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Appendix 10.1: Underwater Noise Technical Report

Array EIA Report

2024

Revision	Comments	Author	Checker	Approver
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Approval for Issue		
For and on behalf of Ossian OWFL	Paul Darnbrough	28 June 2024

Prepared by:	**RPS Energy**
Prepared for:	**Ossian Offshore Wind Farm Limited (OWFL)**
Checked by:	**Caitline Donald**
Accepted by:	**Fraser Malcolm**
Approved by:	**Paul Darnbrough**

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1. INTRODUCTION

1. This technical report presents the results of a desktop study undertaken by Seiche Ltd. considering the potential effects of underwater noise on the marine environment from the development of the Ossian Array (hereafter simply referred to as the 'Array').

2. The Array, which is to be located within the site boundary, is located in the North Sea, approximately 80 km east of the Aberdeenshire coast (Figure 1.1). The planned activities within the site boundary fall into four phases: pre-construction, construction, operation and maintenance, and decommissioning. Within each of these four phases, different underwater noise sources are identified. These noise sources are both continuous and intermittent in characteristics.

3. Noise is readily transmitted into the underwater environment and there is potential for the noise emissions from construction, operation and maintenance and decommissioning of the Array to adversely affect marine mammals and fish. At a close range from a noise source with high noise levels, permanent or temporary hearing damage may occur to marine species, while at a very close range gross physical trauma is possible. At wider ranges, the introduction of any additional noise could potentially cause short term behavioural changes, for example the ability of a species to communicate and to determine the presence of predators, food, underwater features and obstructions. It should be noted, however, despite the topic being an area of active research, current scientific literature is unclear on whether/how close range or short-term impacts may translate to long term population level impacts.

4. The primary purpose of this technical report is to present the likely distances at which the onset of potential auditory injury (i.e. Permanent Threshold Shifts (PTS) in hearing) and behavioural effects on different marine species may occur when exposed to the different anthropogenic noises that occur during different developmental phases of the Array. The results from this technical report have been used to inform the following chapters of the Array Environmental Impact Assessment (EIA) Report in order to determine the potential impact of underwater noise on marine species:

   - volume 2, chapter 9: fish and shellfish ecology;
   - volume 2, chapter 10: marine mammals; and
   - volume 2, chapter 12: commercial fisheries.

5. Consequently, the sensitivity of species, magnitude of potential impact and significance of effect from underwater noise associated with the Array are addressed within the relevant chapters (volume 2, chapters 9, 10 and 12).

6. This technical report uses noise propagation models to calculate the impact ranges to marine mammals and fish for each phase of the Array. Key modelled sources include:

   - clearance of Unexploded Ordnance (UXO);
   - geophysical and geotechnical surveys;
   - impact piling; and
   - vessels and other non-impulsive sources.

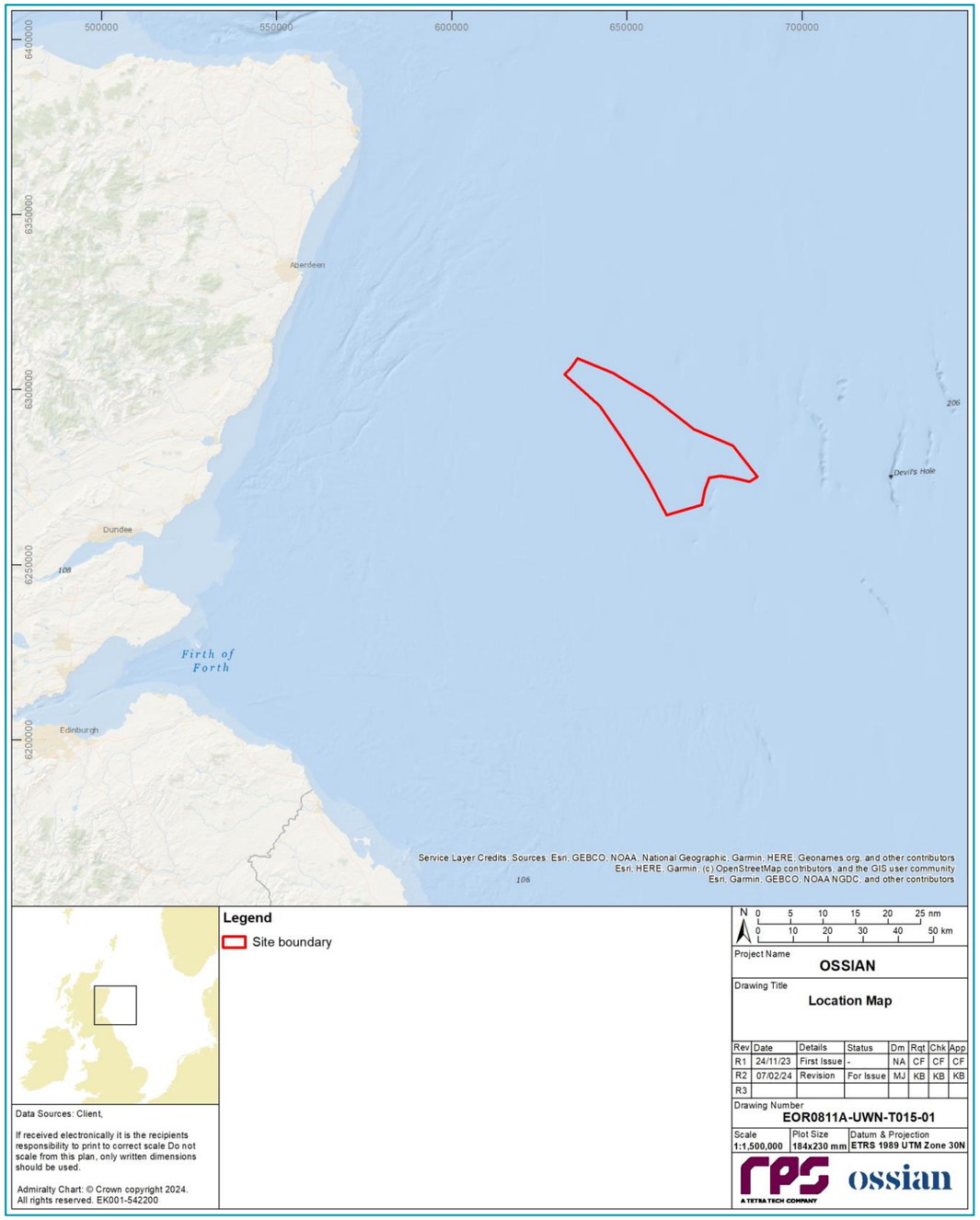

Figure 1.1: Location of the Array

2. STUDY AREA

7. No specific study area has been outlined for underwater noise as this is defined by the receptors and discussed within the relevant topics listed in paragraph 4.

8. The modelled area is approximately 146,000 km^2 and covers the Array and an area extending up to 200 km from the site boundary up to land.

9. Bathymetry data used within the modelling was obtained from the General Bathymetric Chart of the Oceans (GEBCO). The GEBCO 2021 Grid is a global terrain model for ocean and land, providing elevation data, in metres, on a 15 arc-second interval grid.

10. To produce a representative sound speed profile, conductivity, temperature, and depth (CTD) data were obtained from the National Oceanic Atmospheric Administration (NOAA) service WODselect for the closest sample point to the development (NOAA, 2023).

3. ACOUSTIC CONCEPTS AND TERMINOLOGY

11. Noise travels through water as vibrations of the fluid particles in a series of pressure waves. These waves comprise a series of alternating compressions (positive pressure) and rarefactions (negative pressure). As noise consists of variations in pressure, the unit for measuring noise is usually referenced to a unit of pressure, the Pascal (Pa). The decibel (dB) is a logarithmic ratio scale used to communicate the large range of acoustic pressures that can be perceived or detected, with a known pressure amplitude chosen as a reference value (i.e. 0 dB). In the case of underwater noise, the reference value (P_{ref}) is taken as 1 µPa, whereas the airborne noise is usually referenced to a pressure of 20 µPa. To convert from a sound pressure level referenced to 20 µPa to a sound pressure referenced to 1 µPa, a factor of 20 log (20/1) (i.e. 26 dB has to be added to the former quantity). Thus 60 dB re 20 µPa is the same as 86 dB re 1 µPa, although differences in sound speeds and different densities mean that the decibel level difference in sound intensity is much more than 26 dB when converting pressure from air to water. All underwater sound pressure levels in this report are quantified in dB re 1 µPa.

12. There are several descriptors used to characterise a sound wave. The difference between the lowest pressure variation (rarefaction) and the highest-pressure variation (compression) is called the peak-to-peak (or pk-pk) sound pressure level. The difference between the highest variation (either positive or negative) and the mean pressure is called the peak pressure level. Lastly, the Root Mean Square (rms) sound pressure level is used as a description of the average amplitude of the variations in pressure over a specific time window. Decibel values reported should always be quoted along with the P_{ref} value employed during calculations. For example, the measured sound pressure level (SPL_{rms}) value of a pulse may be reported as 100 dB re 1 µPa. These descriptions are shown graphically in Figure 3.1.

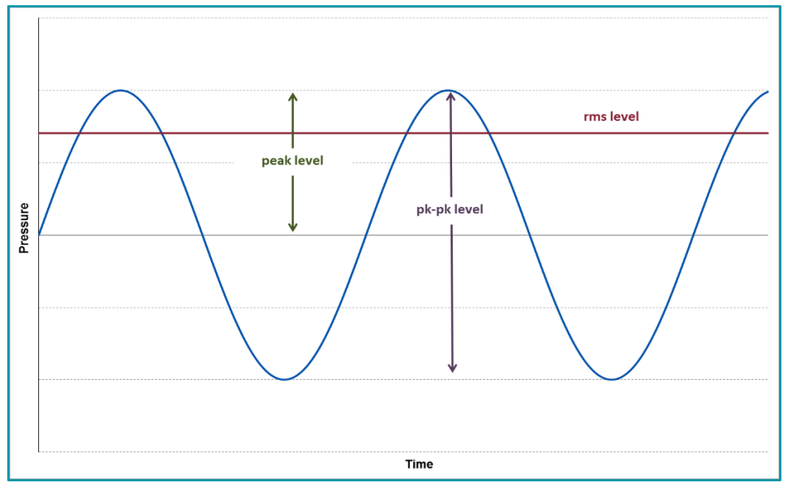

Figure 3.1: Graphical Representation of Acoustic Wave Descriptors

13. The SPL_{rms} is defined as:

$$SPL_{rms} = 10log_{10}\left(\frac{1}{T}\int_0^T\left(\frac{p^2}{p_{ref}^2}\right)dt\right)$$

14. The magnitude of the rms sound pressure level for an impulsive noise (such as airguns from a seismic survey source) will depend upon the integration time, T, used for the calculation (Madsen, 2005). It has become customary to utilise the T90 time period for calculating and reporting rms sound pressure levels[1]. This T90 time period is the interval over which the cumulative energy curve rises from 5% to 95% of the total energy and therefore contains 90% of the sound energy.

15. Another useful measure of noise used in underwater acoustics is the Sound Exposure Level (SEL). This descriptor is used as a measure of the total sound energy of an event or a number of events (e.g. over the course of a day) and is normalised to one second. This allows the total acoustic energy contained in events lasting a different amount of time to be compared on a like for like basis[2]. The SEL is defined as:

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

where T is the integration time of the noise "event", $p^2(t)$ is the squared sound pressure at a time t and $p_{ref}^2 t_{ref}$ is the reference time-integrated squared sound pressure of 1 µPa^{2}s.

16. The frequency of the noise is the rate at which the acoustic oscillations occur in the medium (air/water) and is measured in cycles per second, or Hertz (Hz). When noise is measured in a way which approximates to how a human would perceive it using an A-weighting filter on a noise level meter, the resulting level is described in values of dBA. However, the hearing capability of marine species is not the same as humans, with marine mammals hearing over a wider range of frequencies and with a different sensitivity. It is therefore important to understand how an animal's hearing varies over its entire frequency range to assess

1 The integration time and T90 window are often not reported, particularly in some older studies, meaning that it is often difficult to compare reported rms noise pressure levels between studies.

2 Historically, rms and peak SPL metrics were used for assessing potential effects of noise on marine species. However, SEL is increasingly being used as it allows exposure duration and the effect of exposure to multiple events to be considered.

the effects of anthropogenic noise on marine mammals. Consequently, use can be made of frequency weighting scales (M-weighting) to determine the level of the noise in comparison with the auditory response of the animal concerned. A comparison between the typical hearing response curves for fish, humans and marine mammals is shown in Figure 3.2[3].

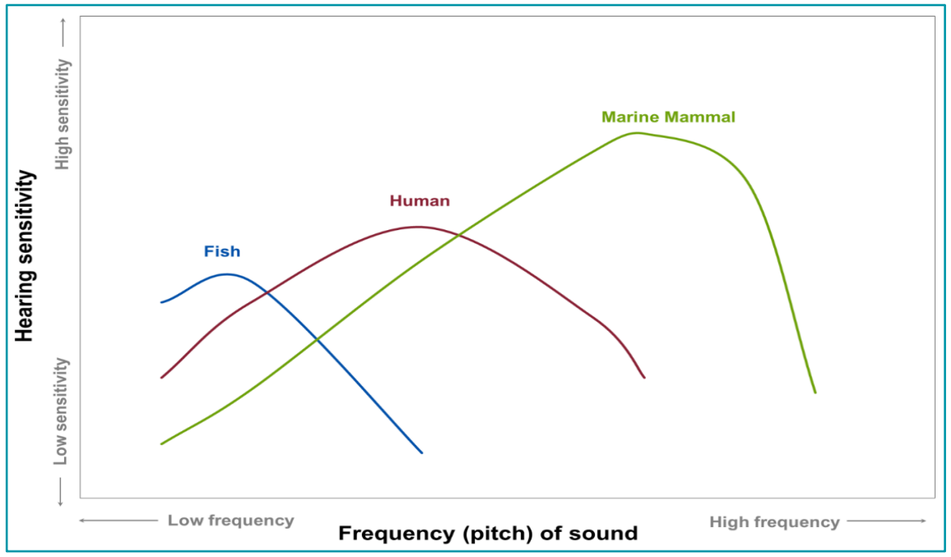

Figure 3.2: Comparison Between Hearing Thresholds of Different Animals

17. The broadband acoustic power (i.e. containing all the possible frequencies) emitted by a noise source, measured/modelled at a location within the Array is generally split into and reported in a series of frequency bands. In marine acoustics, the spectrum is generally reported in standard one-third octave band frequencies, where an octave represents a doubling in noise frequency[4].

18. The source level is the sound pressure level of an equivalent and infinitesimally small version of the source (known as point source) at a hypothetical distance of 1 m from it. The source level is commonly used in combination with the Transmission Loss (TL) associated with the environment to obtain the Received Level (RL) at distances from (in the far field of) the source. The far field distance is chosen so that the behaviour of a distributed source[5] can be approximated to that of a point source. Source levels do not indicate the real sound pressure level at 1 m. TL at a frequency of interest is defined as the loss of acoustic energy as the signal propagates from a hypothetical (point) source location to the chosen receiver location. The TL is dependent on water depth, source depth, receiver depth, frequency, geology, and environmental conditions. The TL values are generally evaluated using an acoustic propagation model (various numerical methods exist) accounting for these dependencies.

The RL is the noise level of the acoustic signal recorded (or modelled) at a given location, that corresponds to the acoustic pressure/energy generated by a known active noise source. This considers the acoustic output of a source and is modified by propagation effects. This RL value is strongly dependant on the source, environmental properties, geological properties, and measurement location/depth. The RL is reported in dB either in rms or peak-to-peak sound pressure level (SPL), and SEL metrics, within the relevant one-third octave band frequencies. The RL is related to the SL as (where TL is the transmission loss of the acoustic energy within the survey region):

$$RL = SL - TL$$

19. The directional dependence of the source signature and the variation of TL with azimuthal direction (which is strongly dependent on bathymetry) are generally combined and interpolated to report a two-Dimensional (2-D) plot of the RL around the chosen source point up to a chosen distance.

4. BASELINE

20. Background or “ambient” underwater noise is created by several natural sources, such as rain, breaking waves, wind at the surface, seismic noise, biological noise, and thermal noise. Anthropogenic noises related to the Array activities can be either impulsive (pulsed) such as impact piling, or non-impulsive (continuous) such as ship engines, and the magnitude of the potential impact on marine species will depend heavily on these characteristics. Biological noise sources include marine mammals (using noise to communicate, build up an image of their environment and detect prey and predators) as well as certain fish and shrimp. Anthropogenic noise sources of noise in the marine environment include fishing boats, ships (non-impulsive), marine construction, seismic surveys, and leisure activities (all could be either impulsive or non-impulsive), all of which add to ambient background noise. Other anthropogenic noise within the vicinity of the Array will arise primarily from shipping, the offshore oil and gas industry, subsea geophysical and geotechnical surveys, and the offshore renewables industry.

21. Historically, research relating to both physiological effects and behavioural disturbance of noise on marine receptors has typically been based on determining the absolute noise level for the onset of that effect (whether presented as a single onset threshold or a dose-response/probabilistic function). Consequently, the available numerical criteria for assessing the effects of noise on marine mammals, fish, and shellfish, tend to be based on the absolute noise level criteria, rather than the difference between the baseline noise level and the noise being assessed (Southall *et al.*, 2019).

22. Baseline or background noise levels vary significantly depending on multiple factors, such as seasonal variations and different sea states. Lack of long term measurements/noise data is a widely recognised gap in knowledge in relation to general noisescape and potential effects of human activities on marine species. Understanding the baseline noise level could therefore be valuable in enabling future studies to assess long term effects related to continuous noise levels over time in addition to activity specific effects such as masking, i.e. interfering with useful noises such as predator or prey activity. However, the value of establishing the precise baseline noise level is limited in relation to the current assessment methods due to the lack of available evidence-based studies on the effects of noise relative to background levels on marine receptors.

3 It is worth noting that hearing thresholds are sometimes shown as audiograms with noise level on the y axis rather than sensitivity, resulting in the graph shape being the inverse of the graph shown.

4 There are two definitions for third octave bands, one using a base 2 and the other using base 10, also known as a decidecade. The frequency ratio corresponding to a decidecade is smaller than a one-third octave (base 2) by approximately 0.08% (ISO, 2017).

5 A distributed source in this context refers to either a combination of two or more smaller sources, or a large source which cannot be treated as a point or monopole source.

5. ACOUSTIC ASSESSMENT CRITERIA

23. Section 5 describes the background and criteria on which the assessment has been based. Agreement on the methodology was agreed with NatureScot via the Array EIA Scoping Report (volume 3, appendix 6.1) and post-Scoping consultation via email on 05 December 2023. Consultation relevant to underwater noise is included in volume 3, appendix 5.1 and responses to consultation have been addressed in volume 2, chapter 10.

5.1. INTRODUCTION

24. Underwater noise has the potential to affect marine species in different ways depending on its noise level and characteristics. Richardson *et al.* (1995) defined four zones of noise influence which vary with distance from the source and level. These are:

- **The zone of audibility**: this is the area within which the animal can detect the noise. Audibility itself does not implicitly mean that the noise will affect the marine mammal.
- **The zone of masking**: this is defined as the area within which noise can interfere with the detection of other noises such as communication or echolocation clicks. This zone is very hard to estimate due to a paucity of data relating to how marine mammals detect noise in relation to masking levels[6] (for example, humans can hear tones well below the numeric value of the overall noise level).
- **The zone of responsiveness**: this is defined as the area within which the animal responds either behaviourally or physiologically. The zone of responsiveness is usually smaller than the zone of audibility because, as stated previously, audibility does not necessarily evoke a reaction.
- **The zone of injury/hearing loss**: this is the area where the noise level is high enough to cause tissue damage in the ear. This can be classified as either a Temporary Threshold Shift (TTS) or PTS. At even closer ranges, and for very high intensity noise sources (e.g. underwater explosions), physical trauma or even death are possible.

25. For the study contained within this technical report, it is the zones of injury and disturbance (i.e. responsiveness) that are of interest (there is insufficient scientific evidence to properly evaluate masking). To determine the potential spatial range of injury and disturbance, a review has been undertaken of available evidence, including international guidance and scientific literature. The following sections summarise the relevant thresholds for onset of effects and describe the evidence base used to derive them.

5.2. INJURY (PHYSIOLOGICAL DAMAGE) TO MAMMALS

26. Noise propagation models can be constructed to allow the received noise level at different distances from the source to be calculated. To determine the potential consequence of these received levels on any marine mammals which might experience such noise emissions, it is necessary to relate the levels to known or estimated potential impact thresholds. The auditory injury (PTS/TTS) threshold criteria proposed by Southall *et al.* (2019) are based on a combination of unweighted peak pressure levels and mammal hearing weighted SEL. The hearing weighting function is designed to represent the frequency characteristics (bandwidth and noise level) for each group within which acoustic signals can be perceived and therefore assumed have auditory effects. The categories include:

- **Low Frequency (LF) cetaceans**: marine mammal species such as baleen whales (e.g. minke whale *Balaenoptera acutorostrata*).
- **High Frequency (HF) cetaceans**: marine mammal species such as dolphins, toothed whales, beaked whales and bottlenose whales (e.g. bottlenose dolphin *Tursiops truncates* and white-beaked dolphin *Lagenorhynchus albirostris*).
- **Very High Frequency (VHF) cetaceans**: marine mammal species such as true porpoises, river dolphins and pygmy/dwarf sperm whales and some oceanic dolphins, generally with auditory centre frequencies above 100 kHz) (e.g. harbour porpoise *Phocoena phocoena*).
- **Phocid Carnivores in Water (PCW)**: true seals (e.g. harbour seal *Phoca vitulina* and grey seal *Halichoreus grypus*); hearing in air is considered separately in the group Phocid Carnivores in Air (PCA).
- **Other Marine Carnivores in Water (OCW)**: including otariid pinnipeds (e.g. sea lions and fur seals), sea otters and polar bears; air hearing considered separately in the group Other Marine Carnivores in Air (OCA).

27. These weighting functions have therefore been used in this study and are shown in Figure 5.1.

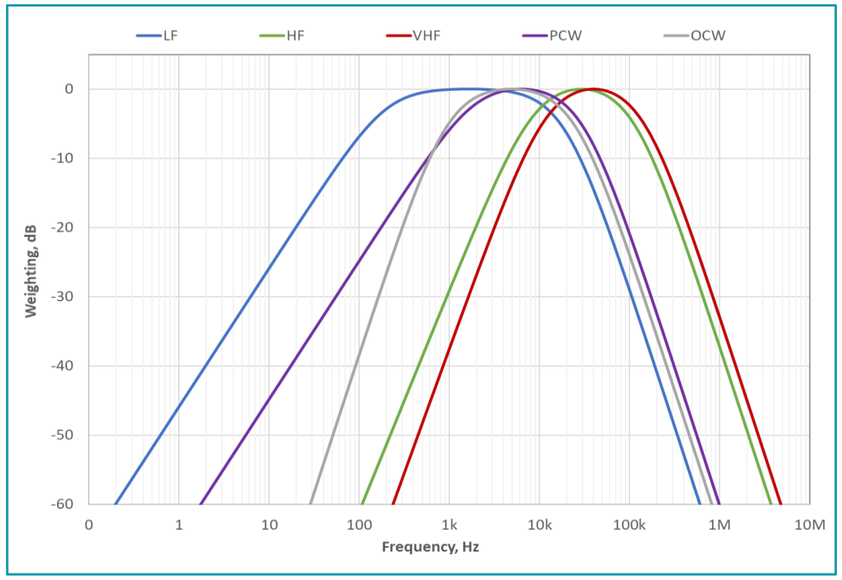

Figure 5.1: Hearing Weighting Functions for Pinnipeds and Cetaceans (Southall *et al.*, 2019)

28. Auditory injury criteria proposed in Southall *et al.* (2019) are for two different types of noise as follows:

- **Impulsive noises** which are typically transient, brief (less than one second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay (ANSI, 1986 and 2005; NIOSH, 1998). This category includes noise sources such as seismic surveys, impact piling and underwater explosions.
- **Non-impulsive noises** which can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent and typically do not have a high peak sound pressure with rapid rise/decay time that impulsive noises do (ANSI, 1995; NIOSH, 1998). This category includes noise sources such as continuous running machinery, sonar, and vessels.

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

29. The criteria for impulsive and non-impulsive noise have been adopted for this study given the nature of the variety of noise source used during the various activities. The relevant criteria proposed by Southall *et al.* (2019) are as summarised in Table 5.1 and Table 5.2.

Table 5.1: Summary of PTS Onset Acoustic Thresholds (Southall *et al.*, 2019; Tables 6 and 7)

Hearing Group	Parameter	Impulsive	Non-Impulsive
LF cetaceans	Peak, unweighted	219	-
	SEL, LF weighted	183	199
HF cetaceans	Peak, unweighted	230	-
	SEL, HF weighted	185	198
VHF cetaceans	Peak, unweighted	202	-
	SEL, VHF weighted	155	173
PCW	Peak, unweighted	218	-
	SEL, PCW weighted	185	201
OCW	Peak, unweighted	232	-
	SEL, OCW weighted	203	219

Table 5.2: Summary of TTS Onset Acoustic Thresholds (Southall *et al.*, 2019; Tables 6 and 7)

Hearing Group	Parameter	Impulsive	Non-Impulsive
LF cetaceans	Peak, unweighted	213	-
	SEL, LF weighted	168	179
HF cetaceans	Peak, unweighted	224	-
	SEL, HF weighted	170	178
VHF cetaceans	Peak, unweighted	196	-
	SEL, VHF weighted	140	153
PCW	Peak, unweighted	212	-
	SEL, PCW weighted	170	181
OCW	Peak, unweighted	226	-
	SEL, OCW weighted	188	199

5.3. DISTURBANCE TO MARINE MAMMALS

30. Beyond the area in which auditory injury may occur, effects on marine mammal behaviour are an important measure of potential impact. Non-trivial disturbance may occur when there is a risk of animals incurring sustained or chronic disruption of behaviour or when animals are displaced from an area, with subsequent redistribution being significantly different from that occurring due to natural variation.

31. To consider the possibility of disturbance resulting from the Array, it is necessary to consider:

- whether or not a noise can be detected/heard by an animal above background noise levels or level of acclimatisation above background levels;
- the likelihood that the noise could cause non-trivial disturbance;
- the likelihood that the sensitive animals will be exposed to that noise; and
- whether the number of animals exposed are likely to be significant at the population level.

32. Assessing these impacts is however a very difficult task due to the complex and variable nature of noise propagation, the variability of documented animal responses to similar levels of noise, and the availability of population estimates, and regional density estimates for all marine mammal species. Behavioural responses are widely recognised as being highly variable and context specific (Southall *et al.*, 2007; 2019; 2021). Assessing the severity of such potential impacts and development of probability-based response functions continues to be an area of ongoing scientific research interest (Graham *et al.*, 2019; Harris *et al.*, 2018; Southall *et al.*, 2021).

33. Southall *et al.* (2007) recommended that at the time the only feasible way to assess whether a specific noise could cause disturbance is to compare the circumstances of the situation with empirical studies. Joint Nature Conservation Committee (JNCC) guidance in the United Kingdom (UK) (JNCC, 2010) indicates that a score of five or more on the Southall *et al.* (2007) behavioural response severity scale could be significant. The more severe the response on the scale, the lower the amount of time that the animals will tolerate it before there could be adverse consequences to life functions, which would constitute a disturbance. The severity scale was revised in Southall *et al.* (2021), which included splitting severity assessment methods on captive studies from assessments on field studies. Behavioural responses related to field studies included impacts to survival, reproduction, and foraging.

34. Southall *et al.* (2007 and 2021) both present a summary of observed behavioural responses for various mammal groups exposed to different types of noise: continuous (non-pulsed) or impulsive (single or multiple pulsed).

35. Disturbance to marine mammals is discussed in more detail in volume 2, chapter 10.

5.3.1. CONTINUOUS (NON-PULSED, NON-IMPULSIVE) NOISE

36. For non-pulsed noise (e.g. installation of pile foundations using drilling, vessels etc.), the lowest sound pressure level at which a score of five or more on the Southall *et al.* (2007) behavioural response severity scale occurs for low frequency cetaceans is 90 dB to 100 dB re 1 µPa (rms). However, this relates to a study involving only migrating gray whales *Eschrichtius robustus*. A study for minke whale showed a response score of three at a received level of 100 dB to 110 dB re 1 µPa (rms), with no higher severity score encountered for this species. For mid frequency cetaceans, a response score of eight was encountered at a received level of 90 dB to 100 dB re 1 µPa (rms), but this was for one mammal (a sperm whale *Physeter macrocephalus*) and might not be applicable for the species likely to be encountered in the vicinity of the Array. For Atlantic white-beaked dolphin, a response score of three was encountered for received levels of 110 dB to 120 dB re 1 µPa (rms), with no higher severity score encountered. For high frequency cetaceans such as bottlenose dolphins a number of individual responses with a response score of six are noted ranging from 80 dB re 1 µPa (rms) and upwards. There is a significant increase in the number of mammals responding at a response score of six once the received sound pressure level is greater than 140 dB re 1 µPa (rms).

37. It is worth noting that the above sound pressure levels are based on the rms sound pressure level metric, which was historically often reported in such studies. More recent studies often use other metrics such as the SEL and care must be taken not to directly compare noise levels quoted using different parameters (refer to section 3 for a discussion of these different metrics).

38. The National Marine Fisheries Service (NMFS) (2005) guidance sets the marine mammal Level B harassment threshold (analogous to disturbance) for continuous noise at 120 dB re 1 µPa (rms). This threshold is based on studies by Malme *et al.* (1984) which investigate the effects of noise from the offshore petroleum industry on migrating gray whale behaviour offshore Alaska. This value sits approximately mid-way between the range of values identified in Southall *et al.* (2007) for continuous noise but is lower than the value at which the majority of marine mammals responded at a response score of six (i.e. once the received rms sound pressure level is greater than 140 dB re 1 µPa). Considering the paucity and high level variation of data relating to onset of behavioural effects due to continuous noise, any ranges predicted using this number are likely to be probabilistic and potentially over precautionary.

39. It is worth nothing that the distinction between impulsive and non-impulsive noise was removed from Southall *et al*. (2021) as "*some source types, such as airguns, may produce impulsive noises near the source and non-impulsive noises at greater ranges*". However, Southall *et al*. (2021) does not present thresholds for assessing disturbance, therefore the thresholds discussed in section 5.3.1 have been adopted.

5.3.2. IMPULSIVE (PULSED) NOISE

40. Southall *et al.* (2007) presents a summary of observed behavioural responses due to multiple pulsed noise, although the data is primarily based on responses to seismic exploration activities (rather than for piling). Although these datasets contain much relevant data for LF cetaceans, there is less data for MF or HF cetaceans within the document. Low frequency cetaceans, other than bowhead whales (*Balaena mysticetus*), were typically observed to respond significantly at 140 dB to 160 dB re 1 µPa (rms). Behavioural changes at these levels during multiple pulses may have included visible startle response, extended cessation or modification of vocal behaviour, brief cessation of reproductive behaviour or brief/minor separation of females and dependent offspring. The data available for MF cetaceans indicate that some significant response was observed at a SPL of 120 dB to 130 dB re 1 µPa (rms), although the majority of cetaceans in this category did not display behaviours of this severity until exposed to a level of 170 dB to 180 dB re 1 µPa (rms). Furthermore, other MF cetaceans within the same study were observed to have no behavioural response even when exposed to a level of 170 dB to 180 dB re 1 µPa (rms).

41. More recently, Graham *et al.* (2019) describes empirical evidence from piling at the Beatrice Offshore Wind Farm (Moray Firth, Scotland) used to derive a dose-response curve for harbour porpoise[7]. The unweighted single pulse SEL contours were plotted in 5 dB increments and applied the dose-response curve to estimate the number of animals that would be disturbed by piling within each stepped contour. The study shows a 100% probability of disturbance at an (unweighted) SEL of 180 dB re 1 μPa^2s, 50% at 155 dB re 1 μPa^2s and dropping to approximately 0% at an SEL of 120 dB re 1 μPa^2s. This approach to understanding the behavioural effects from piling has been applied at other UK offshore wind farms (for example Seagreen Alpha/Bravo Environmental Statement Chapter 10 Marine Mammals (Seagreen Wind Energy, 2018), Hornsea Three Environmental Statement Volume 2 Chapter 4 Marine mammals (Orsted, 2020) and Awel y Môr Environmental Statement Volume 2, Chapter 7: Marine mammals (RWE, 2022)). Similar stepped/probability-based threshold criteria have been used on other studies such as for assessing the response of marine mammals to geophysical activities (e.g. Southall *et al.*, 2017). The data were subsequently used to develop a dose-response curve. The assessment of behavioural response and disturbance is presented in volume 2, chapter 10.

42. Southall *et al.* (2007) suggested that there was a general paucity of data relating to the effects of noise on pinnipeds in particular. One study using ringed *Pusa hispida*, bearded *Erignathus barbatus* and spotted *Phoca largha* seals (Harris *et al.*, 2001) found onset of a significant response at a received sound pressure level of 160 dB to 170 dB re 1 µPa (rms), although larger numbers of animals showed no response at noise levels of up to 180 dB re 1 µPa (rms). It is only at much higher sound pressure levels in the range of 190 dB to 200 dB re 1 µPa (rms) that significant numbers of seals were found to exhibit a significant response. For comparison, for non-pulsed noise one study elicited a significant response on a single harbour seal at a received level of 100 dB to 110 dB re 1 µPa (rms), although other studies found no response or non-significant reactions occurred at much higher received levels of up to 140 dB re 1 µPa (rms).

43. In more recent studies, and following a similar method to Graham *et al.* (2019), a telemetry study undertaken by Russell *et al.* (2016) investigating the behaviour of tagged harbour seals during pile driving at the Lincs Wind Farm in the Wash found that there was a proportional response at different received noise levels. Dividing the study area into a 5 km x 5 km grid, the authors modelled SEL_{ss} levels and matched these to corresponding densities of harbour seals in the same grids during periods of non-piling versus piling to show change in usage. The study found that there was a significant decrease during piling activities at predicted received SEL levels of between 142 dB re 1 μPa^2s and 151 dB re 1 μPa^2s.

44. Southall *et al.* (2007) also noted that due to the uncertainty over whether HF cetaceans may perceive certain noises and due to the paucity of data, it was not possible to present any data on responses of HF cetaceans. However, Lucke *et al.* (2009) showed a single harbour porpoise consistently showed aversive behavioural reactions to pulsed noise at received SPL above 174 dB re 1 µPa (peak-to-peak) or a SEL of 145 dB re 1 μPa^2s, equivalent to an estimated[8] sound pressure level of 166 dB re 1 µPa rms.

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

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

47. The approach to be employed for the Array is therefore to plot unweighted single pulse SEL contours in 5 dB increments and apply the appropriate dose-response curve to estimate the number of animals that would be disturbed by noise from the piling within each stepped contour. For cetaceans, the dose-response curve will be applied from the Beatrice data (Graham *et al.*, 2019) (refer to Figure 5.2), whilst for pinnipeds the dose-response curve will be applied using Whyte *et al.* (2020). Although the Whyte paper derives more recent response curves, these are only proposed for pinnipeds and hence the need to also include data from older sources for other key species.

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

8 Based on an analysis of the time history graph in Lucke *et al.* (2007), the T90 period is estimated to be approximately 8 ms, resulting in a correction of 21 dB applied to the SEL to derive the rmsT90 noise pressure level. However, the T90 was not directly reported in the paper.

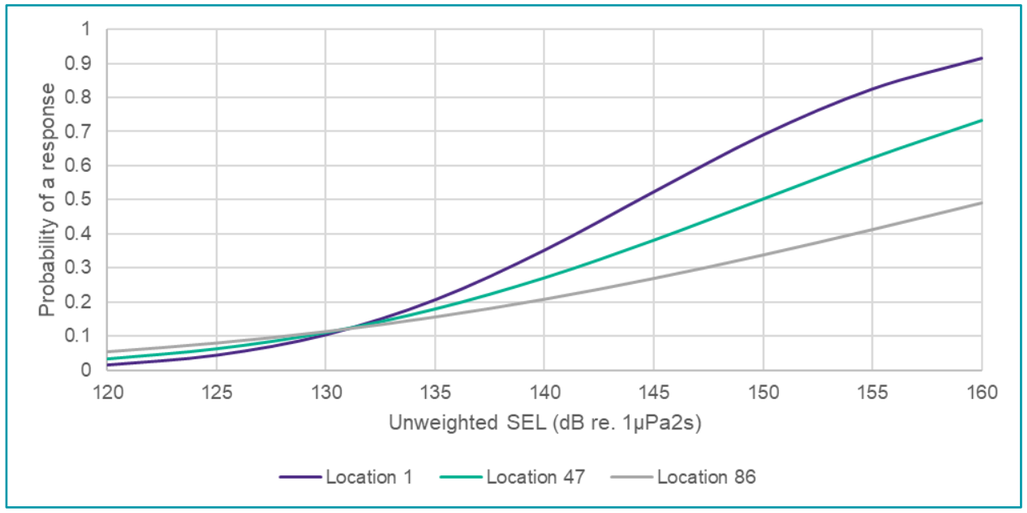

Figure 5.2: The Probability of a Harbour Porpoise Response (24 hrs) in Relation to the Partial Contribution of Unweighted Received Single-Pulse SEL for the First Location Piled (Purple Line), the Middle Location (Green Line) and the Final Location Piled (Blue Line). Reproduced with Permission from Graham *et al.* (2019)

48. The dose-response approach is a widely accepted approach to assessing potential behavioural effects of noise from piling and has been applied at other recent UK offshore wind farms (e.g. Seagreen Alpha/Bravo, Awel y Môr, Hornsea Three and Hornsea Four).

49. For impulsive noise sources other than piling (e.g. UXO clearance, some geotechnical and geophysical surveys), this assessment adopts the NMFS (2005) Level B harassment threshold of 160 dB re 1 µPa (rms) for impulsive noise. Level B harassment is defined by NMFS (2005) as having the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioural patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering but which does not have the potential to injure a marine mammal or marine mammal stock in the wild. This is similar to the JNCC (2010) description of non-trivial disturbance and has therefore been used as the basis for onset of behavioural change in the assessment.

50. For assessing the severity of behavioural response, the distinction between impulsive and non-impulsive noise was removed from Southall *et al.* (2021) as *"some source types, such as airguns, may produce impulsive noises near the source and non-impulsive noises at greater ranges"*. Southall *et al.* (2021) instead assigns categories to various sources based on the operational characteristics and applies revised severity assessments to selected studies in each category. For example, Table 7 within that paper details a number of observational studies of marine mammals and their responses to piling, with an indication of severity of response and in some cases a received level. However, Southall *et al.* (2021) does not present thresholds for assessing disturbance, therefore the thresholds discussed in Table 5.3 have been adopted for this study. The assessment of disturbance and behavioural response is presented in full in volume 2, chapter 10.

51. A recent position statement from Natural Resources Wales (NRW, 2023) presents a number of disturbance criteria specifically for assessing the impacts on harbour porpoise. This document recommends as a first instance using the 143 dB re 1 μPa^2s SEL_{ss} contour as an indicator of disturbance from pile driving, as proposed by Tougaard (2021). This value is based on measurements undertaken to inform the changes to guidelines from the Danish Energy Agency, and the contour was seen to extend to 20 km to 30 km from the piling site.

52. It is important to understand that exposure to noise levels in excess of the behavioural change threshold stated above does not necessarily imply that the noise will result in significant disturbance. As noted previously, it is also necessary to assess the likelihood that the sensitive receptors will be exposed to that noise and whether the numbers exposed are likely to be significant at the population level.

Table 5.3: Disturbance Criteria for Marine Mammals Used in this Technical Report

Effect	Non-Impulsive Threshold	Impulsive Threshold (Non- Piling)	Impulsive Threshold (Piling)
Mild disturbance (all marine mammals)	-	140 dB re 1µPa (rms)	-
Strong disturbance (all marine mammals)	120 dB re 1µPa (rms)	160 dB re 1µPa (rms)	-
Disturbance (all marine mammals)	-	-	Based on SEL 5 dB contours
Disturbance (harbour porpoise only)	-	-	143 dB re 1 μPa^2s SEL_{ss} contour

53. There is, however, a considerable degree of uncertainty and variability in the onset of disturbance and therefore any disturbance ranges should be treated as potentially over precautionary. Another important consideration is that the majority of noise produced by project activities, with the exception of operational wind turbine noise, will be either temporary or transitory, as opposed to permanent and fixed. These important considerations are not taken into account in the noise modelling but will be assessed in the relevant marine ecology topic chapters.

5.4. INJURY AND DISTURBANCE TO FISH

54. For fish, the most relevant criteria for injury effects are considered to be those contained in the Noise Exposure Guidelines for Fishes and Sea Turtles (Popper *et al.,* 2014). These guidelines broadly group fish into the following categories based on their anatomy and the available information on hearing of other fish species with comparable anatomies:

- Group 1: fishes with no swim bladder or other gas chamber (e.g. elasmobranchs, flatfishes and lampreys). These species are less susceptible to barotrauma and are only sensitive to particle motion, not sound pressure. Basking shark *Cetorhinus maximus*, which do not have a swim bladder, also fall into this hearing group.
- Group 2: fishes with swim bladders but the swim bladder does not play a role in hearing (e.g. salmonids). These species are susceptible to barotrauma, although hearing only involves particle motion, not sound pressure.
- Group 3: fishes with swim bladders that are close, but not connected, to the ear (e.g. gadoids and eels). These fishes are sensitive to both particle motion and sound pressure and show a more extended frequency range than Groups 1 and 2, extending to about 500 Hz.
- Group 4: fishes that have special structures mechanically linking the swim bladder to the ear (e.g. clupeids such as herring, sprat and shads). These fishes are sensitive primarily to sound pressure, although they also detect particle motion. These species have a wider frequency range, extending to several kHz and generally show higher sensitivity to sound pressure than fishes in Groups 1, 2 and 3.

- Fish eggs and larvae: separated due to greater vulnerability and reduced mobility. Very few peer-reviewed studies report on the response of eggs and larvae to anthropogenic noise.

55. The guidelines set out criteria for injury effects due to different sources of noise. Those relevant to the Array are considered to be those for impulsive piling sources only, as non-impulsive sources were not considered to be a key potential impact and therefore were screened out of the guidance[9]. The criteria include a range of indices including SEL, rms and peak SPLs. Where insufficient data exist to determine a quantitative guideline value, the risk is categorised in relative terms as "high", "moderate" or "low" at three distances from the source: "near" (i.e. in the tens of metres), "intermediate" (i.e. in the hundreds of metres) or "far" (i.e. in the thousands of metres). It should be noted that these qualitative criteria cannot differentiate between exposures to different noise levels and therefore all sources of noise, no matter how loud, would theoretically elicit the same assessment result. However, because the qualitative risks are generally qualified as "low", with the exception of a moderate risk at "near" range (i.e. within tens of metres) for some types of hearing groups and impairment effects, this is not considered to be a significant issue with respect to determining the potential effect of noise on fish.

56. The injury threshold criteria used in this underwater noise assessment for impulsive piling are given in Table 5.4. In the table, both peak and SEL criteria are unweighted. Physiological effects relating to injury criteria are described below (Popper *et al.*, 2014; Popper and Hawkins, 2016):

- **Mortality and potential mortal injury**: either immediate mortality or tissue and/or physiological damage that is sufficiently severe (e.g. a barotrauma) that death occurs sometime later due to decreased fitness. Mortality has a direct effect upon animal populations, especially if it affects individuals close to maturity.
- **Recoverable injury**: Tissue and other physical damage or physiological effects, that are recoverable, but which may place animals at lower levels of fitness, may render them more open to predation, impaired feeding and growth, or lack of breeding success, until recovery takes place.
- **TTS**: Short term changes in hearing sensitivity may, or may not, reduce fitness and survival. Impairment of hearing may affect the ability of animals to capture prey and avoid predators, and also cause deterioration in communication between individuals affecting growth, survival, and reproductive success. After termination of a noise that causes TTS, normal hearing ability returns over a period that is variable, depending on many factors, including the intensity and duration of noise exposure.

Table 5.4: Criteria for Onset of Injury to Fish Due to Impulsive Piling (Popper *et al.*, 2014)

Type of Animal	Parameter	Mortality and Potential Mortal Injury	Recoverable Injury	TTS
Group 1 Fish: no swim bladder (particle motion detection)	SEL, dB re 1 μPa^2s	>219	>216	>186
	Peak, dB re 1 µPa	>213	>213	-
Group 2 Fish: where swim bladder is not involved in hearing (particle motion detection)	SEL, dB re 1 μPa^2s	210	203	>186
	Peak, dB re 1 µPa	>207	>207	-
Groups 3 and 4 Fish: where swim bladder is involved in hearing (primarily pressure detection)	SEL, dB re 1 μPa^2s	207	203	186
	Peak, dB re 1 µPa	>207	>207	-
	Peak, dB re 1 µPa	>207	-	-
Eggs and larvae	SEL, dB re 1 μPa^2s	>210	(Near) Moderate (Intermediate) Low (Far) Low	(Near) Moderate (Intermediate) Low (Far) Low
	Peak, dB re 1 µPa	>207		

57. The criteria used in this underwater noise assessment for non-impulsive piling and other continuous noise sources, such as vessels, are given in Table 5.5. The only numerical criteria for these sources are for recoverable injury and TTS for Groups 3 and 4 Fish.

9 Guideline exposure criteria for seismic surveys, continuous noise and naval sonar are also presented though are not applicable to this project.

Table 5.5: Criteria for Onset of Injury to Fish Due to Non-Impulsive Noise (Popper *et al.*, 2014)

Type of Animal	Mortality and Potential Mortal Injury	Recoverable Injury	TTS
Group 1 Fish: no swim bladder (particle motion detection)	(Near) Low (Intermediate) Low (Far) Low	(Near) Low (Intermediate) Low (Far) Low	(Near) Moderate (Intermediate) Low (Far) Low
Group 2 Fish: where swim bladder is not involved in hearing (particle motion detection)	(Near) Low (Intermediate) Low (Far) Low	(Near) Low (Intermediate) Low (Far) Low	(Near) Moderate (Intermediate) Low (Far) Low
Groups 3 and 4 Fish: where swim bladder is involved in hearing (primarily pressure detection)	(Near) Low (Intermediate) Low (Far) Low	170 dB re 1µPa (rms) for 48 hours	158 dB re 1µPa (rms) for 12 hours
Eggs and larvae	(Near) Low (Intermediate) Low (Far) Low	(Near) Low (Intermediate) Low (Far) Low	(Near) Low (Intermediate) Low (Far) Low

58. The criteria used in this underwater noise assessment for explosives are given in Table 5.6. It should be noted that there are no thresholds in Popper *et al.* (2014) in relation to eggs and larvae in terms of sound pressure.

Table 5.6: Criteria for Injury to Fish Due to Explosives (Popper *et al.*, 2014)

Type of animal	Parameter	Mortality and Potential Mortal Injury	Recoverable Injury	TTS
Group 1 Fish: no swim bladder (particle motion detection)	Peak, dB re 1µPa	229 to 234	(Near) High (Intermediate) Low (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Group 2 Fish: where swim bladder is not involved in hearing (particle motion detection)	Peak, dB re 1µPa	229 to 234	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Group 3 and 4 Fish: where swim bladder is involved in hearing (primarily pressure detection)	Peak, dB re 1µPa	229 to 234	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) High (Far) Low

59. It should be noted that there are no thresholds in Popper *et al.* (2014) in relation to noise from high frequency sonar (>10 kHz). This is because the hearing range of fish species falls well below the frequency range of high frequency sonar systems. Consequently, the effects of noise from high frequency sonar surveys on fish has not been conducted as part of this study, due to the frequency of the source being beyond the range of hearing and also due to the lack of any suitable thresholds.

60. Behavioural reaction of fish to noise has been found to vary between species based on their hearing sensitivity. Typically, fish sense noise via particle motion in the inner ear which is detected from noise-induced motions in the fish's body (refer to section 9 for further details on particle motion). The detection of sound pressure is restricted to those fish which have air filled swim bladders; however, particle motion (induced by noise) can be detected by fish without swim bladders[10].

61. Highly sensitive species such as herring have elaborate specialisations of their auditory apparatus, known as an otic bulla – a gas filled sphere, connected to the swim bladder, which enhances hearing ability. The gas filled swim bladder in species groups such as cod and salmon may be involved in their hearing capabilities, so although there is no direct link to the inner ear, these species are able to detect lower noise frequencies and as such are considered to be of medium sensitivity to noise. Flat fish and elasmobranchs have no swim bladders and as such are considered to be relatively less sensitive to sound pressure.

62. The most recent criteria for disturbance are considered to be those contained in Popper *et al.* (2014) which set out qualitative criteria for disturbance due to different sources of noise. The risk of behavioural effects is categorised in relative terms as "high", "moderate" or "low" at three distances from the source: "near" (i.e. in the tens of metres), "intermediate" (i.e. in the hundreds of metres) or "far" (i.e. in the thousands of metres), as shown in Table 5.7.

10 It should be noted that the presence of a swim bladder does not necessarily mean that the fish can detect pressure. Some fish have swim bladders that are not involved in the hearing mechanism and can only detect particle motion.

Table 5.7: Criteria for Onset of Behavioural Effects in Fish for Impulsive and Non-Impulsive Noise (Popper *et al.*, 2014)

Type of Animal	Relative Risk of Behavioural Effects		
	Impulsive Piling	Explosives	Non-Impulsive Noise
Group 1 Fish: no swim bladder (particle motion detection)	(Near) High (Intermediate) Moderate (Far) Low	(Near) High (Intermediate) Moderate (Far) Low	(Near) Moderate (Intermediate) Moderate (Far) Low
Group 2 Fish: where swim bladder is not involved in hearing (particle motion detection)	(Near) High (Intermediate) Moderate (Far) Low	(Near) High (Intermediate) High (Far) Low	(Near) Moderate (Intermediate) Moderate (Far) Low
Groups 3 and 4 Fish: where swim bladder is involved in hearing (primarily pressure detection)	(Near) High (Intermediate) High (Far) Moderate	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Eggs and larvae	(Near) Moderate (Intermediate) Low (Far) Low	(Near) High (Intermediate) Low (Far) Low	(Near) Moderate (Intermediate) Moderate (Far) Low

63. It is important to note that the Popper *et al.* (2014) criteria for disturbance due to noise are qualitative rather than quantitative. Consequently, a source of noise of a particular type (e.g. piling) would be predicted to result in the same potential impact, no matter the level of noise produced or the propagation characteristics.

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

5.5. USE OF IMPULSIVE NOISE THRESHOLDS AT LARGE RANGES

65. For any noise of a given amplitude and frequency content, impulsive noise has a greater potential to cause auditory injury than a similar magnitude non-impulsive noise (Southall *et al.*, 2007; 2019; 2021; NMFS, 2018; von Benda-Beckmann *et al.*, 2022). For highly impulsive noises such as those generated by impact piling, UXO detonations and seismic source arrays, the interaction with the seafloor and the water column is complex. In these cases, due to a combination of dispersion (i.e. where the waveform elongates), multiple reflections from the sea surface and seafloor and molecular absorption of high frequency energy, the noise is unlikely to still be impulsive in character once it has propagated some distance (Hastie *et al.*, 2019; Martin *et al.*, 2020; Southall *et al.*, 2019; Southall, 2021). This transition in the acoustic characteristics therefore has implications with respect to which threshold values should be used (impulsive vs. non impulsive criteria) and, consequently, the distances at which potential injury effects may occur.

66. This acoustic wave elongation effect is particularly pronounced at larger ranges of several kilometres and, in particular, it is considered highly unlikely that predicted PTS or TTS ranges for impulsive noise which are found to be in the tens of kilometres are realistic (Southall, 2021). However, the precise range at which the transition from impulsive to non-impulsive noise occurs is difficult to define precisely, not least because the transition also depends on the response of the marine mammals' ear. Consequently, there is currently no consensus as to the range at which this transition occurs or indeed the measure of impulsivity which can be used to determine which threshold should be applied (Southall, 2021). However, evidence for impact pile driving and seismic source arrays does indicate that some measures of impulsivity change markedly within 10 km of the source (Hastie *et al.*, 2019). Additionally, the draft NMFS (2018) guidance suggested 3 km as a transition range, but this was removed from the final document.

67. The cross-over between impulsive and non-impulsive noise is an area of ongoing research and there are a number of potential methods for determining the cross-over point being investigated, such as the kurtosis metric, and the loss of high frequency energy from the spectrum (above 10 kHz, e.g. Southall, 2021). In the meantime, it is considered that any predicted injury ranges in the tens of kilometres are almost certainly an overly precautionary interpretation of existing criteria (Southall, 2021).

68. As disturbance ranges are likely to extend beyond the range at which injury (PTS or TTS) could occur, this transition from impulsive to continuous noise is likely to have even more impact on the disturbance range (e.g. Southall *et al.*, 2021). For example, where dose-response relationships have been derived based on exposure to impulsive noises, particularly where these have been derived based on experiments relatively close to the impulsive source, then extrapolation of the dose-response relationship to larger ranges could be misleading. This is particularly true where the dose-response relationship has been derived using parameters such as unweighted single pulse SEL or $rms_{(T90)}$ SPL, which does not take into account the characteristics (e.g. frequency content of impulsivity) of the noise. Consequently, great caution should be used when interpreting potential disturbance ranges in the order of tens of kilometres. Where appropriate, these should be considered alongside an understanding of potential background noise levels in order to understand the distances at which noises related to an impulsive source may be detected.

6. SOURCE NOISE LEVELS

6.1. GENERAL

69. Underwater noise source level is usually quantified using a dB scale with values generally referenced to 1 µPa pressure amplitude as if measured at a distance of 1 m from a hypothetical, infinitesimally small point source (sometimes referred to as the SL). This quantity is often referred to as an equivalent monopole source level. In practice, it is not usually possible to measure noise at 1 m from a large structure, which is more akin to a distributed noise source, but the source level metric allows comparisons and reporting of different source noise emissions on a like-for-like basis, as well as a standard input parameter for noise propagation models. In reality, for a large noise source such as a monopile, seismic source array or vessel, the source level value at this conceptual point at 1 m from the (theoretical, infinitesimally small) acoustic centre does not exist. Furthermore, the energy is distributed across the source and does not all emanate from this imagined acoustic centre point. Therefore, the stated sound pressure level at 1 m does not occur at any point in space for these large sources. In the acoustic near field (i.e. close to the source), the sound pressure level will be significantly lower than the value predicted by the SL.

70. A wealth of experimental data and literature-based information is available for quantifying the noise emission from different construction operations. This information, which allows us to predict with a good degree of accuracy the noise generated by a source at discrete frequencies in one-third octave bands, will

be employed to characterise their acoustic emission in the underwater environment. Sections 6.2 to 6.7 detail the types of noise sources present during different construction activities, their potential signatures in different frequency bands, and acoustic levels.

6.2. TYPES OF NOISE SOURCES

71. The noise sources and activities which were investigated during the development of this technical report are summarised in Table 6.1.

Table 6.1: Summary of Noise Sources and Activities Included in the Underwater Noise Technical Report

Phase	Source/Activity
Pre-Construction	• Geophysical site investigation activities including: – Multi-Beam Echosounder (MBES); – Sidescan Sonar (SSS); – Sub-Bottom Profilers (SBP); and – 2-D Ultra-High Resolution Seismic (UHRS). • Geotechnical site investigation activities including: – Drilling of boreholes. – Cone Penetration Tests (CPTs). – Vibrocores/piston cores. • Use of geophysical/geotechnical survey vessels. • Clearance of UXOs including potential use of low-order and low-yield techniques as well as possible high order detonation.
Construction	• Impact driven or drilled piled jacket foundations for Offshore Substation Platforms (OSPs). • Impact driven or drilled anchors for floating wind turbine foundations. • Range of construction vessels including: – Main installation vessels (Jack-up barge/ Dynamic Positioning vessel). – Cargo barge/ – Support vessels. – Crew Transfer Vessels (CTV). – Tug/anchor handlers. – Construction support vessels. – Cable installation vessels. – Guard vessels. – Survey vessels. – Trenching support vessel. – Boulder clearance vessel. – Geophys/geotech survey vessel. – Sandwave clearance vessel. – UXO clearance vessel. – Pre-Lay Grapnel Run (PLGR) vessel. – Rock dumping vessel. – Dive Support Vessel (DSV).
Operation and maintenance	• Operational noise from floating wind turbines. • Noise from movements in mooring lines. • Ongoing geophysical surveys. • Operation and maintenance vessels, including: – CTV/workboats. – Tug (anchor handlers) vessels. – Jack-up vessels. – Cable repair vessels. – Support vessels. – DSV.
Decommissioning	• Vessels for a range of decommissioning activities, assumed as per vessel activity described for construction phase.

72. Noise sources included in Table 6.1 are considered in more detail in the following sections.

6.3. PRE-CONSTRUCTION PHASE

6.3.1. GEOPHYSICAL SURVEYS

73. Several sonar-like survey types will potentially be used for the pre-construction site investigation geophysical surveys. During the survey, a transmitter emits an acoustic signal directly toward the seabed (or alongside, at an angle to the seabed, in the case of side scan techniques). The equipment likely to be used can typically work at a range of signal frequencies, depending on the distance to the bottom and the required resolution. The signal is highly directional and acts as a beam, with the energy narrowly concentrated within a few degrees of the direction in which it is aimed. The signal is emitted in pulses, the length of which can be varied as per the survey requirements. The assumed pulse rate, pulse width and beam width used in the assessment are based on a review of typical units used in other similar surveys. It should be noted that sonar like survey sources are classed as non-impulsive noise because they generally comprise a single (or multiple discrete) frequency (e.g. a sine wave or swept sine wave) as opposed to a broadband signal with high kurtosis, high peak pressures and rapid rise times.

74. The characteristics assumed for each device modelled in this technical report are summarised in Table 6.2. these sources are considered to be continuous (non-impulsive).

Table 6.2: Typical Sonar Based Survey Equipment Parameters Used in Assessment

Survey Type	Frequency	Source level, dB re 1 µPa re 1 m (rms)	Pulse Rate (s^{-1})	Pulse Width (ms)	Beam Width
MBES	400 kHz	225	60	0.5	0.9º x 1.9º
SSS	230 kHz (LF) 550 kHz (HF)	210	15	15	0.54º (LF) 0.36º (HF)
SBP	100 kHz (primary) 4, 5, 6, 8, 10, 12 kHz selectable secondary frequencies	248	50	0.07 to 1.5	2.0º

75. The assumed pulse rate has been used to calculate the SEL, which is normalised to 1 s, from the rms sound pressure level. Directivity corrections were calculated based on the transducer dimensions and ping frequency and taken from manufacturer's datasheets. It is important to note that directivity will vary significantly with frequency, but that these directivity values have been used in line with the modelling assumptions stated in Table 6.2.

76. Directivity corrections have been applied to the source noise level data based on directivity characteristics for the proposed sources. Directivity factors were derived based on source take-off angle for an animal on the seabed. This results in a larger correction (reduction in level) due to directivity at distances further from the source than for receivers close to the source.

77. At distances closer to the source (i.e. less than the water depth), no directivity correction is made because the animal could be directly underneath the source. As the source to receiver range increases, the take-off angle between the source and animal becomes larger. Hence, when the range to source is large in comparison to the water depth, the effects of the source's directivity will have a much greater bearing on the received noise level. Once the range to source becomes larger than the water column depth then the source directivity effects will become increasingly more important.

78. Unlike the sonar like survey sources, the UHRS source is likely to utilise a sparker, which produces an impulsive, broadband source signal. The parameters used in the underwater noise modelling are summarised in Table 6.3.

Table 6.3: Typical UHRS Survey Equipment Parameters Used in Assessment

Source	Peak Frequency (kHz)	SL (dB re 1µPa re 1m) (peak)	Source SEL (dB re 1µPa^2s re 1m)	SL (dB re 1µPa re 1m) (rms)	T9 (ms)
UHRS (sparker)	0.05 to 4	219	182	214	0.7

6.3.2. GEOTECHNICAL SURVEYS

79. Source noise data for the proposed CPTs was reported by Erbe and McPherson (2017). In this report, the SEL measurements at two different sites in Western Australia at a measured distance of 10 m were presented. The signature is generally broadband in nature with levels measured generally 20 dB above the baseline noise levels. The report also refers to other paths for acoustic energy including direct air to water transmission and other multipath directions, which implied that measured noise level is strongly dependant on depth and range from the source. The third octave band SEL levels from the CPT extracted are presented in Table 6.4.

Table 6.4: CPT Source Levels in Different Third Octave Band Frequencies (SEL Metric) Used for the Assessment (Erbe and McPherson, 2017)

SEL, dB re 1µPa^2s	Octave Band Centre Frequency (kHz)									
	0.016	0.0315	0.063	0.125	0.25	0.5	1	2	4	8
189	173	173	164	163	172	177	180	182	184	182

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

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

82. It should be noted that if non-seismic CPT were to be used, the noise would be considered non-impulsive if it produced any noise at all, and therefore the assessment of seismic CPT is considered precautionary. As piston core and box core methods are lower in sound energy, CPT has been used as a maximum design scenario across all core measurement techniques.

83. Measurements of a vibro-core test show underwater source sound pressure levels of approximately 187 dB re 1 µPa re 1 m (rms) (Reiser *et al.*, 2011). The SEL has been calculated based on a one hour sample time which, it is understood, is the typical maximum time required for each sample. The vessel would then move on to the next location and take the next sample with approximately one hour break between each operation. The vibro-core noise is considered to be continuous (non-impulsive).

Table 6.5: Vibro-Core Source Levels Used in the Assessment

Parameter	SL	Unit
SEL (unweighted) – based on one-hour operation for single core sample	223	dB re 1 µPa^2s re 1m
rms	187	dB re 1 µPa re 1m

84. The frequency spectral shape for vibro-coring is presented in Figure 6.1.

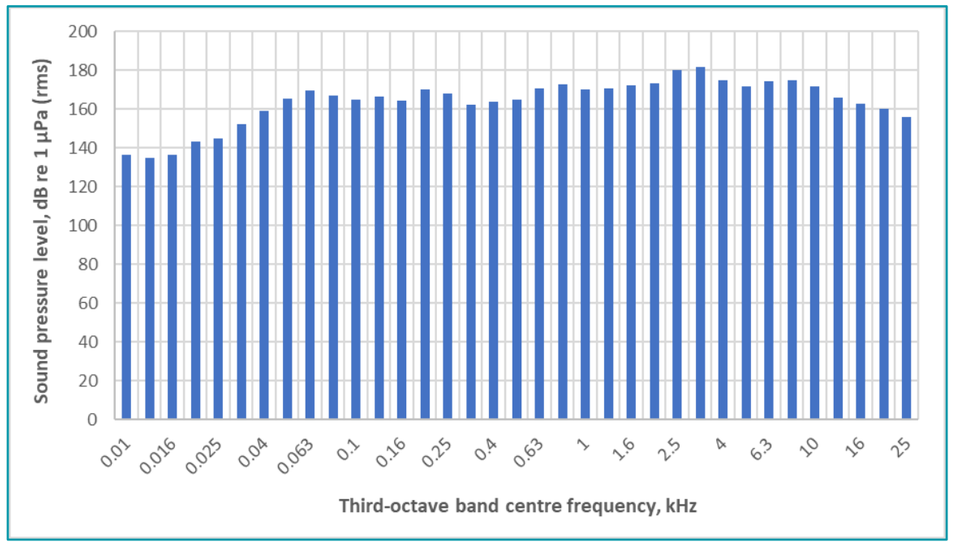

Figure 6.1: Frequency Spectral Shape Used for Vibro-Coring

85. Source levels for borehole drilling was reported in Erbe and McPherson (2017), with source levels of 142 dB to 145 dB re 1 µPa re 1 m (rms). A set of one third octave band levels, calculated from the spectrum presented in the paper are shown in Figure 6.2.

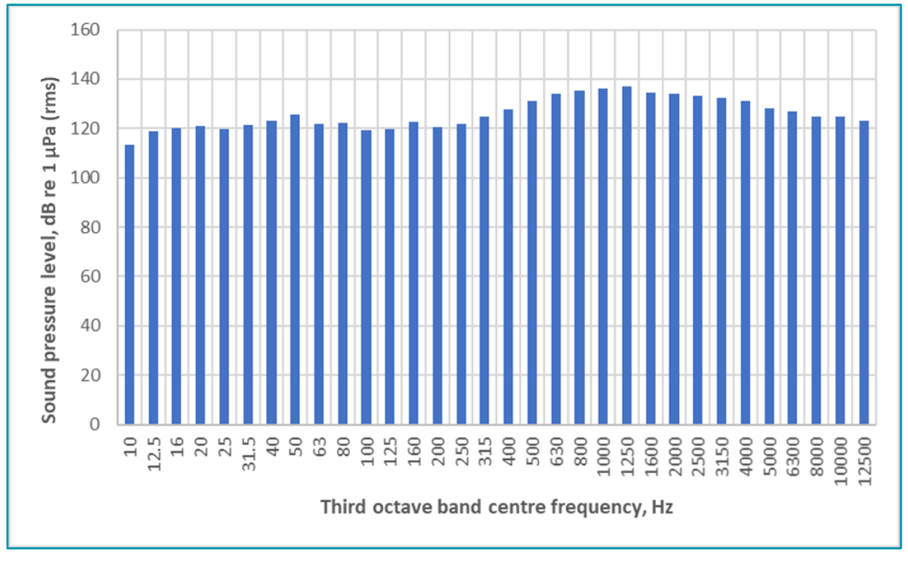

Figure 6.2: Borehole Drilling Source Level Spectrum Shape Used in the Assessment

86. As for other non-impulsive sources, the impact assessment criteria is the SEL metric for a receptor moving away from the source.

6.3.3. UXO CLEARANCE

87. The precise details and locations of potential UXOs is unknown at this time. For the purposes of this assessment, it has been assumed that the Maximum Design Scenario (MDS) will be clearance of UXO with a Net Explosive Quantity (NEQ) of 698 kg cleared by either low-order or high order techniques. Low-order techniques are not always possible and are dependent upon the individual situations surrounding each UXO. The value of 698 kg is derived from a site-specific desktop review undertaken by Ordtek (2022) to understand the potential maximum charge weight and likelihood based on past military activity.

88. There are a number of low-order and low-yield techniques available for the clearance of UXO, with the development of new techniques being a subject of ongoing research. For example, one such technique (deflagration) uses a single charge of 30 g to 80 g NEQ which is placed in close proximity to the UXO to target a specific entry point. When detonated, a shaped charge penetrates the casing of the UXO to introduce a small, clinical plasma jet into the main explosive filling. The intention is to excite the explosive molecules within the main filling to generate enough pressure to burst the UXO casing, producing a deflagration of the main filling and neutralising the UXO.

89. Recent controlled experiments showed low-order deflagration to result in a substantial reduction in acoustic output over traditional high order methods, with SPL_{pk} and SEL being typically significantly lower for the deflagration of the same size munition, and with the acoustic output being proportional to the size of the shaped charge, rather than the size of the UXO itself (Robinson *et al.*, 2020). Using this low-order deflagration method, the probability of a low order outcome is high; however, there is a small inherent risk with these clearance methods that the UXO will detonate or deflagrate violently resulting in higher noise level emissions.

90. It is possible that there will be residual explosive material remaining on the seabed following the use of low-order techniques for unexploded ordnance disposal. In this case, and only for debris of sufficient size to be a risk to fishing activities, recovery will be performed which includes the potential use of a small (500 g) ‘clearing shot’.

91. As a last resort, if it is not possible to carry out low-order or low-yield clearance techniques, it may be necessary to carry out a high order detonation of the UXO. The underwater noise modelling has been undertaken for a range of charge configurations as set out in Table 6.6.

Table 6.6: Details of UXO and their Relevant Charge Sizes Employed for Modelling

Charge Size (kg NEQ)	Notes/Assumptions
Low Order and Low- Yield Donor Charge Configurations	
0.25 kg	Maximum size of donor charge used for low-order technique.
0.5 kg	Maximum size of clearing shot to neutralise any residual explosive material.
Potential UXOs (High Order Disposal)	
227 kg	Realistic worst case UXO charge weight, based on British WW2 mine Mk XIV.
698 kg	Maximum estimated UXO size that is anticipated to be encountered, based on a 1,000 kg German WW2 mine BM1000

92. The source levels for UXO are included within the terms for propagation modelling and are described in section 7.7.

6.3.4. VESSELS

93. Use of vessels is addressed in section 6.7 for all phases of the Array.

6.4. CONSTRUCTION PHASE

6.4.1. IMPACT PILING

94. The noise generated and radiated by a pile as it is driven into the ground is complex, due to the many components which constitute the generation and radiation mechanisms. Larger pile sizes can require a higher energy in order to drive them into the seabed, and different seabed and underlying substrate types can require use of different installation techniques including varying the hammer energies and the number of hammer strikes. In addition, the seabed characteristics can affect how noise propagates from the pile through the sub-surface geology, thus fundamentally affecting the acoustic field around the activity. The type of hammer method used (i.e. the force-impulse characteristics) can also affect the noise characteristics.

    A useful measure of noise used in underwater acoustics is the SEL. This descriptor is used as a measure of the total noise energy of an event or a number of events (e.g. over the course of a day) and is normalised to one second. This allows the total acoustic energy contained in events lasting a different amount of time to be compared on a like for like basis. For impulsive noises it has become customary to utilise the T90 time period for calculating and reporting root mean squared (rms) sound pressure levels. This is the interval over which the cumulative energy curve rises from 5% to 95% of the total energy and therefore contains 90% of the noise energy.

95. The estimation of source levels for noise propagation modelling of piling is an important aspect of the noise modelling methodology. Ideally, use can be made of noise data measurement for similar piles, installed using a similar hammer in similar conditions. However, since noise modelling for proposed wind farms often proposes the use of piles and hammers for which there is no currently available measured data, it is often necessary to utilise an alternative method to estimate the source level inputs to the model. One such method used in some previous noise modelling assessments is the use of energy conversion factors, which involves estimating the proportion of the hammer energy which is transmitted into the water column as noise. However, the subject of noise generation due to impact piling is an active area of research and the evidence base is constantly being updated by new measurements, research and published papers. It is therefore important to ensure that the methodology used for determining the source levels of piling take into account the most recent research.

96. It is proposed to utilise scaling of measured data during pile driving for similar operations to the Array in order to determine source levels. The subject of noise generation due to impact piling is an active area of research and the evidence base is constantly being updated by new measurements, research and published papers. A recent peer-reviewed paper (von Pein *et al.*, 2022) presents a methodology for the dependencies of the SEL on strike energy, diameter, ram weight, and water depth that can be used for scaling measured or computed SELs from one project to another. The method has been shown to be usable within practical ranges of accuracy, especially if the measurement uncertainties are taken into account. The paper suggests that scaling should be performed over either a small number of very similar piling situations or over a larger data set with according averaging. This is a recently published method for deriving the noise source level which provides a more scientifically robust method compared to using an energy conversion factor (the conversion factor method simply assumes that a percentage of the hammer energy is converted into noise irrespective of parameters such as pile size, water depth and hammer specifications). Since the von Pein *et al*. (2022) methodology takes into account several site-specific and pile-specific factors, in addition to hammer energy, and because it is based on a scientifically rigorous and peer reviewed study, it is therefore considered to be a significant improvement on the use of simple conversion factors alone. This methodology is further endorsed by the recent study undertaken by Jasco on behalf of Marine Scotland, which recommends use of scaling methods instead of those relying on conversion factors (Wood *et al.* 2023).

97. Using the equation below (von Pein *et al*. 2022), a broadband source level value is calculates for the noise emitted during impact pile driving operation in each operation window.

$$SEL_1 = SEL_0 + 10log_{10}\left(\frac{E_1}{E_0}\right) + 16.7log_{10}\left(\frac{d_1}{d_0}\right) - 10log_{10}\left(\frac{m_{r,1}}{m_{r,0}}\right) + 750\left[\frac{10log_{10}(|R_0|^2)}{2\,cot(\varphi)}\left(\frac{1}{h_1} - \frac{1}{h_0}\right)\right]$$

98. In this equation, E is the hammer energy employed in Joules, d is the pile diameter, m_r is the ram mass in kg, h is the water depth in m, $|R_0|$ is the reflection coefficient and φ is the propagation angle (approximately 17° for a Mach wave generated by impact piling). The equation allows measured pile noise data from one site (denoted by subscript 0) to be scaled to another site (denoted by subscript 1).

99. To account for the pile penetration and use of submerged piling rigs, a correction is applied through the piling sequence based on Lippert *et al*. (2017) by considering the quotient of wetted pile length L_w and water depth h_w using the following equation:

$$\Delta SEL = 8.3log_{10}(L_w/h_w)$$

100. This methodology therefore considers the following factors:

- pile diameter;
- pile length;
- pile penetration;
- water depth;
- rated maximum hammer energy of the proposed hammer;
- hammer energy being used;
- ram mass for the hammer; and
- acoustical parameters of the soil and water.

101. The peak SPL can be calculated from SEL values via the empirical fitting between pile driving SEL and peak SPL data, given in Lippert *et al*. (2015), as:

$$SPL_{pk} = 1.43 \times SEL - 44.0\,.$$

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

103. The piling scenarios for the Array include the following phases:

- initiation (including slow-start);
- soft start;
- ramp up; and
- full power piling.

104. These phases and the various associated parameters and durations are shown in Table 6.7.

105. The impact piling scenarios that have been modelled for the Array are as follows:

- OSP foundations (piled jacket) using a maximum hammer energy of 4,400 kJ for a duration of up to eight hours, related to the MDS associated with the largest diameter OSP foundations.
- Floating wind turbine foundations anchor piles using a maximum hammer energy of 3,000 kJ for a duration of up to eight hours, related to the MDS associated with the largest diameter wind turbine anchors.

Table 6.7: Modelled Pile Installation Parameters (Pile Diameter 4.5 m for Both Pile Types)

Activity/Stage	Duration (minutes)	Hammer Energy (kJ)	Strike Rate (strikes per minute)	Number of Strikes
OSP Jacket Piles				
Acoustic Deterrent Device (ADD)	30	N/A	N/A	N/A
Initiation	1	660	10	10
Soft start	20	660	30	600
Ramp Up	30	660 to 4,400	30	900
Piling	429	4,400	30	12,870
Total piling duration (minutes)	480	N/A	N/A	N/A
Total no. of strikes	14,380	N/A	N/A	N/A
Foundation Piles:				
ADD	30	N/A	N/A	N/A
Initiation	1	450	10	10
Soft start	20	450	30	600
Ramp up	30	450 to 3,000	30	900
Piling	429	3,000	30	12,870
Total piling duration (minutes)	480	N/A	N/A	N/A
Total no. of strikes	14,380	N/A	N/A	N/A

6.4.2. DRILLED PILE INSTALLATION

106. For drilled pile installation, source noise levels have been based on pile drilling for the Oyster 800 project (Kongsberg, 2011). The hydraulic rock breaking source noise levels are based on those measured by Lawrence (2016). The source levels used in the assessment are summarised in Table 6.8.

107. Rotary drilling is non-impulsive in character and therefore the non-impulsive injury and behavioural thresholds have been adopted for the assessment.

Table 6.8: Drilled Pile Noise Source Levels Used in Assessment (Un-Weighted)

Parameter	Source Level at 1 m
SEL per second of operation @ 1 m, dB re 1 µPa^{2}s	163
Peak sound pressure level @ 1 m, dB re 1 µPa	166
rms) sound pressure level @ 1 m, dB re 1 µPa	163

108. The other noise source potentially active during the construction phase are related to cable installation (i.e. trenching and cable laying activities), and their related operations such as the jack-up rigs. The source levels are presented in Table 6.9.

Table 6.9: Source Levels for Other Sources

Sources	Data Source	RMS, dB re 1 µPa
Cable laying	Wyatt (2008)	180
Cable trenching/cutting	Nedwell *et al.* (2003)	178
Jack-up rig	Nedwell and Edwards (2004)	163

6.4.3. VESSELS

109. Use of vessels is addressed in section 6.7 for all phases of the Array.

6.5. OPERATION AND MAINTENANCE PHASE

6.5.1. OPERATIONAL NOISE FROM WIND TURBINES

110. Operational noise due to the floating wind turbines and mooring lines is dealt with qualitatively in section 8.3.2.

6.5.2. GEOPHYSICAL SURVEYS

111. Routine geophysical surveys will be similar to the geophysical surveys already discussed for the pre-construction phase (refer to section 6.3).

6.5.3. ROUTINE OPERATION AND MAINTENANCE

112. There are very few activities during the operations and maintenance phase that generate significant amounts of underwater noise. These noise generating activities are anticipated at this stage to be characterised by vessel movements.

6.5.4. VESSELS

113. The potential for vessel use to create underwater noise is presented in section 6.7 for all phases of the Array.

6.6. DECOMMISSIONING PHASE

6.6.1. VESSELS

114. Only the potential impact of noise from vessel activity has been included in the underwater noise assessment for the decommissioning phase of the Array. It should be noted that cavitation from the vessels themselves is likely to dominate the noisescape for other decommissioning activities (e.g. removal of

subsea structures). The potential impact of vessels noise emissions is addressed in section 6.7 for all phases of the Array.

6.7. VESSELS (ALL PHASES)

115. The noise emissions from the types of vessels that may be used for the Array are quantified in Table 6.10, based on a review of publicly available data. Noise from the vessels themselves (e.g. propeller, thrusters and sonar (if used)) primarily dominates the emission level, hence noise from activities such as seabed preparation, trenching and rock placement (if required) have not been included separately.

116. In Table 6.10, SELs have been estimated for each source based on 24 hours continuous operation, although it is important to note that it is highly unlikely that any marine mammal or fish would stay at a stationary location or within a fixed radius of a vessel (or any other noise source) for 24 hours. Consequently, the acoustic modelling has been undertaken based on an animal swimming away from the source (or the source moving away from an animal).

117. Source noise levels for vessels depend on the vessel size and speed as well as propeller design and other factors. There can be considerable variation in noise magnitude and character between vessels even within the same class. Therefore, source data for the Array has been based on MDS assumptions (i.e. using noise data toward the higher end of the scale for the relevant class of ship as a proxy). In the case of the cable laying vessel, no publicly available information was available for a similar vessel and therefore measurements on a suction dredger using Dynamic Positioning (DP) thrusters were used as a proxy. This is considered an appropriate proxy because it is a similar size of vessel using dynamic positioning and therefore likely to have a similar acoustic footprint.

Table 6.10: Source Noise Data for Site Preparation, Construction, Operation and Maintenance and Decommissioning Vessels

Item	Description/Assumptions	Data Source	Source SPL at 1 m	
			RMS, dB re 1 µPa	SEL (24h), dB re 1 µPa²s
Sandwave clearance	'Gerardus Mercator' trailer hopper suction dredger using DP as proxy	Wyatt *et al.* (2020)	180	229
Boulder clearance, offshore construction vessel, excavator, backhoe dredger	Back-hoe dredger used as proxy	Nedwell *et al.* (2008)	163	212
Main installation vessels (Barge/DP vessel) cargo vessels	'Gerardus Mercator' trailer hopper suction dredger using DP as proxy	Wyatt *et al.* (2020)	180	229
Jack-up rig/jack up vessel	Jack up rig	Evans (1996)	163	212
Tug/anchor handlers	Tug used as proxy	Richardson (1995)	172	221
Cable laying, installation vessels	'Gerardus Mercator' trailer hopper suction dredger using DP as proxy	Wyatt *et al.* (2020)	180	229
Rock placement vessels	'Gerardus Mercator' trailer hopper suction dredger using DP as proxy	Wyatt *et al.* (2020)	180	229
Guard vessels, workboats	Tug used as proxy	Richardson (1995)	172	221
Survey vessels, geophysical/geotechnical survey vessels	Offshore support vessel used as proxy	McCauley (1998)	179	228
CTVs, Service operation vessels, support vessels, construction support vessels, trenching support vessels, UXO clearance vessel, PLGR vessel, DSVs	Offshore support vessel used as proxy	McCauley (1998)	179	228
Scour/cable protection, seabed preparation, installation vessels, rock dumping vessels, cable repair vessels	Offshore support vessel used as proxy	McCauley (1998)	179	228

7. PROPAGATION MODELLING

7.1. PROPAGATION OF NOISE UNDERWATER

118. As the distance from the noise source increases the level of received or recorded noise reduces, primarily due to the spreading of the noise energy with distance, in combination with attenuation due to absorption of noise energy by molecules in the water. This latter mechanism results in higher attenuation at higher frequency noise than for lower frequencies.

119. The way that the noise spreads (geometrical divergence) will depend upon several factors such as water column depth, pressure, temperature gradients, salinity as well as water surface and bottom (i.e. seabed) conditions. Thus, even for a given locality, there are temporal variations to the way that noise will propagate. However, in simple terms, the noise energy may spread out in a spherical pattern (close to the source) or a cylindrical pattern (much further from the source), although other factors mean that decay in noise energy may be somewhere between these two simplistic cases. The distance at which cylindrical spreading dominates is highly dependent on water depth. Noise propagation in shallow water depths will be dominated by cylindrical spreading as opposed to spherical spreading.

120. In acoustically shallow waters[11] in particular, the propagation mechanism is influenced by multiple interactions with the seabed and the water surface (Lurton, 2002; Etter, 2013; Urick, 1983; Brekhovskikh *et al*, 2003; Kinsler *et al.*, 1999). Whereas in deeper waters, the noise will propagate further without encountering the surface or bottom of the sea (seabed).

121. At the sea surface, the majority of the noise is reflected into the water due to the difference in acoustic impedance (i.e. product of noise speed and density) between air and water. However, the scattering of noise at the surface of the sea can be an important factor in the propagation of noise. In an ideal case (i.e. for a perfectly smooth sea surface), the majority of noise energy will be reflected into the sea. However, for rough seas, much of the noise energy is scattered (e.g. Eckart, 1953; Fortuin, 1970; Marsh, Schulkin, and Kneale, 1961; Urick and Hoover, 1956). Scattering can also occur due to bubbles near the surface such as those generated by wind or fish or due to suspended solids in the water such as particulates and marine species. Scattering is more pronounced for higher frequencies than for low frequencies and is dependent on the sea state (i.e. wave height). However, the various factors affecting this mechanism are complex.

122. As surface scattering results in differences in reflected noise, its effect will be more apparent at longer ranges from the noise source and in acoustically shallow water (i.e. where there are multiple reflections between the source and receiver). The degree of scattering will depend upon the sea state/wind speed, water depth, frequency of the noise, temperature gradient, grazing angle and range from source. It should be noted that variations in propagation due to scattering will vary temporally within an area primarily due to different sea-states/wind speeds at different times. However, over shorter ranges (e.g. several hundred meters or less) the noise will experience fewer reflections and so the effect of scattering should not be significant.

123. When noise waves encounter the seabed, the amount of noise reflected will depend on the geoacoustic properties of the bottom (e.g. grain size, porosity, density, noise speed, absorption coefficient and roughness) as well as the grazing angle and frequency of the noise (Cole, 1965; Hamilton, 1970; Mackenzie, 1960; McKinney and Anderson, 1964; Etter, 2013; Lurton, 2002; Urick, 1983). Thus, seabeds comprising primarily mud or other acoustically soft sediments will reflect less noise than acoustically harder bottoms such as rock or sand. This will also depend on the profile of the bottom (e.g. the depth of the sediment layer and how the geoacoustic properties vary with depth below the seafloor). The effect is less pronounced at low frequencies (a few kHz and below). A scattering effect (similar to that which occurs at the surface) also occurs at the seabed (Essen, 1994; Greaves and Stephen, 2003; McKinney and Anderson, 1964; Kuo, 1992), particularly on rough substrates (e.g. pebbles).

124. The waveguide effect should also be considered, which defines the shallow water columns that do not allow the propagation of low frequency noise (Urick, 1983; Etter, 2013). The cut-off frequency of the lowest mode in a channel can be calculated based on the water depth and knowledge of the sediment geoacoustic properties but, for example, the cut-off frequency as a function of water depth (based on the equations set out in Urick, 1983) is shown in Figure 7.1 for a range of seabed types. Any noise below this frequency will not propagate far due to energy losses through multiple reflections.

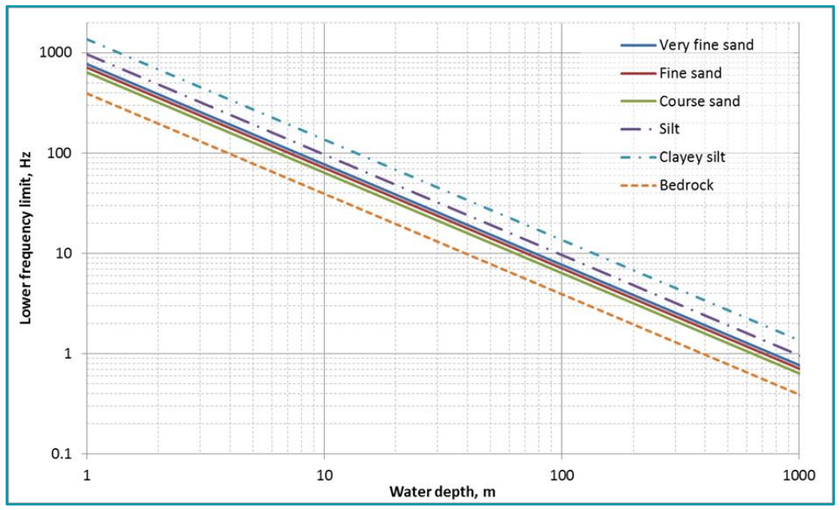

Figure 7.1: Lower Cut-Off Frequency as a Function of Depth for a Range of Seabed Types

125. Changes in the water temperature and the hydrostatic pressure with depth mean that the speed of noise varies throughout the water column. This can lead to significant variations in noise propagation and can also lead to noise channels, particularly for high-frequency noise (Lurton 2002). Noise can propagate in a duct-like manner within these channels, effectively focussing the noise, and conversely, they can also lead to shadow zones. The frequency at which this occurs depends on the characteristics of the noise channel and since the temperature gradient can vary throughout the year there will be potential variation in noise propagation depending on the season.

126. Noise energy is also absorbed due to interactions at the molecular level converting the acoustic energy into heat (Urick 1983). This is another frequency-dependent effect with higher frequencies experiencing much higher losses than lower frequencies.

7.2. MODELLING APPROACH

127. There are several methods available for modelling the propagation of noise between a source and receiver ranging from very simple models which simply assume spreading effects according to a 10 log (R) or 20 log (R) relationship (as discussed above, and where R is the range from source) to full acoustic models (e.g. ray tracing, normal mode, parabolic equation, wavenumber integration and energy flux models). In addition, semi-empirical models are available, in which complexity and accuracy are somewhere in between these two extremes.

128. In choosing the correct propagation model to employ, it is important to ensure that it is fit for purpose and produces results with a suitable degree of accuracy for the application in question, taking into account the context, as detailed in “Monitoring Guidance for Underwater Noise in European Seas Part III”, National Physical Laboratory Guidance (Dekeling *et al.*, 2014) and in Farcas *et al.* (2016). Thus, in some situations (e.g. low risk of auditory injury due to underwater noise, where range dependent bathymetry is not an

[11] Acoustically, shallow water conditions exist whenever the propagation is characterised by multiple reflections with both the sea surface and bottom (Etter, 2013). Consequently, the depth at which water can be classified as acoustically deep or shallow depends upon numerous factors including the noise speed gradient, water depth, frequency of the noise and distance between the source and receiver.

issue, i.e. for non-impulsive noise) a simple (N log R) model might be sufficient, particularly where other uncertainties (such as uncertainties in source level or the impact thresholds) outweigh the uncertainties due to modelling. On the other hand, some situations (e.g. very high source levels, impulsive noise, complex source and propagation path characteristics, highly sensitive receivers, and low uncertainties in assessment criteria) warrant a more complex modelling methodology.

129. The first step in choosing a propagation model is therefore to examine these various factors, such as:

- balancing of errors/uncertainties;
- range dependant bathymetry;
- frequency dependence; and
- source characteristics.

7.3. MODELLING APPROACH FOR VESSLES AND CONTINOUS SOURCES

130. For the noise field model, relevant survey parameters were chosen based on a combination of data provided by the Applicant combined with the information gathered from the publicly available literature. These parameters were fed into an appropriate propagation model routine, in this case the Weston Energy Flux model (for more information refer to Weston, 1971; 1980a; 1980b), suited to the region and the frequencies of interest. The frequency-dependent loss of acoustic energy with distance (TL) values were then evaluated along different transects around the chosen source points. The frequencies of interest in the present study are from 20 Hz to 80 kHz, with different noise sources operating in different frequency bands.

131. The propagation loss is calculated using one of four regions, depending on the distance of the receiver location from the source, and related to the frequency and the seafloor conditions such as depth and its composition.

132. The spherical spreading region exists in the immediate vicinity of the source, which is followed by a region where the propagation follows a cylindrical spread out until the grazing angle is equal to the critical grazing angle. Above the critical grazing angle in the mode stripping region an additional loss factor is introduced which is due to seafloor reflection loss, where higher modes are attenuated faster due to their larger grazing angles. In the final region, the single-mode region, all modes but the lowest have been fully attenuated.

7.4. MODELLING APPROACH FOR IMPACT PILING

133. In the case of offshore pile installation using an impact hammer, the noise source can be thought of as a “line source” extending through the water column (or in the case of installations using a submersible hammer, a line source through a lower portion of the water column). The hammer strike at the top of the pile produces a compression wave in the pile resulting in radial displacement of the pile walls which is transmitted into the surround media (water and sediments) as noise waves. These compressional waves travel through the pile at circa 5,000 m/s, resulting in a conically shaped wavefront in the water column.

134. Underwater acoustic propagation modelling for this project will be undertaken using a combined distributed line-source array normal mode model for low frequencies (<1 kHz) complimented by a line-source energy flux model for high frequencies (>1 kHz). The line source normal mode model is based on the KrakenC solver (Porter 2001) implemented for a line array over the pile length. The line-source energy flux model is based on an implementation of the energy flux model for a directional source set out in de Jong *et al.* (2019).

135. The normal-mode method involves solving a depth-dependent equation based on the assumption of a set of modes of vibration which are roughly akin to the modes of a vibrating string (Jensen, 1994). The complete acoustic field is constructed by summing up contributions of each of the modes weighted in accordance with the source depth. The KrakenC solver finds the normal modes in the complex wavenumber plane, which allows it to deal with elastic seabed layers, and to include the effects of leaky modes, making it a good choice for calculation of low frequencies for both close and long range noise fields. The method is, however, slow at higher frequencies and has therefore only been implemented for low frequencies (<1 kHz).

136. The line-source energy flux model (de Jong *et al.* 2019) used for higher frequencies includes the effect of directionality of the cone shaped wavefront associated with piling noise (circa 17 degrees). This results in damped cylindrical spreading at shorter ranges and mode stripping behaviour at more distant ranges. At even more distant ranges, once the ‘mode stripping’ has eliminated the contribution of all waveguide modes except the lowest mode, propagation is evaluated according to a single mode regime.

137. For estimation of propagation loss of acoustic energy at different distances away from the noise source location (in different directions), the following steps were considered:

- The bathymetry information around this chosen source points will be extracted from the GEBCO database in 72 different transects.
- A geoacoustic model of the different seafloor layers in the survey region will be calculated based on the British Geological Survey (BGS) borehole database and Emodnet sediment database.
- A calibrated line-source propagation model will be employed to estimate the transmission loss matrices for different frequencies of interest (from 25 Hz to 80 kHz) along the 72 different transects.
- Source levels for the line-source array will be determined based on a back-calculation from the received noise level and spectrum shape at 750 m (based on the scaling laws set out in von Pein *et al.* (2022).
- The calculated source level values will be combined with the transmission loss results to achieve a frequency and range dependant RL of acoustic energy around the chosen source position.
- The TTS and PTS potential impact distances for different marine mammal groups will be calculated using relevant metrics and weighting functions (from (Southall *et al*. 2019) and by employing a simplistic animal movement model (directly away from the noise source) where appropriate (as agreed with NatureScot on 27 September 2023; refer to section 7.6.1 for more detail). For assessing marine mammal disturbance using single pulse SEL and for assessing effects on fish, no frequency weighting is applied.

138. The approach to pile modelling using a line source array model has been consulted on with NatureScot and agreement was received via email on 05 December 2023 (*pers. comms.,* 2023).

139. The level of detail presented in terms of noise modelling needs to be considered in relation to the level of uncertainty for animal injury and disturbance thresholds. Uncertainty in the noise level predictions will be higher over larger propagation distances (i.e. in relation to disturbance thresholds) and much lower over shorter distances (i.e. in relation to injury thresholds). Nevertheless, it is considered that the uncertainty in animal injury and disturbance thresholds is likely to be higher than uncertainty in noise predictions. This is further compounded by differences in individual animal response, sensitivity, and behaviour. It would therefore be wholly misleading to present any injury or disturbance ranges as a clear line beyond which no effect can occur, and it would be equally misleading to present any noise modelling results in such a way.

7.4.1. SEICHE LINE SOURCE MODEL CALIBRATION

140. The Seiche Ltd line array model has been benchmarked against the COMPILE benchmark workshop for numerical models for pile driving acoustics (Lippert *et al*., 2016). The COMPILE workshop included modelling results from a number of different organisations in an attempt to compare the performance of acoustic models for piling against pre-defined input parameters. The models included in the benchmarking exercise included those developed by Seoul National University (SNU), Netherlands Organisation for Applied Scientific Research (TNO), Hamburg University of Technology (TUHH), Jasco Applied Sciences, Curtin University and Bundeswehr Technical Centre for Ships and Naval Weapons, Maritime Technology and Research (WTD 71).

141. A comparison between the Seiche model and the benchmark workshop model results is presented in Figure 7.2. The results of the benchmarking exercise show good correlation with the other models with the results most closely matching the TNO model. The Seiche model predicts slightly higher received levels compared to the other models at 20 km range for this particular benchmark scenario (10 m water depth,

sand substrate). Nevertheless, it is considered that the results of the benchmarking exercise demonstrate a good degree of agreement with other noise propagation models for piling.

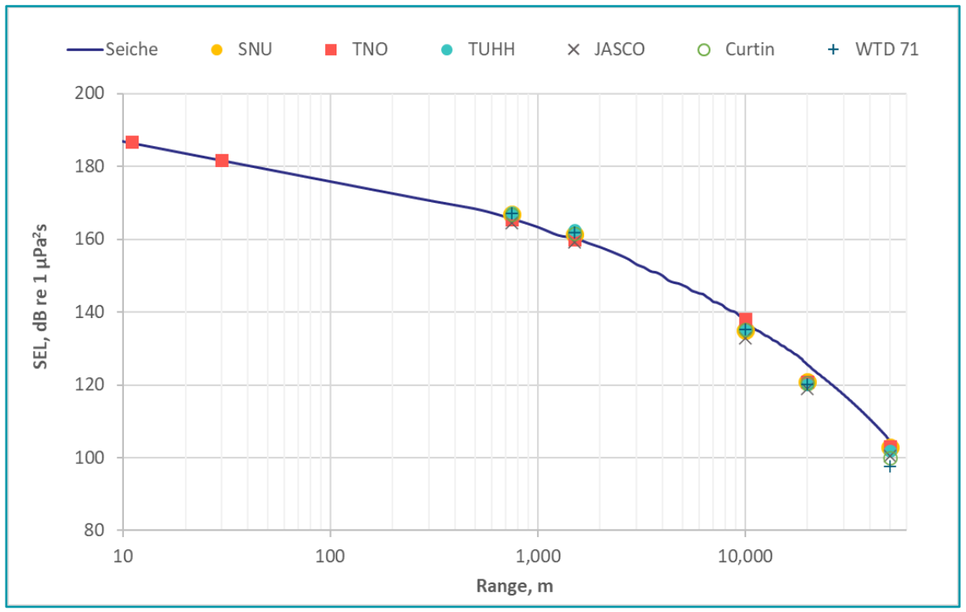

Figure 7.2: Comparison of Seiche Underwater Acoustic Model Against COMPILE Benchmarks

7.5. GEO-ACOUSTIC AND NOISE-SPEED INPUT PARAMETERS

142. Based on BGS core data in the vicinity of the Array, the geo-acoustic model is based on the parameters presented in Table 7.1.

Table 7.1: Geo-Acoustic Model Used in Propagation Model

Start Depth (m)	End Depth (m)	Layer	Compressional Sound Speed (V_p, m/s)	Sheer Sound Speed (V_s, m/s)	Compressional Attenuation Coefficient (α_p, dB/λ_p)	Sheer Attenuation Coefficient (α_s, dB/λ_s)	Density (kg/m^3)
0	20	Sand	1,685	270	0.89	2.5	1,941
20	28	Clay	1,500	100	0.2	1	2,334
28	40	Diamicton	1,836	544	0.6	1.5	2,034
40	48	Clay	1,500	100	0.2	1	2,334
48	52	Sand	1,652	262	0.89	2.5	1,771
52	90	Clay	1,500	100	0.2	1	2,334
90	Halfspace	Siltstone	3,800	2150	0.1	0.25	2,400

143. The sound speed profile has been based on the mean summer temperature and salinity profile for the region, as presented in Figure 7.3. To produce a representative sound speed profile, conductivity, temperature, and depth (CTD) data was obtained from the NOAA service WODselect for the closest sample point to the development[12] (NOAA 2023).

[12] Latitude 56.625 Longitude -0.375

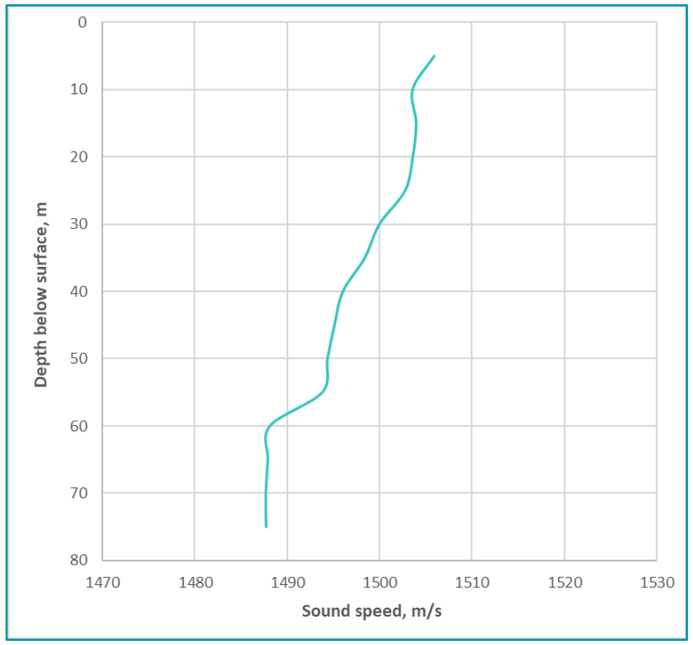

Figure 7.3: Noise Speed Profile Used in Propagation Model

7.6. BATCH PROCESSING

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

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

146. The received levels were evaluated for the SPL_{pk}, SPL_{rms} or SEL metric, for each source type, source location, and azimuthal transect to produce the associated TL. The broadband RL were then calculated for these metrics and from the third octave band results. The set of simulated RL transects were circularly interpolated to generate the broadband RL maps centred around each source point. Representations of these RLs are provided in volume 2, chapter 9 in the form of contour maps.

147. For impact piling, the far-field received peak sound pressure level was calculated from SEL values via the empirical fitting between pile driving SEL and peak SPL data.

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

7.6.1. EXPOSURE CALCULATIONS

149. As well as calculating the unweighted noise levels at various distances from different source, it is also necessary to calculate the received acoustic signal in terms of the SEL metric (where necessary and possible) for a marine mammal using the relevant hearing weighting functions. For different operations related noise sources, the numerical SEL value is equal to the SPL rms value integrated over a one second window as the sources are continuous and non-impulsive. These SEL values are employed for calculation of SEL_{cum} (cumulative SEL) metric for different marine mammal groups to assess potential impact ranges.

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

151. It should be noted that the noise exposure calculations are based on the simplistic assumption that the noise source is active continuously (or intermittently based on source activation timings) over a 24 hour period. The real world situation, however, is more complex. The SEL calculations presented in this study do not take any breaks in activity into account, such as repositioning of the piling vessel, or downtime due to mechanics, logistics or weather.

152. Furthermore, the noise criteria described in the Southall *et al.* (2019) guidelines assume that the animal does not recover hearing between periods of activity. It is likely that both the intervals between operations could allow some recovery from temporary hearing threshold shifts for animals exposed to the noise (von Benda-Beckmann *et al.* 2022) and, therefore, the assessment of sound exposure level is conservative.

153. In order to carry out the moving marine mammal calculation, it has been assumed that a mammal will swim away from the noise source at the onset of activities. For impulsive noises of piledriving the calculation considers each pulse to be established separately resulting in a series of discrete SEL values of decreasing magnitude (see Figure 7.4).

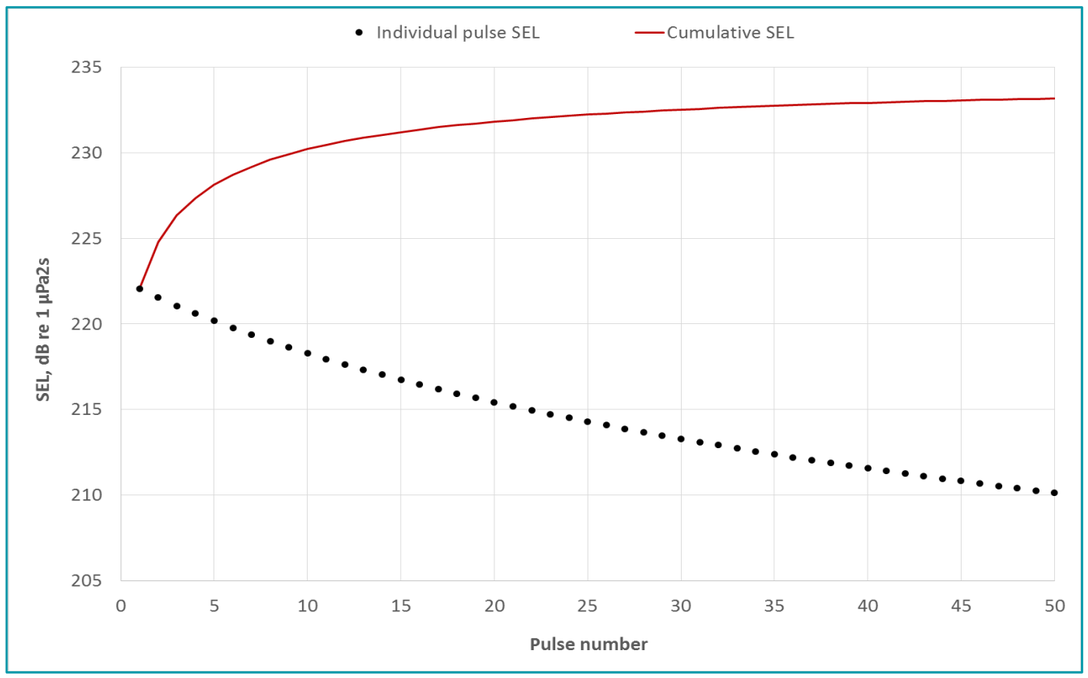

Figure 7.4: A Comparison of Discrete SEL Per Pulse, and Cumulative SEL Values

154. As an animal swims away from the noise source, the noise it experiences will become progressively lower (more attenuated); the cumulative SEL is derived by logarithmically adding the SEL to which the mammal is exposed as it travels away from the source. This calculation was used to estimate the approximate minimum start distance for an animal in order for it not to be exposed to sufficient noise energy to result in the onset of potential auditory injury. It should be noted that the noise exposure calculations are based on the simplistic assumption that the animal will continue to swim away at a fairly constant relative speed. The real world situation is more complex, and the animal is likely to move in a more complex manner: at varying speed and direction.

155. The assumed swim speeds for animals likely to be present across the Array are set out in Table 7.2.

Table 7.2: Assessment Swim Speeds of Marine Mammals and Fish that are Likely to Occur Within the North Sea for the Purpose of Exposure Modelling

Species	Hearing group	Swim speed (m/s)	Source reference
Harbour seal	Phocid Carnivores in Water (PCW)	1.8	Thompson *et al.* (2015)
Grey seal	Phocid Carnivores in Water (PCW)	1.8	Thompson *et al.* (2015)
Harbour porpoise	Very High Frequency (VHF)	1.5	Otani *et al.* (2000)
Minke whale	Low Frequency (LF)	2.3	Boisseau *et al.* (2021)
Bottlenose dolphin	High Frequency (HF)	1.52	Bailey *et al.* (2010)
White-beaked dolphin	High Frequency (HF)	1.52	Bailey *et al.* (2010)
Short beaked common dolphin *Delphinus delphis*	High Frequency (HF)	1.52	Bailey *et al.* (2010)
Risso's dolphin *Grampus griseus*	High Frequency (HF)	1.52	Bailey *et al.* (2010)
All fish hearing groups	Group 1 to 4 fish	0 and 0.5	Popper *et al.* (2014)

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

157. To perform the cumulative exposure calculation, the first step is to parameterise the m-weighted sound exposure levels (or unweighted in the case of fish) for single strikes of a given energy via the 95th percentile line of best fit against the calculated received levels from the model. This function is then used to predict the exposure level for each strike in the planned hammer schedule (periods of slow start, ramp up and full power).

158. In addition to the single source pile driving, simplified situations of simultaneous pile driving from two piling rigs have been considered. The response has been approximated as moving directly away from the point on a line equidistant between the two sources. For simplicity, the sources are considered to be omnidirectional and the piling schedules (soft start, ramp up, etc.) are synchronised, entering each stage of the schedule at the same time.

7.7. UXO NOISE MODELLING

7.7.1. HIGH ORDER DETONATION

159. Acoustic modelling for UXO clearance has been undertaken using the methodology described in Soloway and Dahl (2014) and Arons (1954). The equation provides a simple relationship between distance from an explosion and the weight of the charge (or equivalent trinitrotoluene (TNT) weight) but does not take into account bottom topography or sediment characteristics:

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

where *W* is the equivalent TNT charge weight and *R* is the distance from source to receiver.

160. Since the charge is assumed to be freely standing in mid-water, unlike a UXO which would be resting on the seabed and could potentially be buried, degraded or subject to other significant attenuation, this estimation of the source level can be considered conservative.

161. According to Soloway and Dahl (2014), the SEL can be estimated using the following equation:

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

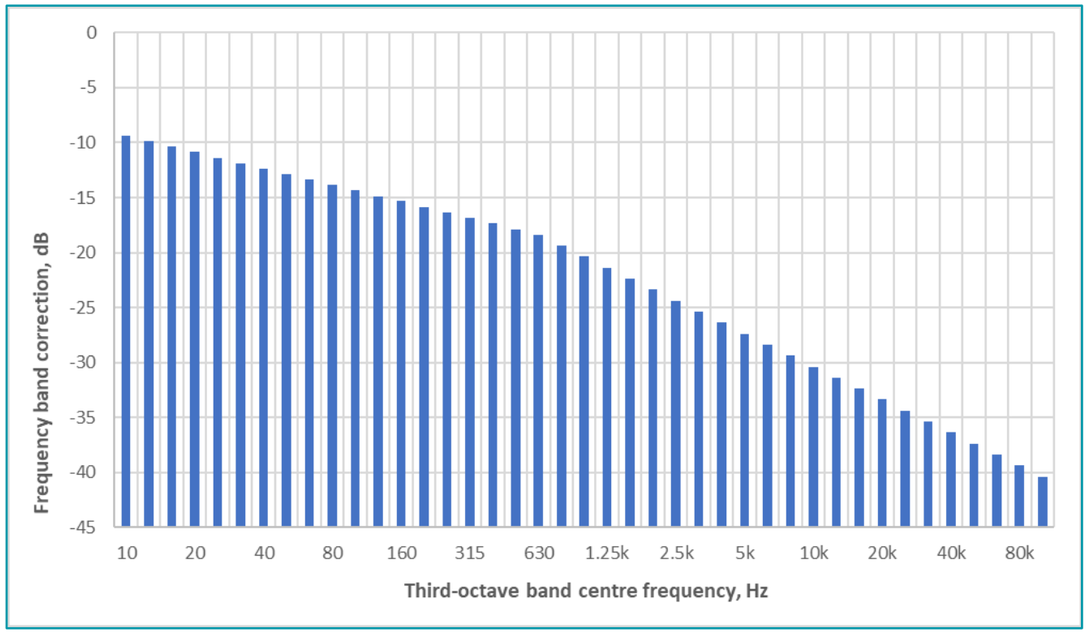

Figure 7.5: Assumed Explosive Spectrum Shape Used to Estimate Hearing Weighting Corrections to SEL reproduced from Weston (1960)

162. In order to compare against the marine mammal hearing weighted thresholds, it is necessary to apply the frequency dependent weighting functions at each distance from the source. This was accomplished by determining a transfer function between unweighted and weighted SEL values at various distances based on an assumed spectrum shape (refer to Figure 7.5) and taking into account molecular absorption at various ranges. Furthermore, because there is potential for more than one UXO clearance event per day (a maximum of two per day is assumed) then it is also necessary to take this into account in the exposure calculation.

7.7.2. LOW ORDER TECHNIQUES

163. According to Robinson *et al.* (2020), deflagration (a specific method of low order UXO clearance) results in a much lower amplitude of peak sound pressure than high order detonations. The study concluded that peak sound pressure during deflagration is due only to the size of the shaped charge used to initiate deflagration and, consequently, that the acoustic output can be predicted for deflagration if the size of the shaped charge is known.

164. Acoustic modelling for low order techniques (such as deflagration) has therefore been based on the methodology described in section 7.7.1 for high order detonations, using a smaller donor charge size (Table 6.6).

8. NOISE MODELLING RESULTS

8.1. PRE-CONSTRUCTION PHASE

165. The estimated ranges for auditory injury to marine mammals due to various proposed activities undertaken during the pre-construction site investigation surveying phase of the operations are presented in this section. These include geophysical and geotechnical survey activities, UXO clearance and supported vessel activities.

166. The potential ranges presented for injury and behavioural response are not a clearly delineated ‘line’ where an impact will occur on one side and not on the other. Potential impact is more probabilistic; in reality, dose dependency in PTS onset, individual variations, and uncertainties regarding behavioural response and swim speed/direction combine to create a probability field around the source location. Defining a single distance around this area of probability allows visualisation of the spatial extent of different source types and levels and allows comparison of the impacts on a like-for-like basis.

8.1.1. GEOPHYSICAL AND GEOTECHNICAL SURVEYS

167. Geophysical surveying includes many sonar like noise sources and the resulting injury and disturbance ranges for marine mammals are presented in Table 8.1, based on a comparison to the non-impulsive thresholds set out in Southall *et al.* (2019). Table 8.2 presents the results for geotechnical investigations. CPT distances are based on a comparison to the Southall *et al.* (2019) thresholds for impulsive noise (with the distances presented in brackets for peak SPL thresholds) whereas borehole drilling and vibro-core results are compared against the non-impulsive thresholds. Borehole drilling source levels were reported as 142 dB to 145 dB re 1 µPa rms at 1 m, indicating little to no disturbance.

168. The potential impact distances from these operations vary based on their frequencies of operation and source levels and are rounded to the nearest 5 m. It should be noted that, for the sonar like survey sources, many of the injury ranges are limited to circa 75 m as this is the approximate water depth in the area. Sonar like systems have very strong directivity which effectively means that there is only potential for injury when a marine mammal is directly underneath the noise source. Once the animal moves outside of the main beam, there is significantly reduced potential for injury. The same is true in many cases for TTS where an animal is only exposed to enough energy to cause TTS when inside the direct beam of the sonar like source. For this reason, many of the TTS and PTS ranges are similar (i.e. limited by the depth of the water). Disturbance thresholds are as shown in Table 5.3 for impulsive and non-impulsive sources respectively, noting that impulsive sources have both a strong and a mild disturbance threshold.

Table 8.1: Potential Impact Ranges (m) for Marine Mammals During the Various Geophysical Investigation Activities Based on Comparison to Southall *et al.* (2019) SEL Thresholds

Source	Potential Impact Range (m)										
	LF		HF		VHF		PCW		OCW		All
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
MBES*	35	5	75	65	75	75	55	5	5	N/E	375
SSS*	65	10	75	75	75	75	75	25	20	N/E	320
SBP*	75	75	220	75	545	310	75	75	75	N/E	1,340
UHRS (sparker)**	240	N/E	N/E	N/E	370	10	45	N/E	N/E	N/E	565 (mild) 80 (strong)

N/E- Not Exceeded
**Non-impulsive threshold*
***Impulsive threshold*

Table 8.2: Potential Impact Ranges for Geotechnical Site Investigation Activities Based on Comparison to Southall *et al.* (2019) SEL Thresholds (Comparison to Ranges for Peak SPL Where Threshold was Exceeded Shown in Brackets)

Source	Potential Impact Range (m)										
	LF		HF		VHF		PCW		OCW		All
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
Borehole drilling*	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	27
Cone penetration testing**	65	N/E	10	N/E	730	45	30	N/E	N/E	N/E	1,330 (mild) 140 (strong)
Vibro-coring*	N/E	N/E	N/E	N/E	467	N/E	N/E	N/E	N/E	N/E	9,101

N/E- Not Exceeded
**Non-impulsive threshold*
***Impulsive threshold*

8.1.2. VESSELS

169. The potential impact ranges for vessels are included in section 8.4, which summarises the vessel modelling results for all phases of the Array.

8.1.3. UXO CLEARANCE

170. The predicted injury ranges for low order disposal are presented in Table 8.3 and for high order detonation of UXOs in Table 8.4. All UXO injury and disturbance ranges are based on a comparison to the relevant impulsive noise thresholds as set out in section 5.3.2.

171. It should be noted that, due to a combination of dispersion (i.e. where the waveform elongates), multiple reflections from the sea surface and seabed and molecular absorption of high frequency energy, the noise is unlikely to still be impulsive in character once it has propagated more than a few kilometres. Consequently, great caution should be used when interpreting any results with predicted injury ranges in the order of tens of kilometres. Furthermore, the modelling assumes that the UXO acts like a charge suspended in open water whereas in reality it is likely to be partially buried in the sediment. In addition, it is possible that the explosive material will have deteriorated over time meaning that the predicted noise levels are likely to be over-estimated. In combination, these factors mean that the results should be treated as precautionary potential impact ranges which are likely to be significantly lower than predicted.

Table 8.3: Potential Impact Ranges for Low Order and Low Yield UXO Clearance Activities

	PTS Range (m)		TTS Range (m)	
	SPL_{pk}	SEL	SPL_{pk}	SEL
0.25 kg Low Order Donor Charge				
LF	186	88	342	1,225
HF	61	N/E	112	43
VHF	1,050	337	1,930	2,120
PCW	206	17	378	232
OCW	50	N/E	91	10
Fish (lower range)	67	-	-	-
Fish (upper range)	40	-	-	-
0.5 kg Clearing Shot				
LF	234	124	431	1,690
HF	77	N/E	141	60
VHF	1,320	448	2,435	2,510
PCW	259	24	477	320
OCW	63	N/E	115	14
Fish (lower range)	85	-	-	-
Fish (upper range)	51	-	-	-

Table 8.4: Potential Impact Ranges for High Order Clearance of UXOs

	PTS Range (m)		TTS Range (m)	
	SPL_{pk}	SEL	SPL_{pk}	SEL
227 kg UXO – High Order Explosion				
LF	1,770	2,305	3,260	22,520
HF	577	83	1,065	870
VHF	10,000	2,930	18,425	7,515
PCW	1,960	437	3,610	4,265
OCW	471	20	870	271
Fish (lower range)	640	-	-	-
Fish (upper range)	384	-	-	-
698 kg UXO – High Order Explosion				
LF	2,575	3,925	4,740	32,735
HF	840	139	1,550	1,310
VHF	14,540	3,710	26,790	8,720
PCW	2,850	745	5,250	6,120
OCW	685	34	1,265	462
Fish (lower range)	930	-	-	-
Fish (upper range)	558	-	-	-

8.2. CONSTRUCTION PHASE

8.2.1. IMPACT PILING

172. The impact piling scenarios modelled were as follows:

- single piling – wind turbine foundation piles (3,000 kJ);
- single piling – OSP jacket piles (4,400 kJ);
- two concurrent piling event – wind turbine foundation piles (3,000 kJ); and
- two concurrent piling events – wind turbine foundation pile (3,000 kJ) and OSP jacket pile (4,400 kJ).

173. All cases are presented both with and without the use of 30 minutes of ADD prior to installation.

174. Impact ranges were modelled for all three locations, as shown in Figure 8.1, however only the most adverse case injury ranges have been reported in this section. The 90th percentile of the transmission loss was used for the calculations, which is considered to be a worst case while taking into account outliers due to extreme changes in bathymetry and sea conditions, for example.

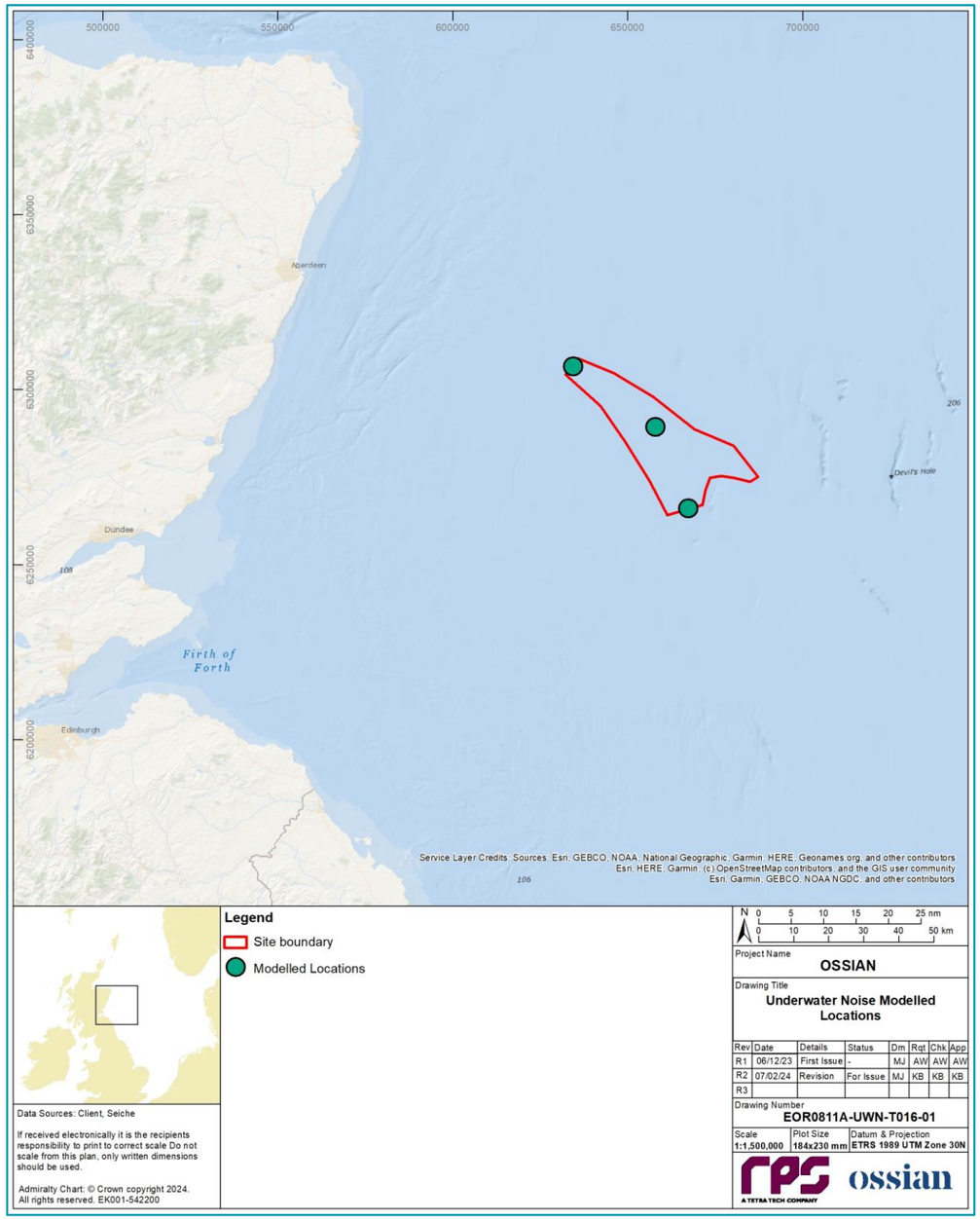

Figure 8.1: Locations Modelled Within the Ossian Array (Red Line)[13]

[13] Note that the central location is used only for the concurrent modelling of disturbance and does not form part of the injury range results. The concurrent scenarios are central with the North point; and central with the South point.

175. All impact piling injury ranges are based on a comparison to the relevant impulsive noise thresholds as set out in section 5. Disturbance effects are presented in volume 2, chapter 10 using the dose-response approach described in section 5.3.

176. The injury ranges for peak sound pressure are based on the noise from the maximum hammer energy over the entire installation.

177. It should be noted that peak sound pressure is a time domain parameter and does not necessarily add together to produce higher received peak sound pressure levels. Even if two piling hammers were to strike their piles synchronously (i.e. to the exact millisecond) the noise waves will arrive at different locations at different times. Consequently, the peak pressure ranges for simultaneous piling do not differ from the peak injury ranges identified for single piling spreads.

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

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

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

8.2.2. SINGLE PILING

181. Distances are presented at which noise levels decrease to below PTS/TTS threshold values in terms of cumulative SEL and peak sound pressure level. It should be noted that the potential PTS/TTS ranges reduce significantly with the use of ADD because it is assumed that an animal swims away from the area for 30 minutes before being exposed to noise from piling, therefore significantly reducing its cumulative SEL for any given start range.

182. Distances are presented in Table 8.5 to Table 8.9 for wind turbine foundation pile installation at 3,000 kJ and Table 8.10 to Table 8.14 for OSP jacket pile installation at 4,400 kJ.

Table 8.5: Marine Mammals: Potential Injury and Disturbance Ranges for Single Wind Turbine Foundation Pile Installation using 3,000 kJ Hammer, Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 μPa^2s)	Range (m)	
		No ADD	30 min ADD
LF	PTS – 183 dB re 1 μPa^2s	990	N/E
	TTS – 168 dB re 1 μPa^2s	29,200	25,000
HF	PTS – 185 dB re 1 μPa^2s	N/E	N/E
	TTS – 170 dB re 1 μPa^2s	N/E	N/E
VHF	PTS – 155 dB re 1 μPa^2s	10	N/E
	TTS – 140 dB re 1 μPa^2s	2,330	N/E
PCW	PTS – 185 dB re 1 μPa^2s	N/E	N/E
	TTS – 170 dB re 1 μPa^2s	565	N/E

Table 8.6: Marine Mammals: Potential Injury and Disturbance Ranges for Single Wind Turbine Foundation Pile Installation at 3,000 kJ Based on the Peak SPL Metric

Species/Group	Threshold, $L_{0\text{-}pk}$, dB re 1 µPa	Range (m)
LF	PTS – 219 dB re 1 µPa (pk)	180
	TTS – 213 dB re 1 µPa (pk)	266
HF	PTS – 230 dB re 1 µPa (pk)	95
	TTS – 224 dB re 1 µPa (pk)	133
VHF	PTS – 202 dB re 1 µPa (pk)	665
	TTS – 196 dB re 1 µPa (pk)	1,130
PCW	PTS – 218 dB re 1 µPa (pk)	192
	TTS – 212 dB re 1 µPa (pk)	285

Table 8.7: Fish: Potential Injury and Disturbance Ranges for Single Wind Turbine Foundation Pile Installation at 3,000 kJ Based on the Cumulative SEL Metric for Moving Fish

Hearing Group	Response	Threshold, SEL (dB re 1 µPa^{2}s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	15
	Recoverable injury	216	20
	TTS	186	8,380
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	32
	Recoverable injury	203	110
	TTS	186	8,380
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	50
	Recoverable injury	203	110
	TTS	186	8,380
Fish eggs and larvae (static)	Mortality	210	1,015

Table 8.8: Fish: Potential Injury and Disturbance Ranges for Single Wind Turbine Foundation Pile Installation at 3,000 kJ Based on the Cumulative SEL Metric for Static Fish

Hearing Group	Response	Threshold, SEL (dB re 1 µPa^{2}s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	328
	Recoverable injury	216	472
	TTS	186	13,200
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	1,015
	Recoverable injury	203	2,300
	TTS	186	13,200
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	1,460
	Recoverable injury	203	2,300
	TTS	186	13,200
Fish eggs and larvae	Mortality	210	1,015

Table 8.9: Fish: Potential Injury and Disturbance Ranges for Single Wind Turbine Foundation Pile Installation at 3,000 kJ Based on the Peak SPL Metric

Hearing Group	Response	Threshold, $L_{0\text{-}pk}$ (dB re 1 µPa)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	213	266
	Recoverable injury	213	266
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	207	414
	Recoverable injury	207	414
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	414
	Recoverable injury	207	414
Fish eggs and larvae	Mortality	207	414

Table 8.10: Marine Mammals: Potential Injury and Disturbance Ranges for Single OSP Jacket Pile Installation at 4,400 kJ Based on the Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 µPa^{2}s)	Range (m)	
		No ADD	30 min ADD
LF	PTS – 183 dB re 1 µPa^{2}s	7,200	3,050
	TTS – 168 dB re 1 µPa^{2}s	79,000	75,000
HF	PTS – 185 dB re 1 µPa^{2}s	N/E	N/E
	TTS – 170 dB re 1 µPa^{2}s	N/E	N/E
VHF	PTS – 155 dB re 1 µPa^{2}s	70	N/E
	TTS – 140 dB re 1 µPa^{2}s	8,000	5,260
PCW	PTS – 185 dB re 1 µPa^{2}s	N/E	N/E
	TTS – 170 dB re 1 µPa^{2}s	6,340	3,110

Table 8.11: Marine Mammals: Potential Injury and Disturbance Ranges for Single OSP Jacket Pile Installation at 4,400 kJ Based on the Peak SPL Metric

Species/Group	Threshold, $L_{0\text{-}pk}$ (dB re 1 µPa)	Range (m)
LF	PTS – 219 dB re 1 µPa (pk)	353
	TTS – 213 dB re 1 µPa (pk)	615
HF	PTS – 230 dB re 1 µPa (pk)	171
	TTS – 224 dB re 1 µPa (pk)	251
VHF	PTS – 202 dB re 1 µPa (pk)	1,600
	TTS – 196 dB re 1 µPa (pk)	2,580
PCW	PTS – 218 dB re 1 µPa (pk)	379
	TTS – 212 dB re 1 µPa (pk)	675

Table 8.12: Fish: Potential Injury and Disturbance Ranges for Single OSP Jacket Pile Installation at 4,400 kJ Based on the Cumulative SEL Metric for Moving Fish

Hearing Group	Response	Threshold, $L_{0\text{-}pk}$ (dB re 1 µPai)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection	Mortality	219	25
	Recoverable injury	216	37
	TTS	186	21,100
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	112
	Recoverable injury	203	1,440
	TTS	186	21,100
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	425
	Recoverable injury	203	1,440
	TTS	186	21,100
Fish eggs and larvae (static)	Mortality	210	2,440

Table 8.13: Fish: Potential Injury and Disturbance Ranges for Single OSP Jacket Pile Installation at 4,400 kJ Based on the Cumulative SEL Metric for Static Fish

Hearing Group	Response	Threshold, SEL (dB re 1 μPa^2s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	855
	Recoverable injury	216	1,220
	TTS	186	26,960
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	2,440
	Recoverable injury	203	5,120
	TTS	186	26,960
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	3,380
	Recoverable injury	203	5,120
	TTS	186	26,960
Fish eggs and larvae	Mortality	210	2,440

Table 8.14: Fish: Potential Injury Ranges for Single OSP Jacket Pile Installation at 4,400 kJ Based on the Peak SPL Metric

Hearing Group	Response	Threshold, $L_{0\text{-}pk}$ (dB re 1 µPa)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	213	615
	Recoverable injury	213	615
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	207	1,055
	Recoverable injury	207	1,055
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	1,055
	Recoverable injury	207	1,055
Fish eggs and larvae	Mortality	207	1,055

183. Potential disturbance ranges for all fish species are sown in Table 8.15 for both the 3,000 kJ and 4,400 kJ case. Disturbance to marine mammals is discussed in volume 2, chapter 9 in terms of dose-response, as shown in Table 5.3 and discussed in section 5.3.

Table 8.15: Fish: Potential Disturbance Ranges for Single Pile Installation Based on the 150 dB re 1µPa (rms) Contour

Range (m)	
3,000 kJ	**4,400 kJ**
32,912	48,915

8.2.3. CONCURRENT PILING

184. Construction may occur utilising two pile installation vessels operating concurrently. The potential cumulative SEL injury ranges for marine mammals and fish due to impact pile driving of piles are modelled as following the same piling plans with all phases starting at the same time. For injury the MDS is considered to be that of two adjacent piles, separated by a distance of 950 m due to the maximal overlap of noise propagation contours leading to the maximum generated noise levels. Conversely, for disturbance the maximum separation between two piling locations would lead to the larger area ensonified at any one time and therefore the greatest disturbance.

185. For the modelling of disturbance, modelling has been undertaken for piling at the northern location concurrently with the central location, and the southern location concurrently with the central location. This is representative of the largest separation of the piling vessels, as detailed within volume 1, chapter 4, and a maximum separation of 30 km. Although there is a possibility of a separation between vessels of up to 41 km, variation in seabed bathymetries and water depths make the separation modelled the scenario resulting in maximum disturbance,

186. In this section, modelling of injury ranges has been undertaken for two adjacent piles at the northern and southern locations. As for the single piling case, the maximum design scenario has been reported here.

187. Injury ranges are presented in terms of cumulative SEL metric in Table 8.16 to Table 8.18 for foundation pile installation at 3,000 kJ at both sites, and in Table 8.19 to Table 8.21 for concurrent piling of OSP jacket pile installation at 4,400 kJ and foundation piles at 3,000 kJ at each site. The peak metric will remain the same as the single installation case. As noted previously, disturbance effects are covered in volume 2, chapter 10 using the dose-response approach described in section 5.3.2.

Table 8.16: Marine Mammal: Potential Injury and Disturbance Ranges for Concurrent Wind Turbine Foundation Pile Installation at 3,000 kJ Based on the Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 µPa^{2}s)	Range (m)	
		No ADD	30 min ADD
LF	PTS – 183 dB re 1 µPa^{2}s	1,445	N/E
	TTS – 168 dB re 1 µPa^{2}s	42,000	38,000
HF	PTS – 185 dB re 1 µPa^{2}s	N/E	N/E
	TTS – 170 dB re 1 µPa^{2}s	N/E	N/E
VHF	PTS – 155 dB re 1 µPa^{2}s	11	N/E
	TTS – 140 dB re 1 µPa^{2}s	3,040	384
PCW	PTS – 185 dB re 1 µPa^{2}s	N/E	N/E
	TTS – 170 dB re 1 µPa^{2}s	1,690	N/E

Table 8.17: Fish: Potential Injury and Disturbance Ranges for Concurrent Wind Turbine Foundation Pile Installation at 3,000 kJ Based on the Cumulative SEL Metric for Fish Moving Away)

Hearing Group	Response	Threshold, SEL (dB re 1 µPa^{2}s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	15
	Recoverable injury	216	20
	TTS	186	11,800
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	219	35
	Recoverable injury	216	171
	TTS	186	11,800
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	219	56
	Recoverable injury	216	171
	TTS	186	11,800
Fish eggs and larvae (static)	Mortality	216	1,990

Table 8.18: Fish: Potential Injury and Disturbance Ranges for Concurrent Wind Turbine Foundation Pile Installation at 3,000 kJ Based on the Cumulative SEL Metric for Static Fish

Hearing Group	Response	Threshold, SEL dB re 1 μPa^{2}s	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	670
	Recoverable injury	216	985
	TTS	186	22,500
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	1,990
	Recoverable injury	203	4,220
	TTS	186	22,500
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	2,760
	Recoverable injury	203	4,220
	TTS	186	22,500
Fish eggs and larvae	Mortality	210	1,990

Table 8.19: Marine Mammal: Potential Injury and Disturbance Ranges for Concurrent OSP Jacket Pile Installation at 4,400 kJ and Wind Turbine Foundation Pile at 3,000 kJ Based on the Cumulative SEL Metric (N/E – Threshold Not Exceeded)

Species/Group	Threshold, SEL (dB re 1 μPa^{2}s)	Range (m)	
		No ADD	30 min ADD
LF	PTS – 183 dB re 1 μPa^{2}s	9,740	5,610
	TTS – 168 dB re 1 μPa^{2}s	91,000	87,000
HF	PTS – 185 dB re 1 μPa^{2}s	N/E	N/E
	TTS – 170 dB re 1 μPa^{2}s	N/E	N/E
VHF	PTS – 155 dB re 1 μPa^{2}s	203	N/E
	TTS – 140 dB re 1 μPa^{2}s	9,620	7,300
PCW	PTS – 185 dB re 1 μPa^{2}s	N/E	N/E
	TTS – 170 dB re 1 μPa^{2}s	9,020	5,780

Table 8.20: Fish Injury Ranges for Concurrent OSP Jacket Pile Installation at 4,400 kJ and Wind Turbine Foundation Pile at 3,000 kJ Based on the Cumulative SEL Metric for Fish Moving Away

Hearing Group	Response	Threshold, SEL (dB re 1 μPa^{2}s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	26
	Recoverable injury	216	40
	TTS	186	31,200
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	219	143
	Recoverable injury	216	1,920
	TTS	186	31,200
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	219	605
	Recoverable injury	216	1,920
	TTS	186	3,120
Fish eggs and larvae (static)	Mortality	216	4,460

Table 8.21: Fish: Potential Injury and Disturbance Ranges for Concurrent OSP Jacket Pile Installation at 4,400 kJ and Wind Turbine Foundation Pile at 3,000 kJ Based on the Cumulative SEL Metric for Static Fish

Hearing Group	Response	Threshold, SEL (dB re 1 μPa^{2}s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	219	1,680
	Recoverable injury	216	2,360
	TTS	186	45,100
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	4,460
	Recoverable injury	203	9,060
	TTS	186	45,100
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	6,120
	Recoverable injury	203	9,060
	TTS	186	45,100
Fish eggs and larvae	Mortality	210	4,460

8.2.4. DRILLED PILE INSTALLATION

188. The potential impact ranges for drilled pile installation are small (or not exceeded) for all marine mammal species groups, due to the low broadband SEL levels expected from these operations, at 160 dB re 1 μPa2s (see Table 8.22). The behavioural threshold range for all marine mammal groups is also reported.

Table 8.22: Potential Impact and Disturbance Ranges (m) for Marine Mammal Exposed to Drilled Pile Installation

Potential Impact Ranges (m)											
Source	LF		HF		VHF		PCW		OCW		All
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Behaviour
Drilled pile installation	N/E	N/E	N/E	N/E	12	N/E	N/E	N/E	N/E	N/E	309

189. The ranges for recoverable injury and TTS for Group 3 and 4 Fish are presented in Table 8.23 based on the thresholds contained in Popper *et al*. (2014). Note that the guidance only states numerical thresholds for Group 3 and 4 Fish. It should be noted that fish would need to be exposed within these potential impact ranges for a period of 48 hours continuously in the case of recoverable injury and 12 hours continuously in the case of TTS for the effect to occur. It is therefore considered that these ranges are highly precautionary, and injury is unlikely to occur.

Table 8.23: Median Potential Impact and Disturbance Ranges (m) for Group 3 and 4 Fish Exposed to Drilled Pile Installation

Source	Recoverable Injury	TTS
	170 dB re 1 µPa (rms) for 48 hrs	158 dB re 1 µPa (rms) for 12 hrs
Drilled pile installation	N/E	N/E

8.2.5. OTHER CONSTRUCTION OPERATIONS

190. The potential impact ranges from other construction related activities (such as cable trenching, cable laying and supporting jack-up rigs) on different marine mammal groups are presented in Table 8.24. The potential impact ranges for fish are presented in Table 8.25.

Table 8.24: Potential Impact Ranges (m) for Marine Mammals During Other Construction Related Operations

Source	Potential Impact Ranges (m)										
	LF		HF		VHF		PCW		OCW		All
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
Cable trenching	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	2,729
Cable laying	N/E	N/E	N/E	N/E	227	15	N/E	N/E	N/E	N/E	2,224
Jack-up rig	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E

Table 8.25: Median Potential Impact and Disturbance Ranges (m) for Group 3 and 4 Fish Exposed to Other Construction Related Operations

Source	Injury Zone Radius (m)	
	Recoverable Injury	TTS
	170 dB re 1 µPa (rms) for 48 hrs	158 dB re 1 µPa (rms) for 12 hrs
Cable trenching	N/E	N/E
Cable laying	N/E	21
Jack-up rig	N/E	N/E

8.2.6. CONSTRUCTION VESSELS

191. The potential impact ranges for vessels are included in section 8.4, which summarises the vessel modelling results for all phases of the Array.

8.3. OPERATION AND MAINTENANCE

8.3.1. OPERATIONAL VESSELS

192. The potential impact ranges for vessels are included in section 8.4, which summarises the vessel modelling results for all phases of the Array.

8.3.2. OPERATIONAL NOISE FROM WIND TURBINES AND MOORING LINES

193. It is well recognised that installation of offshore wind farm infrastructure into the marine environment has the potential to result in increased anthropogenic noise in the marine environment during the construction phase. More recently, stakeholders in Scotland are raising concerns around the potential for infrastructure such as wind turbines, to also contribute to elevated anthropogenic noise levels in the marine environment during the operational phase of a project. Similar responses were received in response to the Array EIA Scoping Report (MD-LOT, 2023).

194. Due to a limited number of operational floating wind farms at the time of writing this technical report, and those in operation being of small scale (in terms of wind turbine numbers and size) it is not possible to define a representative operational sound source level for use in modelling. As such, the operational noise from wind turbines and mooring lines have been assessed qualitatively.

195. As well as the structure-borne noises resulting from the operation of any wind turbine, regardless of foundation type, in the case of floating structures there is the potential for underwater noise to be generated by the slackening and sudden re-tension in a mooring line resulting from higher sea-states (large amplitude and/or high frequency waves, (Liu 1973)). Whilst existing mooring lines have been designed to be permanently taut and, therefore, should not exhibit these periods of slackening and tensioning (partly to avoid the risk of marine mammal entanglement (Statoil 2015)), there is some evidence that mooring lines associated with floating offshore wind farm infrastructure have the potential to produce transient ‘pinging’ or ‘snapping’ noises during their operational phase, particularly with the development of novel mooring techniques and materials.

196. Underwater acoustic measurements at the Hywind test site in the Norwegian North Sea were undertaken by Jasco between March and May 2011 (Martin *et al,* 2011). The study concluded that the Hywind structure, during operation, generates a variety of signature components that can be detected above the background noise level, which appear to be related to gear meshing and electrical generation. None of

these components were shown to exhibit levels that exceeded a Power Spectral Density (PSD) of 115 dB re 1 μPa^2Hz^{-1}. The structure was also shown to produce occasional 'snapping' transient noise events that resulted in received peak sound pressure levels (at a distance of 150 m) above 160 dB re 1 µPa. The frequency content of the transient noise events extended throughout the recorded frequency range of 0 Hz to 20 kHz. Between 0 and 23 of these transient noise events occurred per day throughout the survey and were thought to be related to tension releases in the mooring system.

197. This data was further analysed by Xodus Group as part of the Hywind EIA underwater noise assessment and found to be insufficient in detail to determine a SEL from the measured peak sound pressure levels (Stephenson, 2015). Through extrapolation of the data, Xodus Group was able to derive a rms sound pressure level at 150 m of around 145 dB re 1 µPa (rms) and the SEL per "snap" was estimated to be 135 dB re 1 μPa^2s. The 23 events at one turbine were then extrapolated to a theoretical array and it was found that with up to 115 of these snapping events per day, the resultant potential cumulative SEL over a 24-hour period was 156 dB re 1 μPa^2s at 150 m from the turbines. This represented a level below the onset criteria for impulsive noises for injury to marine mammals based on the Southall *et al.* (2007) thresholds. These thresholds have since been updated, and later studies have shown that the noises generated by mooring systems were not impulsive. Therefore, although the study provides a useful background, the applicability of this data to future projects is limited.

198. Between October 2020 and January 2021, Jasco undertook underwater noise measurements at the completed Hywind site, off the Scottish coast (Burns *et al*. 2022). Measurements were also taken at a control site approximately 14 km from the Hywind site, in order to provide a representative background for comparison. The study used an array of four coupled hydrophones, allowing directional analysis to determine which turbines caused the various noises recorded.

199. Unlike the Hywind pilot studies, Burns *et al.* (2022) reports three distinct transient noises which were characterised as a 'bang', a 'creak' and a 'rattle', but which were shown to be characteristics unique to individual turbines (for example, only turbine HS-2 exhibited the 'creak'), but with little evidence of the sharp 'snap' previously recorded. It was theorised that this was caused by differences in the specifics of the mooring methodology. The occurrence of the transient noises was also shown to correlate positively with wave height but only to a limited extent with wind speed, and the noises were shown to originate from close to the turbine, with no evidence of mooring noise being generated from further down the mooring system. Analysis of the combination of tonal, turbine and mooring transient noises for different wind speeds resulted in the lowest derived broadband source level (5th percentile) as 156.7 dB re 1 μPa^2m^2 and occurred in 10 kt wind speed. The highest (95th percentile) was 172.0 dB re 1 μPa^2m^2 in 25 kn wind speed. The dominant turbine-related tonal noise was measured at 24 Hz and 71 Hz. This was then used to define a noise field across the array to determine the potential impact on marine mammals. It was found that a very high frequency cetacean such as harbour porpoise would need to stay within 50 m of a turbine throughout a full 24-hour period to accumulate sufficient energy for the onset of temporary TTS, assuming 15 kt winds. This was the maximum for all marine mammal groups (40 m for LF cetaceans, Table 8.26). It is therefore concluded that PTS is unlikely to occur. It is very unlikely that a mammal would stay in such a small area for the full 24-hour period.

Table 8.26: Modelled Maximum Distances to TTS Threshold Levels (Southall et al. 2019) for 15 kn Wind Speed, Reproduced from Burns *et al.* (2022)

Auditory Group	TTS Onset Level (dB re 1 μPa^2s)	Maximum Distance to Weighted SEL_{24h} TTS Isopleth (m)	
		50th Percentile	75th Percentile
LF cetaceans	179	40	50
HF cetaceans	178	10	20
VHF cetaceans	153	50	80
Phocid pinnipeds	181	20	30
Otariid pinnipeds	199	<10	<10

200. In contrast to the studies performed on the Hywind test site, the noises recorded by Jasco[14] were shown, through detailed analysis of the kurtosis metric (a measure of the "peakiness" of a signal), to not be considered impulsive. Consequently, the thresholds which should be applied to the recorded levels to assess the impact on marine ecology are those for continuous noise sources (Southall *et at.* 2019). Although the Jasco study makes no attempt to quantify the disturbance, the levels reported represent a low level of risk to injury, and the areas of disturbance are unlikely to extend further than those for fixed turbine foundations.

201. Further measurements undertaken at both the Kincardine and Hywind Scotland sites were reported in the Supergen 2023 report (Risch *et al.* 2023). The study reported limited information about the noise from mooring lines, but did report that transients similar to those observed by Burns *et al.* (2022) were seen during periods of higher wind speeds and "significant wave height", although did not report what constituted as 'significant'. The energy of these transients was often seen to be distributed across the analysis bandwidth (10 Hz – 48 kHz) and were of short duration (one second or less). In terms of the number of events occurring, considerably more were observed at Kincardine than at Hywind Scotland although both sites showed great variability. The kurtosis value at Hywind Scotland was shown to be similar between the two measurement locations, which indicates that the soundscape was comparable in terms of impulsiveness to that of vessel noise. The kurtosis at Kincardine was reported to be "higher at the 600 m measurement location", but the value of the metric was not reported, nor was any reasoning attributed to this difference.

202. General operational noise levels were also reported in the Supergen 2023 report. Source levels for operational turbines were reported to increase with wind speed as would be expected (measurements of 25 Hz – 20 kHz). At wind speeds of 15 m/s, operational noise levels were reported to be higher at Kincardine than at Hywind Scotland, 148.8 dB re 1 µPa and 145.4 dB re 1 µPa respectively, which was attributed to differences in the power ratings, gear box vs direct drive or the differences in mooring structures. It was also noted that the predicted noise fields for unweighted sound pressure levels were above the median ambient noise levels in the North Sea for a maximum of 3.5 km – 4.0 km from the centre of the Kincardine site and 3.0 km – 3.7 km from the centre of Hywind Scotland, noting that both sites are comprised of five turbines.

203. Limited though the existing studies are, both in number and in the number of turbines studied, they do agree that the risk to marine mammals and fish from underwater noise, both from the structure-borne noise expected from any offshore wind turbine, regardless of foundation type, and the additional noise generated by movements in the mooring lines, is low. The upper bound for TTS derived in the Burns *et al.* 2022 study

[14] Recordings incorporate both noise from mooring lines and from turbines.

was found to be 80 m for VHF cetaceans. This is an order of magnitude less than the turbine separation and therefore presents a very low chance of injury.

Operational Noise: Structure-borne Noise from Fixed Turbines as a Proxy.

204. Structure-borne underwater noise from operational offshore wind turbines derives in the main from the moving mechanical parts in the nacelle, which is generally found to be of frequencies below 1 kHz (Pangerc *et al.*, 2016).

205. Vibration of the wind turbine's gear box and generator is transmitted down the tower and radiated as sound from the tower wall. Sound radiation by surface waves is difficult to quantitatively predict, in particular for the boundary regions, and is highly dependent upon the conditions of both the wind turbine itself, including generator and tower condition, and on the seawater conditions. There have been few empirical investigations of operational offshore wind farms, and as such measurement data is also scarce. Those that have been measured in situ are almost exclusively from traditional foundation methods, rather than the floating foundations employed here. Due to the general lack of investigation into the subject, wind turbines of a variety of foundation types have been included in this section.

206. The distances and exposures of mammals and fish reported by studies that investigate the impact of operational offshore wind farms present a range of values, but the majority conclude that in the order of hundreds of metres distance from the wind turbines, sound levels would likely be audible but not at a level sufficient to cause injury or behavioural changes (Betke, 2006; Nedwell et al., 2007; Norro, et al., 2011; Ward, et al., 2006; Jansen, 2016). Norro et al. (2011) compared measurements of a range of different foundation types and wind turbine ratings in the Belgian part of the North Sea, as well as comparing those to other European waters. A summary of these studies is shown in Table 8.27. The authors found a slight increase in SPL compared to the ambient noise measured before the construction of the wind farms. They concluded that even the highest increases found within the dataset (20 to 25 dB re 1 µ Pa) are unlikely to cause a significant impact and are significantly lower than those during the construction phase. They do however caution that this noise is of a much longer duration over the operational lifespan of the wind farm, and that little is known of the long-term impacts to aquatic life.

Table 8.27: Desktop Study of Operational Noise from Wind Turbines

Paper	Turbine	Foundation Type	Location	Notes
Betke, 2006	Vestas V80-2 MW 70 m hub height	Monopiles	Horns Rev	Peak at 118 dB re 1 µPa @ 150 Hz Measured at 100 m
Nedwell *et al.*, 2007	Vestas V80-2 MW	Monopiles	North Hoyle	Inside wind farm 128 dB re. 1 µPa Outside 120 dB re. 1 µPa No tonal components
	Vestas V80-2 MW 68 m hub height	Steel monopiles 4.8 m diameter	Scroby Sands	Inside wind farm 130 dB re. 1 µPa Outside 132 dB re. 1 µPa States that the background level is higher inside the wind farm, perhaps due to shallow water No tonal component
	Vestas V90-3 MW 70 m hub height	Monopiles	Kentish Flats	Inside wind farm 114 dB re. 1 µPa Outside 113 dB re. 1 µPa Clear tonal components dependent upon separation
Norro *et al.*, 2011	Vestas V90-3 MW 75 m hub height	Steel monopiles 4.75 m diameter	Barrow	Inside wind farm 124 dB re. 1 µPa Outside 122 dB re. 1 µPa No tonal components. No consistent relationship between distance and level, thought due to wind noise
	Senvion (Repower) 5 MW 95 m hub height	Gravity base	Thorntonbank	Increase of 8 dB above background
	Vestas V90-3 MW 72 m hub height	Steel monopile foundations	Belwind Bligh Bank	Increase of 20 dB to 25 dB above background
Jansen and De Jong, 2016	Vestas V80-2 MW	Steel monopiles 4 m diameter	Princess Amalia wind farm	Noted to be next to busy shipping lanes - no difference in level between 100 m and 3.8 km

207. There is ongoing research into the particular area of floating wind is ongoing (Supergen, 2022). Given that sound is more readily transmitted from structures which are coupled together, the case of operational noise from piled foundation turbines is considered a worst case.

8.4. VESSELS AND OTHER CONTINUOUS NOISES (ALL PHASES)

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

209. It should be borne in mind that there is a considerable degree of uncertainty and variability in the onset of disturbance and therefore any disturbance ranges should be treated as potentially over precautionary. Another important consideration is that vessels and construction noise will be temporary and transitory, as opposed to permanent and fixed. In this respect, construction noise is unlikely to differ significantly from vessel traffic already in the area.

210. The estimated median ranges for onset of TTS or PTS for different marine mammal groups exposure to different noise characteristics of different vessel traffic are shown in Table 8.28. The exposure metrics for different marine mammal and swim speeds (as detailed in section 7.6) were employed.

Table 8.28: Estimated Potential PTS and TTS Ranges from Different Vessels for Marine Mammals

Source/Vessel	Range (m)										
	LF		HF		VHF		PCW		OCW		All
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
Sandwave clearance	N/E	N/E	N/E	N/E	227	15	N/E	N/E	N/E	N/E	2,224
Boulder clearance, offshore construction vessel, excavator, backhoe dredger	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	302
Main Installation Vessels (Barge/DP vessel)	N/E	N/E	N/E	N/E	227	15	N/E	N/E	N/E	N/E	2,224
Jack up rig/jack up vessel	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E
Tug/Anchor Handlers	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	1,131
Cable Laying, Installation Vessels	N/E	N/E	N/E	N/E	227	15	N/E	N/E	N/E	N/E	2,224
Rock Placement Vessels	N/E	N/E	N/E	N/E	227	15	N/E	N/E	N/E	N/E	2,224
Guard Vessels, workboats	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	1,131
Survey Vessels, geophysical/geotechnical survey vessels	N/E	N/E	N/E	N/E	24	N/E	N/E	N/E	N/E	N/E	3,259
Crew Transfer Vessels, Service Operation Vessels, support vessels, construction support vessels, trenching support vessels, UXO clearance vessel, PLGR Vessel, DSVs, SOV vessels	N/E	N/E	N/E	N/E	24	N/E	N/E	N/E	N/E	N/E	3,259

211. The ranges for recoverable injury and TTS for Groups 3 and 4 Fish are presented in Table 8.29 based on the thresholds contained in Popper *et al.* (2014). It should be noted that fish would need to be exposed within these potential impact ranges for a period of 48 hours continuously in the case of recoverable injury and 12 hours continuously in the case of TTS for the effect to occur. It is therefore considered that these ranges are highly precautionary, and injury is unlikely to occur.

Table 8.29: Estimated Recoverable Injury and TTS Ranges from Vessels for Groups 3 and 4 Fish

Source/Vessel	Injury Zone Radius (m)	
	Recoverable injury	TTS
	170 dB re 1 µPa (rms) for 48 hrs	158 dB re 1 µPa (rms) for 12 hrs
Sandwave clearance	N/E	21
Boulder clearance, offshore construction vessel, excavator, backhoe dredger	N/E	N/E
Main Installation Vessels (Barge/DP vessel)	N/E	21
Jack up rig/jack up vessel	N/E	N/E
Tug/Anchor Handlers	N/E	N/E
Cable Laying, Installation Vessels	N/E	21
Rock Placement Vessels	N/E	21
Guard Vessels, workboats	N/E	N/E
Survey Vessels, geophysical/geotechnical survey vessels	N/E	13
Crew Transfer Vessels, Service Operation Vessels, support vessels, construction support vessels, trenching support vessels, UXO clearance vessel, PLGR Vessel, DSVs, SOV vessels	N/E	13

9. PARTICLE MOTION

9.1. INTRODUCTION

212. This technical report provides an analysis of the effects of noise on marine species. However, there are uncertainties in relation to the presence of compression and interface waves at the water/ground substrate boundary during piling, and the potential effect on fish and invertebrates. Although the risk of injury to fish with and without swim bladders is addressed through the use of SEL and peak pressure thresholds (Popper *et al*., 2014), it is possible that some fish are only sensitive to particle motion. These fish could experience high levels of particle motion in close proximity to piling. However, the Popper *et al*. (2014) paper primarily addresses high amplitude noises and high dynamic pressure, rather than particle motion.

213. The majority of measurements during piling for offshore wind farms are undertaken using hydrophones in the water column which includes contributions from both direct radiated noise from the pile into the water, as well as ground-borne radiated noise, and there are uncertainties with respect to how effectively the ground borne energy couples into the sea. If measurements were taken in an evanescent (non-propagating) field then high particle motion would not be reflected in the associated dynamic pressure measurements, particularly if those measurements were taken in shallow water and the energy is below the cut-off frequency. Consequently, it is possible that the effects on benthic fauna close to the pile could be under-estimated, particularly for species primarily sensitive to vibration of the seafloor sediment.

214. To put this issue into perspective, under section 5.1 entitled “Death or Injury”, Popper *et al*. (2014) states that “*extreme levels of particle motion arising from various impulsive sources may also have the potential to injure tissues, although this has yet to be demonstrated for any source*”. It would therefore appear that

there is currently a lack of criteria for (or detailed measurements of) particle motion during piling operations for this issue to be currently assessed. Thus, in terms of potential damage to fish, volume 2, chapter 9 has addressed the impact as far as is practicable with the existing state of knowledge, based primarily on exposure to sound pressure.

215. The purpose of this chapter is to provide an overview of the acoustic aspects of particle motion. Potential effects on marine species are dealt with in the marine ecology topic chapters of the Array EIA Report.

9.2. OVERVIEW OF PARTICLE MOTION

216. Particle motion is defined as the motion of an infinitesimally small part of the medium relative to the rest of the medium, that is caused by a noise wave (Popper *et al*., 2014). Unlike the pressure variation caused by the wave, which is a scalar quantity and therefore has no direction, the particle motion is a three-dimensional (3-D) vector quantity (i.e. directional). Particle motion can be described by the velocity, acceleration, and displacement of the particle. These are related by the following equations (Nedelec *et al*., 2016):

$$a = u \times 2\pi f$$

$$\xi = \frac{u}{2\pi f}$$

where a = acceleration (m/s^2), u = particle velocity (m/s), 2πf = angular frequency, and ξ = displacement (m).

217. In the same way as the unit for sound pressure is referenced to the Pascal (Pa), likewise in the case of particle motion, the decibel (dB) unit is referenced to either the displacement, velocity or acceleration as appropriate. Therefore, units will be in the form of dB re m, m/s or m/s^2.

218. Particle motion can also be related to measured sound pressure and can be approximated from the sound pressure in simplified circumstances such as a plane wave. For a plane wave, or a wave for which a plane wave is a good approximation of its behaviour (a wave in the free field), the following relationship holds:

$$u = \frac{P}{\rho c}$$

where P = acoustic pressure (Pa), ρ = density of the water (kgm^{-3}), and c = noise speed (ms−1). The quantity ρc is also known as the characteristic acoustic impedance.

219. The following relationship holds true for the near field of a point source. The source must be far from any boundaries that could lead to the wave not propagating due to cut off frequency, or reflections that could interfere with the propagation of the wave:

$$\xi = \frac{p}{2\pi f \rho c}\left[1 + \left(\frac{\lambda}{2\pi r}\right)^2\right]^{1/2}$$

where r = distance to noise source (m). All other symbols are consistent throughout the equations presented here.

220. A plane wave is a wave that can be considered to have a flat wavefront. This generally occurs far from both the source of the wave and any sources of reflected waves. The term 'far' is relative to the wavelength of the noise and the size of the source as both will change the distance at which the wave can be considered a plane wave. In shallow coastal and sea-shelf habitats these far-field conditions are not often met at the acoustic frequencies relevant to fish and invertebrates. This means that there is usually not a reliable way to derive particle motion from sound pressure measurement in these habitats. Technically a relationship between particle motion and sound pressure can be derived for more complicated wavefronts (e.g. by assuming that the wavefront has an idealised geometry). However, this is not necessarily reliable, and, in most cases where plane waves cannot be assumed, the only reliable solution is to measure directly (Nedelec *et al*., 2016).

221. In those situations where it is appropriate to assume that waves generated by a monopole are plane waves (i.e. in the acoustic far field), it is possible to approximate the magnitude of the particle motion. It is important to understand where it is appropriate to make these assumptions. Spherical spreading occurs when noise propagates from a source without any interference and the applicability of the plane wave assumption is based on the frequency of interest and the waveguide (i.e. the duct formed by the surface and bottom of the water column), which encapsulates the water depth, distance to source, source type, and the noise speed in water and sediment. The values that are key for this assumption are the wavelength of the lowest frequency of interest (λ) and the cut off frequency (f_0) based on the waveguide. These values can be calculated from the following equations (Nedelec *et al*., 2021):

$$\lambda = \frac{c_w}{f}$$

$$f_0 = \frac{c_w}{4D\sqrt{1 - \left(\frac{c_w}{c_b}\right)^2}}$$

where f_0 is the cut off frequency, D is the water depth, c_w is the noise speed in water, and c_b is the noise speed in sediment.

222. If the distance to the noise source is greater than one wavelength and the lowest frequency is greater than the cut off frequency, then it is possible to estimate the magnitude of the particle motion from an SPL measurement. However, it must be noted that this only applies to a travelling plane wave and as such the signal to noise ratio must be high enough to consider other noises negligible (Nedelec *et al.*, 2021).

223. It should also be borne in mind that noise produced from piling is, in reality, not a monopole source. The pile acts as a line source throughout the water column and in the sediment and produces a complex Mach wavefront. Consequently, the above simplifications may not be appropriate to assess the particle motion produced by piling.

9.3. HEARING IN FISH AND INVERTEBRATES

224. All fish, and many invertebrates, detect the particle motion of a noise wave with mechanosensory organs such as the inner ear, statocyst or lateral line (Nedelec *et al*., 2021). The ability to hear their surroundings gives fish, and many invertebrates, an abundance of information about their environment. This ability is unaffected by light levels and is omnidirectional, allowing for the most abundant information about the environment. Of all the senses that fish, and many invertebrates, use to assess their surroundings, hearing is the most versatile in a marine environment. In particular, their hearing is able to give rapid feedback with relatively long distance 3-D information (Popper and Hawkins, 2019).

225. The detection of noise and characterisation of the immediate noisescape is something that is key to the way that fish and many vertebrates live. This ability allows them to detect the direction of predators, and subsequently avoid them, or detect prey and move towards them. Furthermore, this ability can be used to recognise others within their own species and select a mate. Although not all fishes, or invertebrates, produce noise for communication, they are all known to use it for awareness of their surroundings. As such, any interference with this ability could impact the survival of the fish (Popper and Hawkins, 2019).

226. There have been several studies into the hearing capabilities of fish and invertebrates. However, very few of them have used conditions that are truly representative of the environment that they would encounter in open water. This is due to tank conditions or methodologies used to observe them in an offshore environment. Furthermore, few of these studies have focussed on particle motion specifically (Popper and Hawkins, 2019).

227. Taking this into account it is possible to establish a reasonable assumption for hearing range of various species. Most fish appear to be able to detect noise that falls between 10 Hz and 500 Hz. If the fish or invertebrates are capable of detecting sound pressure, then they may be able to detect noises at higher frequencies up to approximately 1 kHz or more. There are also a small number of fish that are capable of hearing between 3 Hz and 4 kHz due to various specialisations that they have (Popper and Hawkins,

2019). The values presented here are the upper and lower estimates of each range, there is a degree of variability in each of the values. This is in part due to the complexity of the noise field in a tank or enclosure (Popper *et al*., 2019). Likewise, invertebrates are also typically sensitive to lower frequencies (Nedelec *et al*., 2016).

9.4. EFFECTS OF NOISE AND PARTICLE MOTION

228. Potential effects of noise and particle motion on fishes and invertebrates can be summarised as follows (Popper *et al*., 2014; Popper and Hawkins, 2018; Nedelec *et al*., 2016):

- Death and injury
- Exposure to very high amplitude noises can cause injury and death in fish and other marine species. In addition, the effect of sudden pressure changes (barotrauma) must be considered.
  - Barotrauma is the tissue injury that is caused by a sudden change in pressure resulting in a shock wave effect (e.g. primarily caused by explosions, as opposed to non-shock wave propagation as is typically caused by impulsive piling). Rapid pressure changes can cause the gases in blood to come out of solution and can cause rapid movement in the swim bladder. This can damage other organs and even rupture the swim bladder.
  - Sudden changes in pressure (such as that from impulsive noises) are more likely to cause damage than gradual ones.
  - Extreme levels of particle motion may have the potential to cause tissue damage, but this has not been proven yet (Popper *et al*., 2014).
- Effects on hearing
  - Hearing loss can be permanent or temporary (PTS and TTS) with PTS being caused by damage to the tissue in the auditory pathway (including the swim bladder)
  - TTS results from temporary damage to the hairs in the inner ear or to the auditory nerves. In fish (unlike in mammals) the hairs of the inner ear are constantly added and replaced if damaged. Therefore, loss of hearing due to damage to these hairs may be mitigated over time in fish.
  - While experiencing TTS, fish may have a decrease in fitness in terms of communication, detecting predators or prey, and/or assessing their environment.
  - Masking is an impairment with respect to the relevant noise sources normally detected within the noisescape. The consequences of masking are not fully understood for fish. It is likely that higher levels of masking occur with a higher noise level from the masker.
- Effects on behaviour
  - It is possible that anthropogenic noise will have a detrimental effect on the communication of species between conspecifics, it may also hinder their identification of predator and prey.
  - There have been a variety of behavioural reactions observed from fish, including changes in swimming patterns and startle reactions. These reactions may habituate over repeated exposure to the noise.
  - There has been very limited research carried out to date in relation to the effects of particle motion on marine invertebrates (Popper and Hawkins, 2018). However, they are expected to have the same types of effect even if the severity is unclear.

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

- Fishes with no swim bladder or other gas chamber. These fish are less susceptible to barotrauma and only detect particle motion, however, some barotrauma may occur from exposure to sound pressure.
- Fish with swim bladders in which hearing does not involve the swim bladder or some other gas volume. These species again only detect particle motion; however, they are susceptible to barotrauma due to the presence of the swim bladder.
- Fish in which the swim bladder (or other gas volume) is involved in hearing. These species detect sound pressure as well as particle motion and are susceptible to barotrauma. The frequency sensitivity range of this group is higher than the other groups due to the ability to detect the pressure component of the sound signal as well as the particle motion.
- Fish eggs and larvae.

230. These groups are known to be able to detect particle motion. However, it is also likely that marine invertebrates are able to detect particle motion (Popper and Hawkins, 2018; Discovery of Noise in the Sea (DOSITS)). Furthermore, some marine invertebrates can detect the vibrations directly from the substrate. This makes them susceptible not only to the particle motion in the water but also the rolling waves, and associated particle motion, in the substrate. It has been observed that benthic marine invertebrates respond directly to anthropogenic noise that has been generated in the substrate or very close to its surface (Hawkins *et al.*, 2021; Aimon *et al*., 2021). This is particularly important for construction processes like piling that generate a large amount of noise into the substrate. The repercussions of this are that offshore construction activity may affect the benthic habitat, and many benthic invertebrates have a key role in how the substrate is structured. Considerable disturbance of these creatures for a prolonged period could affect habitat quality in addition to any potential impacts associated with sound pressure. It has also been suggested that some species use the noise that travels through the substrate to communicate or to find food sources, loud noises that mask these noises could make it difficult for them to operate normally (Popper and Hawkins, 2018).

231. There have been several studies into the hearing abilities of fish for a relatively small number of species. From these studies, the upper limit of detection for particle motion was found to be between 200 Hz and 400 Hz and the lower limit was 0.1 Hz (Sigray and Anderson, 2011). It is considered likely that all teleost fish have a similar extent of ability to detect particle motion (Radford *et al*., 2012). Elasmobranchs are also considered to have a similar range of detection for particle motion. For piling, specifically, it is currently considered that most fish would be able to detect particle motion from 750 m away (Thomsen *et al*., 2015). Marine invertebrates are generally not considered to be sensitive to the pressure wave component of noise as they lack an air-filled space in their bodies. Research still needs to be carried out to understand the hearing capabilities of marine invertebrates. The research that has been undertaken so far has primarily focused on crustaceans and molluscs. A need has been identified to develop species specific audiograms to improve the understanding of the detection thresholds.

232. Hammar *et al*. (2014) discussed the impact of the Kattegat offshore wind farm (offshore Sweden) on Atlantic cod Gadus morhua in the region. Estimates of operational noise were predicted as 150 dB re 1µPa (rms) at 1 m for the 6 MW wind turbines and 250 dB re 1 µPa (rms) for the pile driving based on measurements on the Burbo Bank offshore wind farm taken by Parvin and Nedwell (2006). Using these estimates Hammar *et al*. (2014) established that developed Atlantic cod were likely to suffer physical injury within several hundred meters of pile driving. However, studies have shown that fish often group around operational wind turbines (Sigray and Andersson, 2011; Engås *et al*., 1995; Wahlberg and Westerberg, 2005). This suggests that operational noise is not enough to cause them to vacate the area, however it is not clear if it results in higher stress levels in fish in the area.

9.5. POTENTIAL RANGE OF EFFECTS DUE TO PARTICLE MOTION

233. Due to the current state of understanding and existing (validated) modelling methodologies it is not considered feasible at this time to provide a quantitative assessment of the effects of particle motion on marine species for the Array.

234. Predicting the levels of particle motion from anthropogenic noise sources is difficult. There is a small amount of measured data available on which to base such predictions and some of these data are not necessarily applicable to full scale industrial procedures such as installation of wind turbine foundations. The measurements that do exist mostly come from small scale tank testing. Some of this testing has been conducted in flooded dock style locations with small scale piles. Other recordings have used play-back speakers to generate a simulated piling noise (Roberts *et al*., 2016; Ceraulo *et al*., 2016). There is some debate about the validity of comparing measurements from tank tests or from playback speakers to full scale piling operations, as the way that particles move within a tank or smaller scale system is different to the full scale in the open ocean. Furthermore, the way that a speaker will agitate the particles is different

to that of a cylindrical pile with an exposed length in the water column and sediment. However, there is one commonality between all measurements so far: the particle motion attenuates rapidly close to the source and more slowly further from it (Mueller-Blenkle *et al*., 2010).

235. One such experiment was studied by Ceraulo *et al*. (2016), which consisted of measurements during piling at several locations within a flooded dock that incorporated a simulated seabed layer (approximately 3.5 m thick). This allowed the piling to be measured from different ranges. Through this experiment it was found that the noise propagation was close to cylindrical in nature. The levels of particle motion (particle velocity) were found to be 102 dB re 1 nm/s at a distance of 2 m from the pile and this dropped to 86 dB re 1 nm/s at 30 m. There was an interesting observation that the pressure wave appeared to have a cut off frequency at 400 Hz for shallow water and 300 Hz for deep water, although the particle motion does not share this cut off. The study was able to confirm that there is a roughly linear relation between particle motion and pressure although it also found that the particle motion levels were higher than expected.

236. An added complication in predicting particle motion is the propagation of noise through the substrate. This is particularly prominent in piling operations as the pile being driven into the ground will generate considerable waves through the substrate. This particle motion can impact the benthic species in the area due to behavioural reactions and potential injury. This has been identified as an area that requires more research and should be monitored alongside particle motion within the water column itself. Furthermore, the waves passing through the substrate can add to those in the water column, making the noise field in the water more complex (Mueller-Blenkle *et al*., 2010).

237. A study by Thomsen *et al*. (2015) investigated particle motion around the installation of piles at offshore wind sites. The study found that higher hammer energies elicited higher levels of particle motion and that particle motion levels at 750 m from the pile were higher than baseline ambient levels throughout the frequency spectrum, except at very low frequencies. Thomsen *et al*. (2015) showed that with mitigation (a bubble curtain) turned on however, particle motion levels reduced considerably. It should be noted that the range cited of 750 m was likely due to the regulatory requirement for monitoring at 750 m from a pile and this number is therefore somewhat arbitrary in terms of the potential range of effect for particle motion (i.e. it is the most common measurement range for sound pressure rather than being the range over which particle motion effects were thought likely to occur).

238. Nevertheless, the study concluded that, for most fish, particle motion levels at 750 m are high enough to be detected during pile driving of even a mitigated pile. However, for elasmobranchs, the study concluded that detectability of mitigated piles is likely restricted to relatively short ranges from the source depending on the ambient noise in the area. For invertebrates the study concluded that there is even less information on how they perceive particle motion, but the Thomsen *et al*. (2015) study would indicate that some invertebrates should be able to detect the piling noise at a distance of 750 m, whether mitigated or not.

239. Taking the above into consideration, it is thought likely that particle motion will be detectable for many fish and invertebrates within the order of 750 m from piling at the Array, although it is not feasible to quantify this further at this stage. Furthermore, it is not possible at this time to determine whether the detection of noise by these species at this range is likely to result in an effect, such as behavioural disturbance or injury. Likewise, it is not possible at this time to define the requirements for, or potential effectiveness of, mitigation for particle motion. However, it is likely that potential injury due to particle motion will be confined to a smaller range than disturbance and detectability. Ultimately, until such a time as considerably more data become available, both in terms of measured particle motion during full scale piling and effects on marine species, it is considered that the assessment of effects as set out in this report represents a robust assessment based on the current state of knowledge.

10. SUMMARY

240. Acoustic modelling has been undertaken to determine distances at which potential effects on marine mammals and fish may occur due to noise from piling activities and other underwater noise generating activities associated with site preparation, construction and operation and maintenance of the Array. Modelling was undertaken for the maximum parameters proposed. The results for piling, which is the dominant noise generating activity, are summarised in Table 10.1 which shows the maximum injury range for each group of mammals and fish, for individual and concurrent piling (the MDS of cumulative SEL or peak), with only the most adverse concurrent piling case shown. The potential PTS impact range is typically dominated by nearest pile, so these ranges do not change for single or concurrent pile driving (except for LF cetaceans where the noise propagates further).

241. It should be noted that the greatest distance value at which noise levels decrease to below either the cumulative SEL or peak SPL PTS threshold criteria, whichever is the highest, as presented in the Table 10.1.

Table 10.1: Summary of Potential Maximum PTS Injury Ranges for Marine Mammals, and Mortality for Fish Due to Impact Piling Based on Highest Range of Peak Pressure or SEL (SEL marked with *) Without the Use of ADD

Species Group	Range (m)		
	Single Piling Foundation Piles (3,000 kJ)	Single Piling OSP Jacket Piles (4,400 kJ)	Concurrent Piling Foundation Piles and OSP Jacket Piles (3,000 and 4,400 kJ)
Marine Mammals			
Low frequency cetacean	990*	7,200*	9,740*
High frequency cetacean	95	171	171
Very high frequency cetacean	665	1,600	1,600
Phocid carnivores	192	379	379
Fish, Eggs/Larvae (Moving Away)			
Group 1 Fish: no swim bladder	15	25	26
Group 2 Fish: where swim bladder is not involved in hearing	32	112	143
Group 3 to 4 Fish: where swim bladder is involved in hearing	50	425	605
Eggs and larvae	1,015	2,440	4,460

242. Underwater noise emissions from the wind turbines, pre-construction activities, other relevant operational noises, and vessels during the operations and maintenance phase are unlikely to be at a level sufficient to cause injury to marine mammals or fish. Discussion of disturbance to marine mammals is provided within volume 2, chapter 10.

Table 10.2: Summary of Potential Maximum PTS Injury Ranges for Marine Mammals Due to Impact Piling Based on Highest Range of Peak Pressure or SEL (SEL marked with *) Including the Use of ADD (N/E - Threshold Not Exceeded)

Species Group	Range (m)		
	Single Piling Foundation Piles (3,000 kJ)	Single Piling OSP Jacket Piles (4,400 kJ)	Concurrent Piling Foundation Piles and OSP Jacket Piles (3,000 and 4,400 kJ)
Marine Mammals			
Low frequency cetacean	180	3,050*	5,610*
High frequency cetacean	95	171	171
Very high frequency cetacean	665	1,600	1,600
Phocid carnivores	192	379	379

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sse Renewables · Marubeni · CIP Copenhagen Infrastructure Partners

Ossian Offshore Wind Farm Limited
Inveralmond House
200 Dunkeld Road
Perth
PH1 3AQ

Project Office
Fourth Floor
10 Bothwell Street
Glasgow
G2 6NT

ossianwindfarm.com