm (but relatively close to the WTGs, so that some noise above background can be detected).

The WTG sizes for AyM are larger than those shown in Table 49, and AyM is also situated in greater water depths. As such, estimations of a scaling factor must be conservative to minimise the risk of underestimating the noise. It is recognised that the available data on which to base the scaling factor is limited and the extrapolation that must be made is significant.

The operational source levels (as SPL_{RMS}) for the measured sites are given in Table 50 (Cheesman, 2016), with estimated source levels for AyM at the bottom of the table. To predict operational WTG noise levels at AyM, the extrapolated source level for the measured data at each of the sites has been taken, and then a linear correction factor has been included to scale up the source levels (Figure 13). A linear fit was applied to the data to keep conservatism in the extrapolation and to take account of the deeper water depths, leading to the highest, and thus worst-case, estimation of source level noise from the larger WTGs. This resulted in an estimated source level of 164 dB re 1 µPa (SPL_{RMS}) @ 1 m; 18 dB higher than the 120 m rotor WTG and at the high end of all measurements presented in a large study on all available operational turbines by Tougaard *et al.* (2020).

Table 50: Measured operational WTG noise taken at operational wind farms, and the predicted source level for the maximum WTG size considered at AyM

Site	Unweighted source level
Lynn (107 m)	141 dB re 1 µPa (SPL_{RMS}) @ 1 m
Inner Dowsing (107 m)	142 dB re 1 µPa (SPL_{RMS}) @ 1 m
Gunfleet Sands 1 & 2 (107 m)	145 dB re 1 µPa (SPL_{RMS}) @ 1 m
Gunfleet Sands 3 (120 m)	146 dB re 1 µPa (SPL_{RMS}) @ 1 m
AyM (300 m)	164 dB re 1 µPa (SPL_{RMS}) @ 1 m

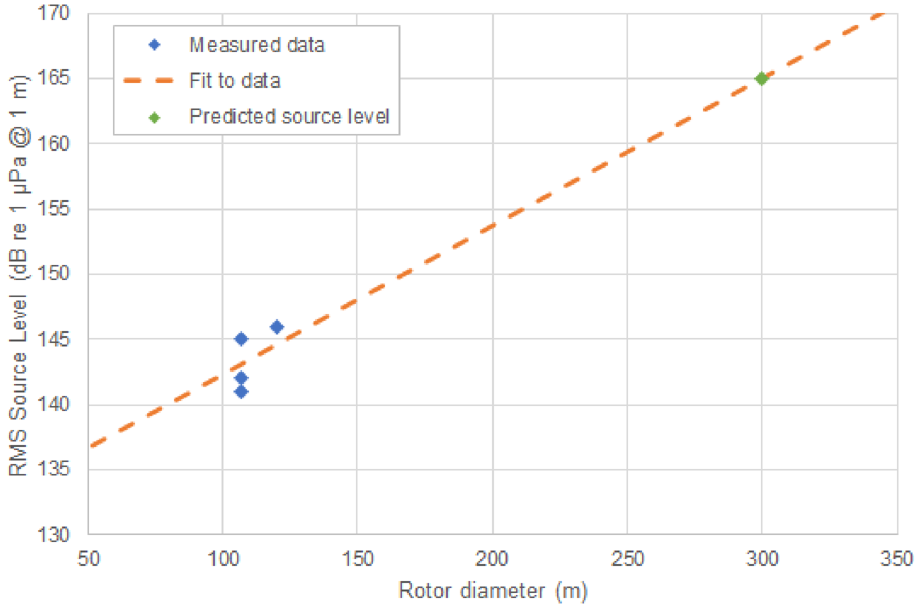

Figure 13: Extrapolated source levels from operational WTGs plotted with a linear fit to estimate the source level for a WTG with a rotor diameter of 300 m

It is acknowledged that this fit is speculative: the available data is limited. Newer, larger, direct drive (gearbox-less) designs tend to be more efficient and losses (e.g., in energy which produce noise and vibration) are significantly reduced. Preliminary measurements of such direct-drive WTGs have been collected off the east coast of the United States (HDR, 2019), showing extrapolated source levels of 136 dB re 1 µPa (SPL_{RMS}) @ 1 m for a 6 MW WTG. Stöber and Thomsen (2021) suggest that direct-drive designs may be 10 dB quieter than equivalent gearboxed models. Thus, the linear extrapolation above represents a considerably greater noise output and can be considered highly precautionary.

A summary of the predicted impact ranges is given in Table 51 and Table 52. All SEL_{cum} criteria use the same assumptions and fleeing speeds as presented in section 2.2, and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. The operational WTG source is considered a non-impulsive sound by Southall *et al*. (2019) and a continuous source by Popper *et al*. (2014). For SEL_{cum} calculations it has been assumed that the operational WTG noise is present 24 hours a day.

Table 51: Summary of the impact ranges for the proposed operational WTGs using the non-impulsive noise criteria from Southall et al. (2019) for marine mammals

Southall *et al*. (2019)		**Operational WTG (300 m rotor diameter)**
PTS Weighted SEL_{cum}	199 dB (LF)	< 100 m
	198 dB (HF)	< 100 m
	173 dB (VHF)	< 100 m
	201 dB (PCW)	< 100 m
TTS Weighted SEL_{cum}	179 dB (LF)	< 100 m
	178 dB (HF)	< 100 m
	153 dB (VHF)	< 100 m
	181 dB (PCW)	< 100 m

Table 52: Summary of the impact ranges for the proposed operational WTGs using the continuous noise criteria from Popper et al. (2014) for fish

Popper *et al*. (2014)	**Operational WTG (300 m rotor diameter)**
Recoverable injury Unweighted $SPL_{RMS,}$ 170 dB (48 hours)	< 50 m
TTS Unweighted $SPL_{RMS,}$ 158 dB (12 hours)	< 50 m

These results show that, for noise from operational WTGs, injury risk is minimal when assuming a fleeing animal model over 24 hours.

6.3 UXO clearance

There is a potential that UXO devices may be found within the boundaries of AyM covering a range of charge weights (or quantity of contained explosive). Once identified, these need to be cleared before any construction can begin. These UXO may contain a variety of explosive types, many of which 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 has been found at similar sites and, in each case, it has been assumed that the maximum explosive charge in each device is present and detonates with the clearance.

6.3.1 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 is based in the equivalent weight of TNT, sometimes referred to as 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 it will affect the sound produced by detonation, are usually unknown and cannot be directly considered in this type of assessment. 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 is that the noise levels produced, particularly by the larger explosives under consideration, are likely to be over-estimated as some degree of degradation would be expected.

The range of equivalent charge weights for the potential UXO devices that could be present at AyM have been estimated as devices with NEQs of 25, 55, 131, 240, and 525 kg; with the 131 kg NEQ representing the ‘Smallest Hazard Item’ of a German ‘Type II’ sea mine. Estimation of the source noise level for each charge weight has been carried out in accordance with the methodology of Soloway and Dahl (2014), which follows Arons (1954) and the Marine Technical Directorate (MTD) (1996).

6.3.2 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}:

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

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

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 and Irish Seas in similar depths to those present at AyM. This includes a frequency dependent sound absorption term dependent on the range, temperature, depth and other typical environmental parameters of the water in this area.

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 equations above for small charges at ranges of less than 1 km, although the results do agree with measurements presented by von Benda-Beckmann *et al*. (2015). At these larger ranges, greater confidence is expected with the SEL calculations compared to the SPL_{peak} 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 smoother (i.e., the pulse becomes longer) over distance (Cudahy and Parvin, 2001), meaning that injurious potential of a wave at greater ranges can be even lower than just a reduction in the absolute noise level. An assessment in respect of SEL is considered preferential at long range as it considers the overall energy, and the smoothing of the peak 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 a non-pulse at greater distance. This study has presented impact ranges for both impulsive and non-impulsive criteria, suggesting that, at greater ranges, it may be more appropriate to use the non-pulse criteria.

A summary of the unweighted UXO source levels calculated using the equations above are given in Table 53.

Table 53: Summary of the unweighted SPL_{peak} and SEL_{ss} source levels used for UXO modelling

NEQ	25 kg	55 kg	131 kg	240 kg	525 kg
SPL_{peak} source level (dB re 1 µPa @ 1 m)	284.9	287.4	290.3	292.2	294.8
SEL_{ss} source level (dB re 1 µPa^{2}s @ 1 m)	227.9	230.1	232.5	234.2	236.4

6.3.3 Impact ranges

Table 54 to Table 57 present the impact ranges for UXO detonation, considering various charge weights and impact criteria. It should be noted that Popper *et al*. (2014) gives specific impact criteria for explosions (Table 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}. Thus, fleeing animal assumptions do not apply.

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

As with the previous sections, ranges smaller than 50 m have not been presented.

Table 54: 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}		**25 kg**	**55 kg**	**131 kg**	**240 kg**	**525 kg**
PTS	219 dB (LF)	810 m	1.0 km	1.4 km	1.7 km	2.2 km
	230 dB (HF)	260 m	340 m	460 m	560 m	730 m
	202 dB (VHF)	4.6 km	6.0 km	8.0 km	9.8 km	13 km
	218 dB (PCW)	900 m	1.1 km	1.5 km	1.9 km	2.5 km
TTS	213 dB (LF)	1.5 km	1.9 km	2.6 km	3.2 km	4.1 km
	224 dB (HF)	490 m	640 m	850 m	1.0 km	1.3 km
	196 dB (VHF)	8.5 km	11 km	15 km	18 km	23 km
	212 dB (PCW)	1.6 km	2.1 km	2.9 km	3.5 km	4.6 km

Table 55: 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}		**25 kg**	**55 kg**	**131 kg**	**240 kg**	**525 kg**
PTS (Impulsive)	183 dB (LF)	2.1 km	3.2 km	4.8 km	6.5 km	9.5 km
	185 dB (HF)	< 50 m	< 50 m	< 50 m	< 50 m	50 m
	155 dB (VHF)	560 m	740 m	980 m	1.1 km	1.4 km
	185 dB (PCW)	380 m	560 m	860 m	1.1 km	1.6 km
TTS (Impulsive)	168 dB (LF)	29 km	41 km	60 km	76 km	103 km
	170 dB (HF)	150 m	210 m	310 m	390 m	530 m
	140 dB (VHF)	2.4 km	2.8 km	3.2 km	3.5 km	4.0 km
	170 dB (PCW)	5.2 km	7.4 km	11 km	14 km	20 km

Table 56: 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}		**25 kg**	**55 kg**	**131 kg**	**240 kg**	**525 kg**
PTS (Non-Impulsive)	199 dB (LF)	120 m	190 m	290 m	390 m	570 m
	198 dB (HF)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 50 m	< 50 m	70 m	100 m	130 m
	201 dB (PCW)	< 50 m	< 50 m	50 m	70 m	100 m
TTS (Non-Impulsive)	179 dB (LF)	4.4 km	6.4 km	9.7 km	13 km	19 km
	178 dB (HF)	< 50 m	60 m	90 m	110 m	160 m
	153 dB (VHF)	730 m	940 m	1.2 km	1.4 km	1.7 km
	181 dB (PCW)	780 m	1.1 km	1.7 km	2.3 km	3.3 km

Table 57: Summary of the impact ranges for UXO detonation using the unweighted SPL_{peak} explosion noise criteria from Popper et al. (2014) for species of fish

Southall *et al.* (2019) Weighted SEL_{ss}	**25 kg**	**55 kg**	**131 kg**	**240 kg**	**525 kg**
234 dB (Mortality and potential mortal injury)	170 m	230 m	300 m	370 m	490 m
229 dB (Mortality and potential mortal injury)	290 m	380 m	510 m	620 m	810 m

The maximum PTS range calculated here for the largest, 525 kg TNT equivalent, UXO is 9.5 km for the LF cetacean category, based on the weighted SEL criteria. In comparison with measurements of UXO noise propagation published by Salomons *et al*. (2021) the impact ranges above are expected to be precautionary. Salomons *et al.* (2021) presented measured noise levels for a 325 kg and 140 kg NEQ charge weight UXO with high-order detonation at distances between 1.5 km and 12 km, in approximately 20 m of water. SPL_{peak} measurements were found to be 7 to 17 dB lower than the equivalent estimations above, with the greatest deviations at longest range, as expected. A similar divergence was found for SEL, except at close range, where the measurements were up to 3.8 dB greater. However, at this range the smaller device had greater noise levels than the larger device, so there may be other complications in the measured data.

As explained earlier, this assumes no degradation of the UXO and no smoothing of the pulse over that distance, which is very precautionary. Although an assumption of non-pulse could underestimate the potential impact (Martin *et al*., 2020) (the equivalent range based on LF cetacean non-impulsive criteria is 570 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 is very precautionary.

7 Summary and conclusions

Subacoustech Environmental have undertaken a study on behalf of Awel y Mor Offshore Wind Farm Limited to assess the potential underwater noise, and its effects, created during the construction and operation of AyM.

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

Two representative modelling locations were chosen for the WTG foundations to give spatial variation as well as accounting for changes in water depth around AyM. At each location worst-case monopile and multi-leg foundations were considered. These are listed below:

- Worst-case monopile foundation – a 15 m diameter pile installed with a maximum blow energy of 5,000 kJ over 272 minutes, with a maximum of two foundations installed in a single 24-hour period; and
- Worst-case multi-leg foundation – a 3.5 m diameter pile installed with a maximum blow energy of 3,000 kJ over 230 minutes, with a maximum of four foundations installed in a single 24-hour period.

The loudest levels of noise, and greatest potential impact ranges, have been predicted for worst-case monopile foundations at the NW location. Smaller ranges are predicted at the SE location, due to the shallower water depths and proximity to the coastline, and for the multi-leg foundation scenarios. When considering simultaneous installation of two multi-leg foundations at the same location, the predicted impact ranges exceed those of the monopile foundations.

The modelling results were analysed in terms of relevant noise metrics and criteria to assess the effect of the impact piling noise 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 8.5 km when considering the worst-case monopile foundations at the NW location. For fish, the largest TTS ranges were predicted to be 16 km for a fleeing receptor, increasing to 30 km for a stationary receptor.

The noise from the impact piling of sheet piles near landfall for cofferdam installation was also considered. Due to the small piles, low blow energies and shallow water, most impact ranges predicted for cofferdam installation using impact piling are expected to be negligible.

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

UXO clearance has also been considered, and for the potential UXO detonation noise, there is a risk of PTS up to 9.5 km from the largest UXO considered, a 525 kg device, using the impulsive Southall *et al*. (2019) criteria for LF cetaceans using the SEL criteria, of 13 km for VHF cetaceans using the Southall *et al*. (2019) SPL_{peak} criteria. However, this is likely to be very precautionary as the impact range is based on worst case criteria that do not account for any smoothing of the pulse over long ranges, which reduces the pulse peak and other characteristics of the sound that cause injury.

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

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Appendix A Additional results

A.1 Non-impulsive impact piling results

Following from the Southall et al. (2019) impact ranges presented in section 5.1 of the main report, Table 58 to Table 61 present the modelling results for non-impulsive criteria from impact piling noise at AyM, as discussed in section 2.2.1. The predicted ranges fall well below the impulsive criteria presented in the main report.

Table 58: Summary of the impact ranges from the worst-case monopile foundation modelling at the NW location using the non-impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing receptor

Southall *et al*. (2019) Weighted SEL_{cum}		Worst-case monopile foundations – NW location			
		Area	**Max range**	**Min 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)	310 km²	14 km	5.9 km	9.6 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	91 km²	6.6 km	4.1 km	5.3 km
	PCW (181 dB)	0.4 km²	450 m	250 m	350 m

Table 59: Summary of the impact ranges from the worst-case monopile foundation modelling at the SE location using the non-impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing receptor

Southall *et al*. (2019) Weighted SEL_{cum}		Worst-case monopile foundations – SE location			
		Area	**Max range**	**Min 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)	80 km²	8.2 km	2.0 km	4.6 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	29 km²	4.3 km	1.9 km	2.9 km
	PCW (181 dB)	< 0.1 km²	100 m	< 100 m	< 100 m

Table 60: Summary of the impact ranges from the worst-case multi-leg foundation modelling at the NW location using the non-impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing receptor

Southall *et al*. (2019) Weighted SEL_{cum}		Worst-case multi-leg foundations – NW location			
		Area	**Max range**	**Min 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)	220 km²	11 km	4.8 km	8.0 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	60 km²	5.3 km	3.3 km	4.3 km
	PCW (181 dB)	< 0.1 km²	150 m	100 m	120 m

Table 61: Summary of the impact ranges from the worst-case multi-leg foundation modelling at the SE location using the non-impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing receptor

Southall *et al*. (2019) Weighted SEL_{cum}		**Worst-case multi-leg foundations – SE location**			
		Area	**Max range**	**Min 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)	42 km²	6.2 km	1.2 km	3.3 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	16 km	3.3 km	1.3 km	2.2 km
	PCW (181 dB)	< 0.1 km²	100 m	< 100 m	< 100 m

A.2 Simultaneous modelling

Table 62 and Table 63 expand on the results presented in section 5.3 for simultaneous multi-leg piling at the same location, covering the non-impulsive criteria from Southall *et al*. (2019) for marine mammals.

Table 62: Summary of the impact ranges from the worst-case multi-leg foundation modelling at the SE location using the non-impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing receptor

Southall *et al*. (2019) Weighted SEL_{cum}		**Simultaneous worst-case multi-leg foundations NW location**			
		Area	**Max range**	**Min 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)	390 km²	15 km	6.3 km	11 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	140 km²	8.3 km	4.9 km	6.7 km
	PCW (181 dB)	4.7 km²	1.5 km	880 m	1.2 km

Table 63: Summary of the impact ranges from the worst-case multi-leg foundation modelling at the SE location using the non-impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing receptor

Southall *et al*. (2019) Weighted SEL_{cum}		**Simultaneous worst-case multi-leg foundations NW location**			
		Area	**Max range**	**Min 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)	100 km²	9.4 km	2.1 km	5.2 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	49 km²	5.6 km	2.3 km	3.8 km
	PCW (181 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m

A.3 Cofferdam impact piling modelling

Table 64 and Table 65 present the non-impulsive Southall *et al*. (2019) criteria for cofferdam sheet pile modelling, expanding on the results presented in section 5.4. Using these criteria, all the results for PTS and TTS are expected to be negligible.

Table 64: Summary of the impact ranges from cofferdam sheet piling modelling using the non-impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing receptor at MHWS

Southall *et al*. (2019) Weighted SEL_{cum}		Worst-case multi-leg foundations – NW location			
		Area	**Max range**	**Min range**	**Mean range**
PTS	**LF** (183 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	**LF** (168 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m

Table 65: Summary of the impact ranges from cofferdam sheet piling modelling using the non-impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing receptor at MLWS

Southall *et al*. (2019) Weighted SEL_{cum}		Worst-case multi-leg foundations – SE location			
		Area	**Max range**	**Min range**	**Mean range**
PTS	**LF** (183 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	**LF** (168 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m

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P274R0100	05	20/04/2021	Initial writing and internal review
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