BERWICK BANK WIND FARM
OFFSHORE ENVIRONMENTAL IMPACT ASSESSMENT

APPENDIX 10.1: SUBSEA NOISE TECHNICAL REPORT

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1. INTRODUCTION

1. This Subsea Noise 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 construction of the Berwick Bank Wind Farm (hereafter referred to as the 'Proposed Development').

2. The location of the Proposed Development in the North Sea, in the outer Firth of Forth and Tay, is illustrated in Figure 1.1. The planned activities at this site fall into four categories of pre-construction, construction, operation and maintenance, and decommissioning based events. Within each of these four working categories different underwater noise sources are identified. These noise sources are both continuous and intermittent in characteristics.

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

4. The primary purpose of this underwater noise study is to predict the likely range for the onset of potential injury (i.e. permanent threshold shifts (PTS) in hearing) and behavioural effects on different marine fauna when exposed to the different anthropogenic noises that occur during different phases of the Proposed Development. The results from this underwater noise appraisal have been used to inform the following volume 2 chapters of the Environmental Impact Assessment (EIA) Report in order to determine the potential impact of underwater noise on marine life:

- volume 2, chapter 8: Benthic Subtidal and Intertidal Ecology;
- volume 2, chapter 9: Fish and Shellfish Ecology; and
- volume 2, chapter 10: Marine Mammals.

5. Consequently, the sensitivity of species, magnitude of potential impact and significance of effect from underwater noise associated with the development are addressed within the relevant chapters.

1.1. CONVERSION FACTORS

6. A comprehensive study evaluating the evidence and justification for different conversion factors has been undertaken following advice received during the Marine Mammal Road Map pre-application consultation process (see volume 3, appendix 10.1, annex A). From the conversion factors evaluated, a variable conversion factor (β) has been used in the underwater noise assessment ranging from β = 4% at the start of piling to β = 0.5% at the end of piling when the pile is almost fully embedded in the seabed.

7. This scenario has been chosen as it was considered to represent the best balance of realism and precaution in conversion factor, particularly compared to a conversion factor of 10% reducing to 1% which was considered over-precautionary and therefore misrepresentative of the potential kinetic energy converted to sound energy. A 1% constant conversion factor was considered less representative compared to 4% reducing to 0.5% for a partially submersible hammer as would be used for the Proposed Development. Note, however, to adopt a precautionary assessment and to mitigate for uncertainties in the true value of the conversion factor the marine mammal EIA took forward the predicted ranges from either the 4% reducing conversion factor or 1% constant conversion factor, whichever led to the greatest ranges using the relevant noise thresholds for injury and disturbance. Volume 3, appendix 10.5 provides quantitative outcomes (impact ranges and number affected) of underwater noise modelling for the range of conversion factors modelled.

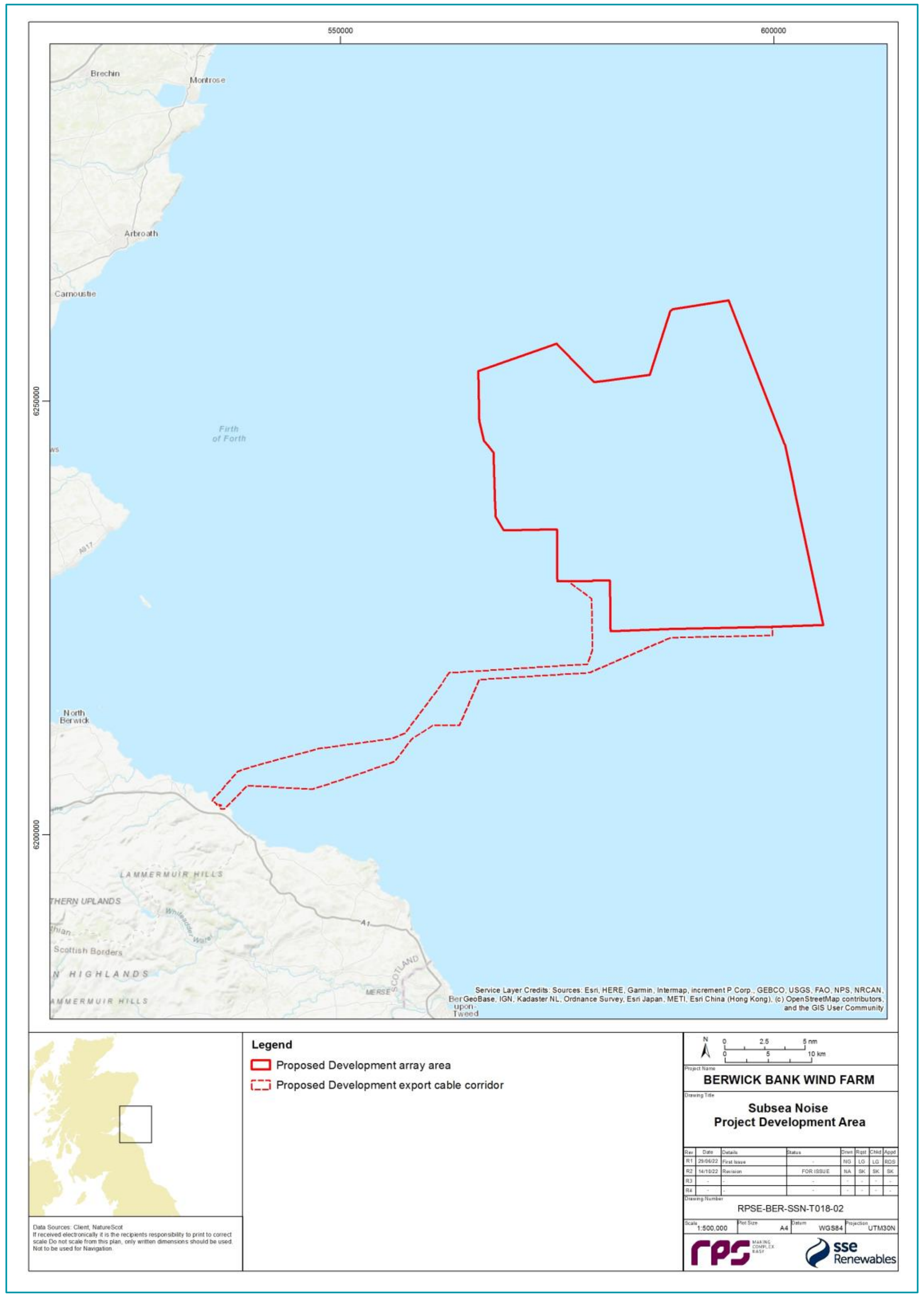

Figure 1.1: The Proposed Location of Berwick Bank Wind Farm in the North Sea

2. STUDY AREA

8. The modelled area is approximately rectangular and covers the Proposed Development array area and export cable corridor (Figure 1.1) and an area extending to about 60 km from the boundaries north, east, and south and the Firth of Forth estuary to the west. The site covers the Firth of Forth Banks Complex Nature Conservation Marine Protected Area (ncMPA). Bathymetry data used for modelling purposes was obtained from the General Bathymetric Chart of the Oceans (GEBCO) and showed the water depth (lowest astronomical tide (LAT)) within the Proposed Development array area to range between 35 m and 70 m deep. Within the modelling area, the water depth is typically shallower than 80 m, with some limited regions to the south being 110 m deep, and to the north being 140 m deep.

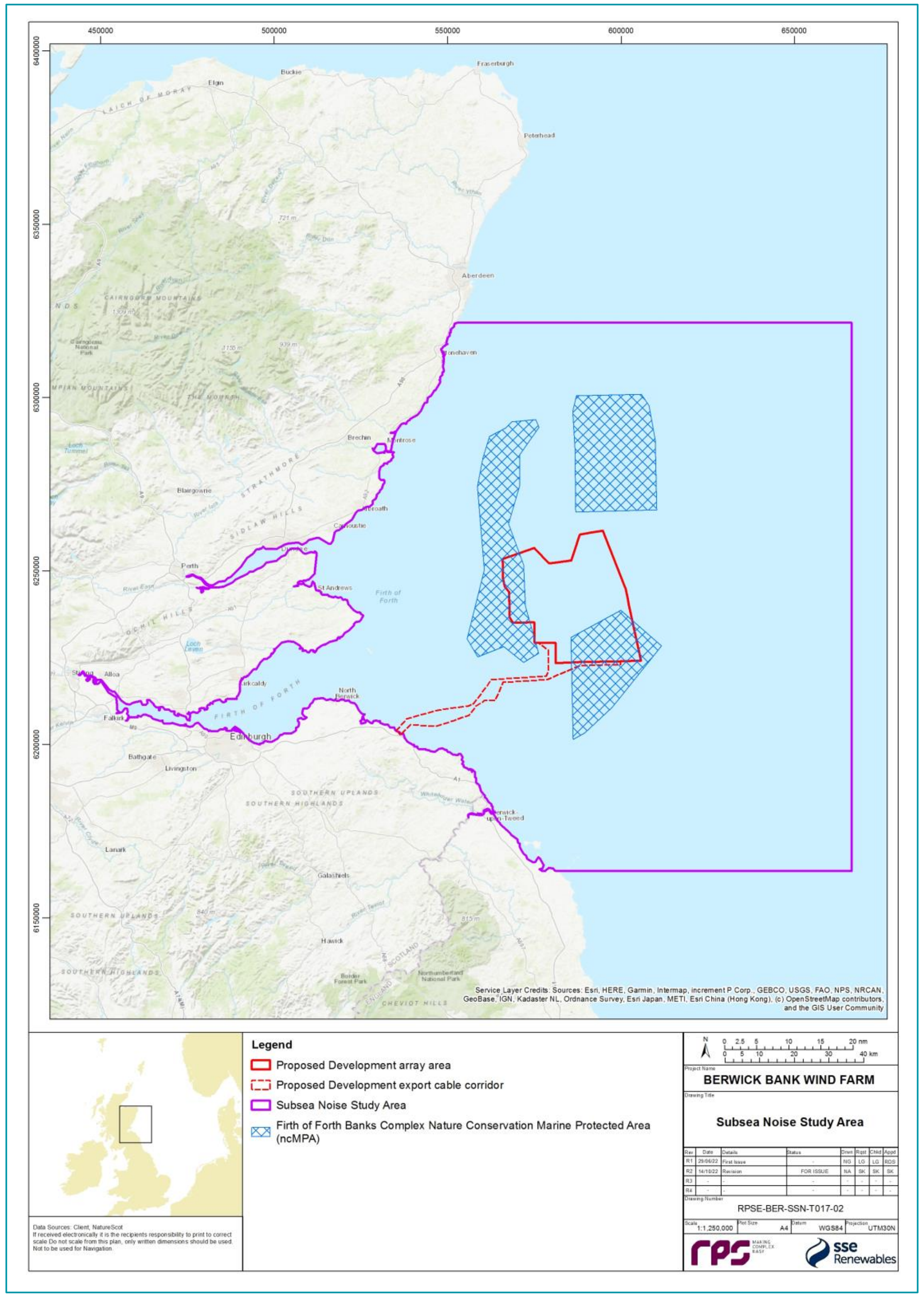

Figure 2.1: Subsea Noise Study Area

3. ACOUSTIC CONCEPTS AND TERMINOLOGY

9. Sound travels through the 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). Because sound consists of variations in pressure, the unit for measuring sound is usually referenced to a unit of pressure, the Pascal (Pa). The decibel (dB) scale is used to conveniently communicate the large range of acoustic pressures encountered, with a known pressure amplitude chosen as a reference value (i.e. 0 dB). In the case of underwater sound, the reference value (Pref) is taken as 1 µPa, whereas the airborne sound is usually referenced to a pressure of 20 µPa. To convert from a sound pressure level referenced to 20 µPa to one referenced to 1 µPa, a factor of 20 log (20/1) (i.e. 26 dB has to be added to the former quantity). Thus 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 the 26 dB when converting pressure from air to water. All underwater sound pressure levels in this report are quantified in dB re 1 µPa.

10. 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 Pref value employed during calculations. For example, the measured Sound Pressure Level (SPLrms) value of a pulse may be reported as 100 dB re 1 µPa. These descriptions are shown graphically in Figure 3.1.

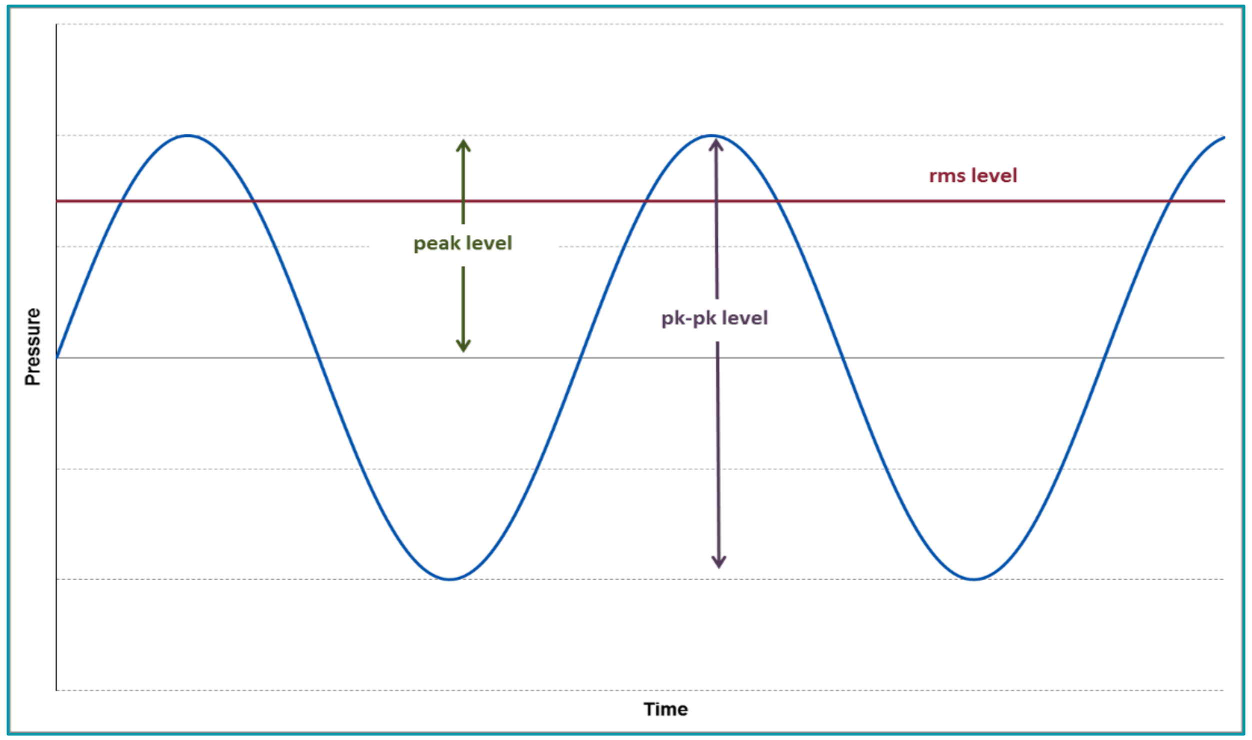

Figure 3.1: Graphical Representation of Acoustic Wave Descriptors

11. The SPL_{rms} is defined as:

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

12. The magnitude of the rms sound pressure level for an impulsive sound (such as that from a seismic source array) 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. 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 sound energy.

13. Another useful measure of sound 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[1]. The SEL is defined as:

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

14. The frequency, or pitch, of the sound 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 sound is measured in a way which approximates to how a human would perceive it using an A--weighting filter on a sound level meter, the resulting level is described in values of dBA. However, the hearing faculty of marine mammals 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 the effects of anthropogenic sound on marine mammals. Consequently, use can be made of frequency weighting scales (M--weighting) to determine the level of the sound in comparison with the auditory response of the animal concerned. A comparison between the typical hearing response curves for fish, humans and marine mammals is shown in Figure 3.2[2].

15. Other relevant acoustic terminology and their definitions used in the report are detailed in paragraphs 16 to **Error! Reference source not found.**.

16. Third octave bands - The broadband acoustic power (i.e. containing all the possible frequencies) emitted by a sound source, measured/modelled at a location within the survey region 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 sound frequency.

17. Source level (SL) - 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 may be combined with the transmission loss (TL) associated with the environment to obtain the received level (RL) in the far field of the source. The far field distance is chosen so that the behaviour of the distributed source can be approximated to that of a point source. Source levels do not indicate the real sound pressure level at 1 m.

18. 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 the above dependencies.

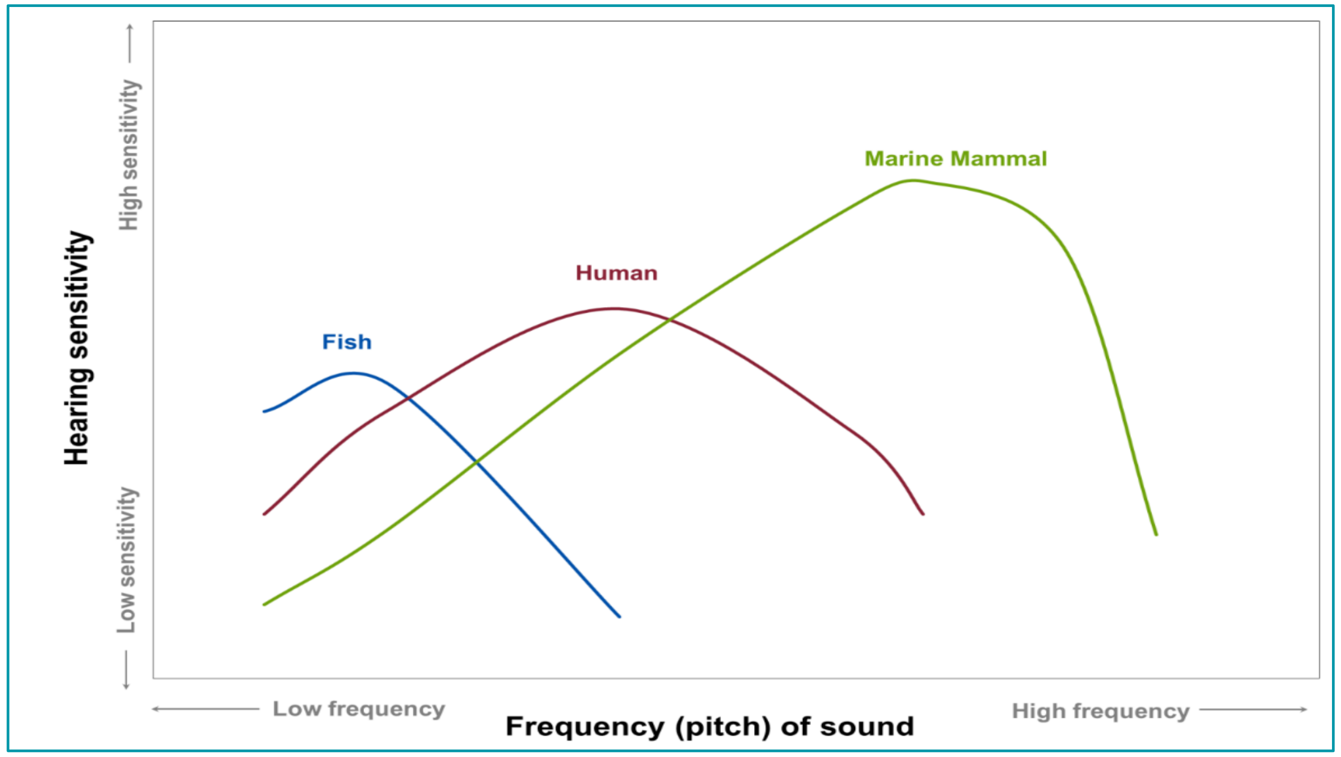

Figure 3.2: Comparison Between Hearing Thresholds of Different Animals

19. The RL is the sound level of the acoustic signal recorded (or modelled) at a given location, that corresponds to the acoustic pressure/energy generated by a known active sound 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 SPL, and SEL metrics, within the relevant one-third octave band frequencies. The RL is related to the SL as:

$$RL = SL - TL \qquad (3)$$

where TL is the transmission loss of the acoustic energy within the survey region.

[1] *Historically, use was primarily made of rms and peak SPL metrics for assessing the potential effects of sound on marine life. However, the SEL is increasingly being used as it allows exposure duration and the effect of exposure to multiple events to be considered.*

[2] *It is worth noting that hearing thresholds are sometimes shown as audiograms with sound level on the y axis rather than sensitivity, resulting in the graph shape being the inverse of the graph shown*

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

4. ACOUSTIC ASSESSMENT CRITERIA

4.1. INTRODUCTION

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

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

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

4.2. INJURY (PHYSIOLOGICAL DAMAGE) TO MAMMALS

23. Sound propagation models can be constructed to allow the received noise level at different distances from the source to be calculated. To determine the 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 injury criteria proposed by Southall *et al*. (2019) are based on a combination of linear (i.e. un-weighted) peak pressure levels and mammal hearing weighted SEL. The hearing weighting function is designed to represent the bandwidth for each group within which acoustic exposures can have auditory effects. The categories include:

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

24. These weightings have therefore been used in this study and are shown in Figure 4.1.

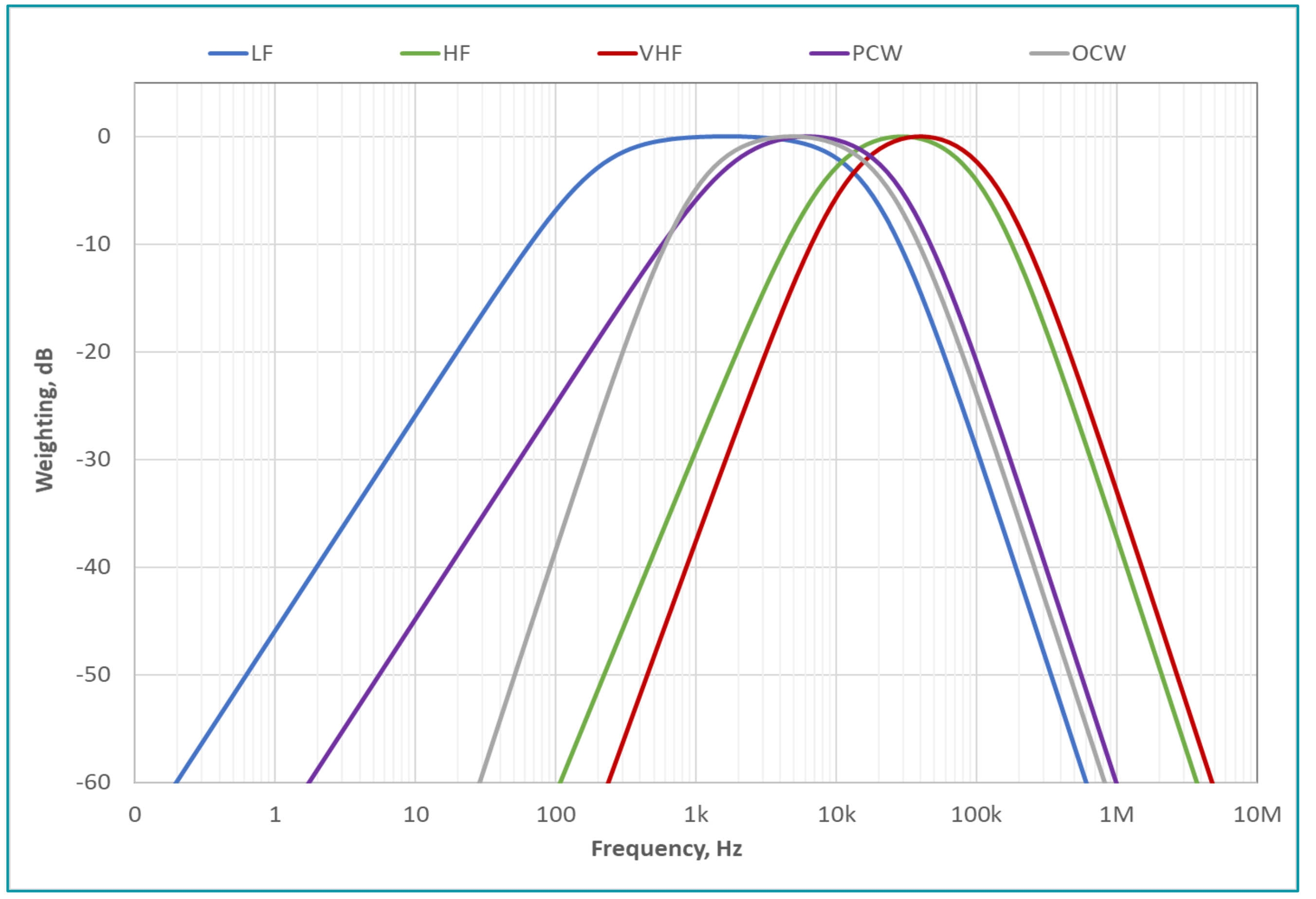

Figure 4.1: Hearing Weighting Functions for Pinnipeds and Cetaceans (Southall *et al.*, 2019)

25. Injury criteria are proposed in Southall *et al.* (2019) are for two different types of sound as follows:

- impulsive sounds which are typically transient, brief (less than one second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay (ANSI, 1986 and 2005; NIOSH, 1998).

This category includes sound sources such as seismic surveys, impact piling and underwater explosions; and

- non-impulsive sounds which can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent and typically do not have a high peak sound pressure with rapid rise/decay time that impulsive sounds do (ANSI, 1995; NIOSH, 1998). This category includes sound sources such as continuous running machinery, sonar, and vessels.

26. The criteria for impulsive and non-impulsive sound have been adopted for this study given the nature of the sound source used during construction activities. The relevant criteria proposed by Southall *et al*. (2019) are as summarised in Table 4.1 and Table 4.2.

27. These updated marine mammal injury criteria were published in March 2019 (Southall *et al*., 2019). The paper utilised the same hearing weighting curves and thresholds as presented in the preceding regulations document NMFS (2018) (and prior to that Southall *et al.* (2007)) with the main difference being the naming of the hearing groups and introduction of additional thresholds for animals not covered by NMFS (2018). A comparison between the two naming conventions is shown in Table 4.3.

28. For avoidance of doubt, the naming convention used in this report is based upon those set out in Southall *et al*. (2019). Consequently, this assessment utilises criteria which are applicable to both NMFS (2018) and Southall *et al*. (2019).

Table 4.1: 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 4.2: 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

Table 4.3: Comparison of Hearing Group Names between NMFS (2018) and Southall *et al.* (2019)

NMFS (2018) hearing group name	Southall *et al*. (2019) hearing group name
Low-frequency cetaceans (LF)	LF
Mid-frequency cetaceans (MF)	HF
High-frequency cetaceans (HF)	VHF
Phocid pinnipeds in water (PW)	PCW

4.3. DISTURBANCE TO MARINE MAMMALS

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

30. To consider the possibility of significant disturbance resulting from the Proposed Development, it is therefore necessary to consider the likelihood that the sound could cause non-trivial disturbance, the likelihood that the sensitive receptors will be exposed to that sound and whether the number of animals exposed are likely to be significant at the population level. Assessing this is however a very difficult task due to the complex and variable nature of sound propagation, the variability of documented animal responses to similar levels of sound, and the availability of population estimates, and regional density estimates for all marine mammal species.

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

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

4.3.1. CONTINUOUS (NON-PULSED, NON-IMPULSIVE) SOUND

33. For non-pulsed sound (e.g. drilled piles, vessels etc.), the lowest sound pressure level at which a score of five or more occurs for low frequency cetaceans is 90 dB to 100 dB re 1 μPa (rms). However, this relates to a study involving migrating grey whales. A study for minke whales showed a response score of three at a received level of 100 dB to 110 dB re 1 μPa (rms), with no higher severity score encountered for this species. For mid frequency cetaceans, a response score of eight was encountered at a received level of 90 dB to 100 dB re 1 μPa (rms), but this was for one mammal (a sperm whale *Physeter macrocephalus*) and might not be applicable for the species likely to be encountered in the vicinity of the Proposed Development. For Atlantic white-beaked dolphin *Lagenorhynchus albirostris*, a response score of three was encountered for received levels of 110 to 120 dB re 1 μPa (rms), with no higher severity score encountered. For high frequency cetaceans such as bottlenose dolphins *Tursiops truncatus*, a number of individual responses with a response score of six are noted ranging from 80 dB re 1 μPa (rms) and upwards. There is a significant increase in the number of mammals responding at a response score of six once the received sound pressure level is greater than 140 dB re 1 μPa (rms).

34. The NMFS (2005) guidance sets the marine mammal level B harassment threshold for continuous noise at 120 dB re 1 µPa (rms). This value sits approximately mid-way between the range of values identified in Southall *et al.* (2007) for continuous sound but is lower than the value at which the majority of mammals responded at a response score of six (i.e. once the received rms sound pressure level is greater than 140 dB re 1 µPa). Considering the paucity and high level variation of data relating to onset of behavioural effects due to continuous sound, it is recommended that any ranges predicted using this number are viewed as probabilistic and potentially over precautionary.

4.3.2. IMPULSIVE (PULSED) SOUND

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

36. A more recent study is described in Graham *et al*. (2017). Empirical evidence from piling at the Beatrice Offshore Wind Farm (Moray Firth, Scotland) was used to derive a dose-response curve for harbour porpoise. The unweighted single pulse SEL contours were plotted in 5 dB increments and applied the dose-response curve to estimate the number of animals that would be disturbed by piling within each stepped contour. The study shows a 100% probability of disturbance at an (un-weighted) SEL of 180 dB re 1 µPa^{2}s, 50% at 155 dB re 1 µPa^{2}s and dropping to approximately 0% at an SEL of 120 dB re 1 µPa^{2}s. This is an accepted approach to understanding the behavioural effects from piling and has been applied at other UK offshore wind farms (for example Seagreen and Hornsea Three).

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

38. Southall *et al*. (2007) also notes that, due to the uncertainty over whether HF cetaceans may perceive certain sounds and due to paucity of data, it was not possible to present any data on responses of HF cetaceans. However, Lucke *et al*. (2009) showed a single harbour porpoise consistently showed aversive behavioural reactions to pulsed sound at received SPL above 174 dB re 1 µPa (peak-to-peak) or a SEL of 145 dB re 1 µPa^{2}s, equivalent to an estimated[3] rms sound pressure level of 166 dB re 1 µPa.

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

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

41. This assessment adopts a conservative approach and uses the NMFS (2005) Level B harassment threshold of 160 dB re 1 µPa (rms) for impulsive sound, excluding piling which is assessed based on SEL in volume 2, chapter 10. Level B Harassment is defined by NMFS (2005) as *having the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioural patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering but which does not have the potential to injure a marine mammal or marine mammal stock in the wild*. This is similar to the JNCC (2010) description of non-trivial disturbance and has therefore been used as the basis for onset of behavioural change in this assessment.

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

Table 4.4: Disturbance Criteria for Marine Mammals Used in this Study

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

4.4. FISH

43. Adult fish not in the immediate vicinity of the noise generating activity are generally able to vacate the area and avoid physical injury. However, larvae and eggs are not highly mobile and are therefore more likely to incur injuries from the sound energy in the immediate vicinity of the sound source, including damage to

[3] *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 rms$_{T90}$ sound pressure level. However, the T90 was not directly reported in the paper.*

their hearing, kidneys, hearts and swim bladders. Such effects are unlikely to happen outside of the immediate vicinity of even the highest energy sound sources.

44. For fish, the most relevant criteria for injury are considered to be those contained in the recent Sound Exposure Guidelines for Fishes and Sea Turtles (Popper *et al*., 2014). Popper *et al*. (2014) guidelines do not group by species but instead broadly group fish into the following categories based on their anatomy and the available information on hearing of other fish species with comparable anatomies:

- Group 1: fishes with no swim bladder or other gas chamber (e.g. elasmobranchs, flatfishes and lampreys). These species are less susceptible to barotrauma and are only sensitive to particle motion, not sound pressure. Basking shark *Cetorhinus maximus*, which does not have a swim bladder, falls into this hearing group.
- Group 2: fishes with swim bladders but the swim bladder does not play a role in hearing (e.g. salmonids). These species are susceptible to barotrauma, although hearing only involves particle motion, not sound pressure.
- Group 3: Fishes with swim bladders that are close, but not connected, to the ear (e.g. gadoids and eels). These fishes are sensitive to both particle motion and sound pressure and show a more extended frequency range than Groups 1 and 2, extending to about 500 Hz.
- Group 4: Fishes that have special structures mechanically linking the swim bladder to the ear (e.g. clupeids such as herring *Clupea harengus*, sprat *Sprattus spp.* and shads (*Alosinae*)). These fishes are sensitive primarily to sound pressure, although they also detect particle motion. These species have a wider frequency range, extending to several kHz and generally show higher sensitivity to sound pressure than fishes in Groups 1, 2 and 3.
- Sea turtles: There is limited information on auditory criteria for sea turtles and the effect of impulsive noise is therefore inferred from documented effects to other vertebrates. Bone conducted hearing is the most likely mechanism for auditory reception in sea turtles and, since high frequencies are attenuated by bone, the range of hearing are limited to low frequencies only. For leatherback turtle *Dermochelys coracea* the hearing range has been recorded as between 50 Hz and 1,200 Hz with maximum sensitivity between 100 Hz and 400 Hz; and
- Fish eggs and larvae: separated due to greater vulnerability and reduced mobility. Very few peer-reviewed studies report on the response of eggs and larvae to anthropogenic sound.

45. The guidelines set out criteria for injury due to different sources of noise. Those relevant to the Proposed Development are considered to be those for injury due to impulsive piling sources only, as non-impulsive sources were not considered to be a key potential impact and therefore were screened out of the guidance[4]. The criteria include a range of indices including SEL, rms and peak SPLs. Where insufficient data exist to determine a quantitative guideline value, the risk is categorised in relative terms as “high”, “moderate” or “low” at three distances from the source: “near” (i.e. in the tens of metres), “intermediate” (i.e. in the hundreds of metres) or “far” (i.e. in the thousands of metres). It should be noted that these qualitative criteria cannot differentiate between exposures to different noise levels and therefore all sources of noise, no matter how noisy, would theoretically elicit the same assessment result. However, because the qualitative risks are generally qualified as “low”, with the exception of a moderate risk at “near” range (i.e. within tens of metres) for some types of animal and impairment effects, this is not considered to be a significant issue with respect to determining the potential effect of noise on fish.

46. The injury criteria used in this noise assessment for impulsive piling are given in Table 4.5. In the table, both peak and SEL criteria are unweighted. Physiological effects relating to injury criteria are described below (Popper *et al*., 2014; Popper and Hawkins, 2016):

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

Table 4.5: Criteria for Onset of Injury to Fish and Sea Turtles due to Impulsive Piling (Popper *et al*., 2014)

Type of Animal	Parameter	Mortality and Potential Mortal Injury	Recoverable Injury	TTS
Group 1 Fish: no swim bladder (particle motion detection)	SEL, dB re 1 µPa²s	>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 µPa²s	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 µPa²s	207	203	186
	Peak, dB re 1 µPa	>207	>207	-
Sea turtles	SEL, dB re 1 µPa²s	210	(*Near*) High (Intermediate) Low (*Far*) Low	(*Near*) High (Intermediate) Low (*Far*) Low
	Peak, dB re 1 µPa	>207		
Eggs and larvae	SEL, dB re 1 µPa²s	>210	(*Near*) Moderate (Intermediate) Low (*Far*) Low	(*Near*) Moderate (Intermediate) Low (*Far*) Low
	Peak, dB re 1 µPa	>207		

47. The criteria used in this noise assessment for non-impulsive piling and other continuous noise sources, such as vessels, are given in Table 4.6. The only numerical criteria for these sources are for recoverable injury and TTS for Groups 3 and 4 Fish.

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

Table 4.6: Criteria for Onset of Injury to Fish and Sea Turtles due to Non-Impulsive Sound (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 1 µPa (rms) for 48 hours	158 dB re 1 µPa (rms) for 12 hours
Sea turtles	(*Near*) Low (Intermediate) Low (*Far*) Low	(*Near*) Low (Intermediate) Low (*Far*) Low	(*Near*) Moderate (Intermediate) Low (*Far*) Low
Eggs and larvae	(*Near*) Low (Intermediate) Low (*Far*) Low	(*Near*) Low (Intermediate) Low (*Far*) Low	(*Near*) Low (Intermediate) Low (*Far*) Low

48. The criteria used in this noise assessment for non-impulsive piling and other continuous noise sources, such as vessels, are given in Table 4.7.

Table 4.7: 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 1 µPa	229 - 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 1 µPa	229 - 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 1 µPa	229 - 234	(*Near*) High (Intermediate) High (*Far*) Low	(*Near*) High (Intermediate) High (*Far*) Low

49. 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.

50. Behavioural reaction of fish to sound has been found to vary between species based on their hearing sensitivity. Typically, fish sense sound via particle motion in the inner ear which is detected from sound-induced motions in the fish's body. The detection of sound pressure is restricted to those fish which have air filled swim bladders; however, particle motion (induced by sound) can be detected by fish without swim bladders[5].

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

52. The most recent criteria for disturbance are considered to be those contained in Popper *et al*. (2014) which set out criteria for disturbance due to different sources of noise. The risk of behavioural effects is categorised in relative terms as "high", "moderate" or "low" at three distances from the source: "near" (i.e. in the tens of metres), "intermediate" (i.e. in the hundreds of metres) or "far" (i.e. in the thousands of metres), as shown in Table 4.8.

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

Table 4.8: Criteria for Onset of Behavioural Effects in Fish and Sea Turtles for Impulsive and Non-Impulsive Sound (Popper *et al*., 2014)

Type of Animal	Relative Risk of Behavioural Effects		
	Impulsive Piling	Explosives	Non-Impulsive Sound
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
Sea turtles	(Near) High (Intermediate) Moderate (Far) Low	(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

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

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

5. SOURCE NOISE LEVELS

5.1. GENERAL

55. Underwater noise sources are usually quantified in dB scale with values generally referenced to 1 μPa pressure amplitude as if measured at a hypothetical distance of 1 m from the source (called the Source Level). In practice, it is not usually possible to measure at 1 m from a source, but the metric allows comparison and reporting of different source levels on a like-for-like basis. In reality, for a large sound source this imagined point at 1 m from the acoustic centre does not exist. Furthermore, the energy is distributed across the source and does not all emanate from this imagined acoustic centre point. Therefore, the stated sound pressure level at 1 m does not occur for large sources. In the acoustic near field (i.e. close to the source), the sound pressure level will be significantly lower than the value predicted by the SL.

56. A wealth of experimental data and literature-based information is available for quantifying the noise emission from different construction operations. This information, which allows us to predict with a good degree of accuracy the sound generated by a noise source at discrete frequencies in one-third octave bands, will be employed to characterise their acoustic emission in the underwater environment. Sections 5.2 to 5.7 will detail the types of noise sources present during different parts of the construction activities, their potential signatures in different frequency bands, and acoustic levels.

5.2. TYPES OF NOISE SOURCES

57. The noise sources and activities which were investigated during the underwater noise assessment study are summarised in Table 5.1.

Table 5.1: Summary of Noise Sources and Activities Included in the Underwater Noise Assessment

Phase	Source/Activity
Pre-Construction	• geophysical site investigation activities including: – Multi-Beam Echo-Sounder (MBES); – Sidescan Sonar (SSS); – Single Beam Echosounder (SBES); – Sub-Bottom Profilers (SBP); and – Ultra-High Resolution Seismic (UHRS). • geotechnical site investigation activities including: – Drilling of boreholes; – Cone Penetration Tests (CPTs); and – Vibrocores. • use of geophysical/geotechnical survey vessels; • clearance of unexploded ordnances (UXOs) using preferred approach of low order techniques (possible low risk of some high order detonation therefore this has also been assessed up to 300 kg UXO);

Phase	Source/Activity
Construction	• impact and/or drill piled jacket foundations for wind turbine and Offshore Substation Platforms (OSPs)/Offshore convertor station platforms; • vessels used for a range of construction activities including (e.g. boulder clearance, sand wave clearance, drilling and trenching); • range of construction vessels including: – installation vessels; – cargo barges; – support vessels; – tug/anchor handlers; – cable installation vessels; – guard vessels; – survey vessels; – crew transfer vessels; – scour/cable protection installation vessels; and – resupply vessels.
Operation and maintenance	• operation noise from wind turbines; • routine geophysical surveys; • operation and maintenance vessels, including: – crew transfer vessels; – jack up vessel; – support vessels; – cable repair vessel; – service operations vessels and daughter craft; – cable survey vessel; and – excavator/backhoe dredger.
Decommissioning	• vessels for a range of decommissioning activities, assumed as per vessel activity described for construction phase.

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

5.3. PRE-CONSTRUCTION PHASE

5.3.1. GEOPHYSICAL SURVEYS

59. It is understood that several sonar based survey types will potentially be used for the geophysical surveys. Sound source data for the types of equipment likely to be used has been provided by the Applicant.

60. 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 based survey sources are classed as non-impulsive sound because they generally compromise 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.

61. The characteristics assumed for each device modelled in this assessment are summarised in Table 5.2. For the purpose of potential impacts, these sources are considered to be continuous (non-impulsive).

Table 5.2: Sonar Based Survey Equipment Parameters Used in Assessment

Survey Type	Frequency (kHz)	Source Level, (dB re 1 µPa re 1 m) (rms)	Pulse Rate, s^{-1}	Pulse Width (ms)	Beam Width
MBES	200-400	180-240	10	0.5	0.9º
SSS	200-900	190-245	15	15	0.4º
SBES	200-400	180-240			
SBP (pinger and chirp)	0.5 – 12 (chirp) 4 (pinger) 100 (pinger)	200-240 chirp 200-235 pingers	4	1.5	2º

62. The assumed pulse rate has been used to calculate the SEL, which is normalised to one second, 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 above.

63. Unlike the sonar-based surveys, the UHRS is likely to utilise a sparker, which produces an impulsive, broadband source signal. The parameters used in the noise modelling are summarised in Table 5.3.

Table 5.3: UHRS Survey Equipment Parameters Used in Assessment

Source	Peak Frequency (kHz)	Source Level (dB re 1 µPa re 1 m) (peak)	Source SEL (dB re 1 µPa^{2}s re 1 m)	Source Level (dB re 1 µPa re 1 m) (rms)	T90 (ms)
Ultra-high-resolution seismic (sparker)	19.5 - 33.5	219	182	170-200	0.7

5.3.2. GEOTECHNICAL SURVEYS

64. 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 acoustic ocean noise floor. The report also mentions other paths for acoustic energy including direct air to water transmission and other multipath directions, which implied that measured sound 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 5.4. For the purpose of potential impacts, these sources are considered as continuous (non-impulsive) sounds.

Table 5.4: CPT Source Levels in Different Octave Band Frequencies (SEL metric) Used for the Assessment (Erbe and McPherson, 2017)

SEL (dB re 1 µPa^{2}s)	Third 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

65. CPT noise is classified as impulsive at source since it has a rapid rise time and a high peak level of 220 dB re 1 µPa (pk).

66. 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.

67. Measurements of a vibro-core test (Reiser *et al*., 2011) show underwater source sound pressure levels of approximately 187 dB re 1 µPa re 1 m (rms). 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 sound is considered to be continuous (non-impulsive).

Table 5.5: Vibro-Core Source Levels Used in the Assessment

Parameter	Source Level	Unit
SEL (unweighted) – based on one-hour operation for single core sample	223	dB re 1 µPa^{2}s re 1 m
RMS T90	187	dB re 1 µPa re 1 m
Peak	190	dB re 1 µPa re 1 m

68. The frequency spectral shape for vibro-coring is presented in Figure 5.1

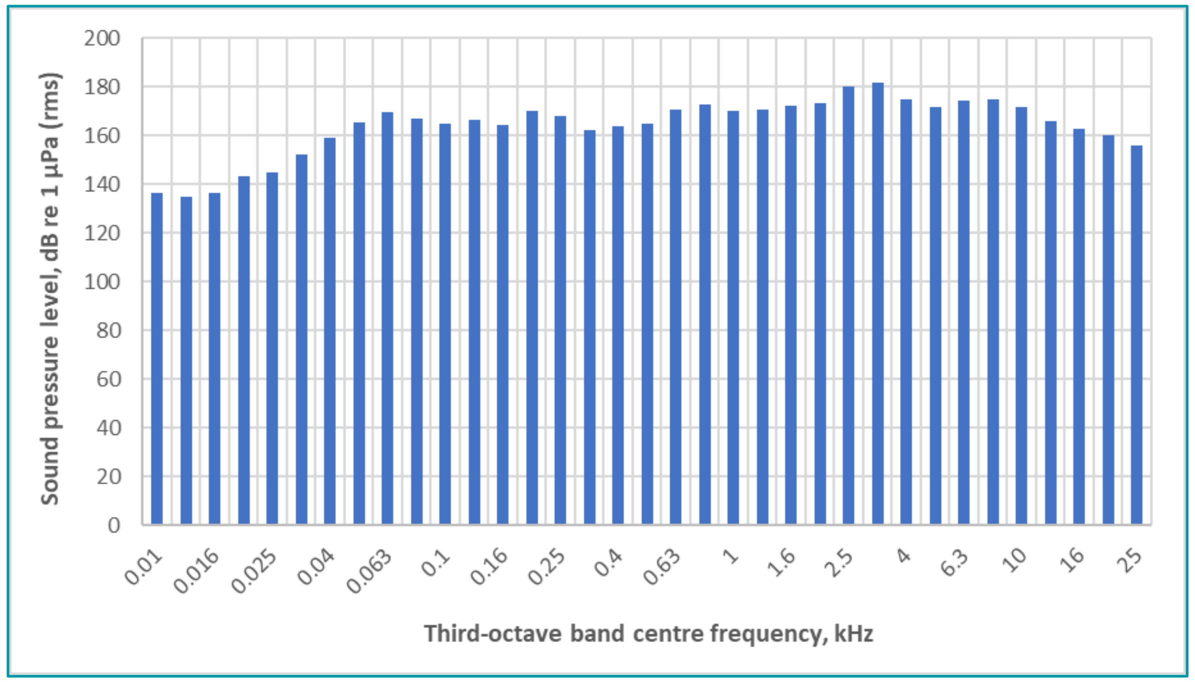

Figure 5.1: Frequency Spectral Shape Used for Vibro-Coring

69. Source levels for borehole drilling ahead of standard penetration testing 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 5.2.

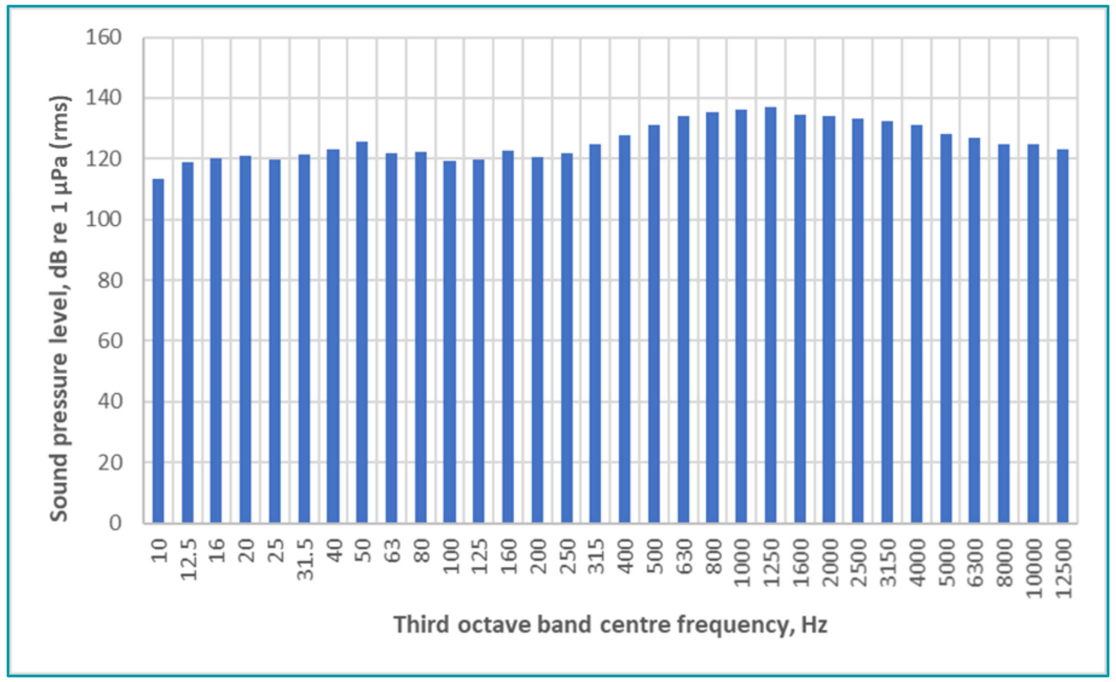

Figure 5.2: Borehole Drilling Source Level Spectrum Shape Used in the Assessment

70. As for other non-impulsive sources, impact assessment criteria is the SEL metric applied to a fleeing target.

5.3.3. VESSELS

71. Vessels are dealt with in section 5.7 for all phases of the project.

5.3.4. UXO CLEARANCE

72. 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 realistic worst case will be 300 kg.

73. The Applicant has committed to the use of low order techniques (subsonic combustion) as the intended methodology for clearance of UXO. For example, one such technique (deflagration) uses a single charge of 30 g to 80 g Net Explosive Quantity (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.

74. 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.

75. 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, recovery will be performed as outlined in paragraph 73, including the potential need of a small (500 g) ‘clearing shot’.

76. The noise modelling has been undertaken for a range of donor charge configurations as set out in Table 5.6. In addition, the noise modelling investigated the potential range of effects for an accidental high order detonation based on a realistic maximum scenario UXO size of 300 kg.

Table 5.6: Details of UXO and their Relevant Charge Sizes Employed for Modelling

Charge Size (kg TNT Equivalent)	Notes/Assumptions
Deflagration (Low Order Disposal)	
0.08 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
Detonation (High Order Disposal)	
300 kg	Realistic worst case UXO size

77. The source levels for UXO are included within the terms for propagation modelling and are described in section 6.5.

5.4. CONSTRUCTION PHASE

5.4.1. IMPACT PILING

78. The sound generated and radiated by a pile as it is driven into the ground is complex, due to the many components which make up the generation and radiation mechanisms. However, a wealth of experimental data is available which allow us to predict with a good degree of accuracy the sound generated by a pile at discrete frequencies. Third octave band noise spectra have been presented in literature for various piling activities (e.g. Matuschek and Betke, 2009; De Jong and Ainslie, 2008; Wyatt, 2008; Nedwell *et al*., 2003; Nedwell and Edwards, 2004; Nedwell *et al*., 2007; CDoT, 2001; Nehls *et al*., 2007; Thomsen *et al*., 2006; Robinson *et al*., 2020; Lepper *et al*., 2009).

79. For the Proposed Development, the assessments have been carried out for the wind turbine installation of up to 5.5 m diameter piles with an average maximum hammer energy typically at 3,000 kJ (maximum spatial scenario), but also considering an absolute maximum hammer energy of 4,000 kJ. Assessments have been carried out for the offshore substation platform installation of up to 4 m diameter piles, with a maximum hammer energy up to 4,000 kJ.

80. The assessment has been carried out at two locations on opposite sides of the Proposed Development array area, chosen to represent extremes of location. The bathymetry of the site is relatively flat, therefore the two locations were selected to represent the points closest and furthest away from the shoreline. In this case, these are represented by the indicative wind turbine foundation locations (e.g. wind turbine 1 and wind turbine 179, or wind turbine 40 and wind turbine 135 (Figure 6.2). Results are therefore presented as a range from smallest to largest ranges of potential impact.

81. Using the equation below (De Jong and Ainslie, 2008), a broadband source level value is evaluated for the noise emitted during impact pile driving operation in each operation window.

$$\mathrm{SEL} = 120 + 10\,log_{10}\left(\frac{\beta E C_0 \rho}{4\pi}\right).$$

82. In this equation, β is the energy transmitted from the pile into the water column, E is the hammer energy employed in joules, C_0 is the speed of sound in the water column, and ρ is the density of the water. From the SEL result calculated using the equation above, source level spectra can also be calculated for different third octave frequency bands.

83. The assumption used for the modelling is that the amount of sound radiated into the water column depends on both the hammer energy and the length of pile exposed above the seabed in the water column. During the Marine Mammal Road Map pre-Application consultation process, the validity of different conversion factors relating to how energy is converted between hammer energy (kinetic) into sound energy was discussed with key stakeholders (NatureScot, Marine Scotland Licensing and Operations Team (MS-LOT) and Marine Scotland Science (MSS), and it was agreed that a range of values should be investigated with a robust justification for the conversion factor that would be taken forward to the full Marine Mammal Impact Assessment. The underwater noise modelling study therefore investigated the following:

- a constant conversion factor of 1% (a conservative value that was evaluated for Seagreen alongside the 0.5% conversion factor applied to the assessment);
- a reducing conversion factor commencing at 10% reducing to 1% (with the starting value derived from a study by Thompson *et al.,* 2020); and
- a reducing conversion factor commencing at 4% reducing to 0.5% (with the starting value based on studies by Lippert *et al.,* 2017).

84. A comprehensive study evaluating the evidence and justification for different conversion factors was undertaken following advice received during the Marine Mammal Road Map pre-Application consultation process (volume 3, appendix 10.1, annex A). Consequently, a variable conversion factor (β) has been used ranging from β = 4% at the start of piling to β = 0.5% at the end of piling when the pile is almost fully embedded in the seabed. This scenario has been chosen as it was considered to represent the best balance of realism and precaution in conversion factor, particularly compared to a conversion factor of 10% reducing to 1% which was considered over-precautionary and therefore misrepresentative of the potential kinetic energy converted to sound energy. A 1% constant conversion factor was considered less representative compared to 4% reducing to 0.5% for a partially submersible hammer as would be used for the Proposed Development. Note, however, to adopt a precautionary assessment and to mitigate for uncertainties in the true value of the conversion factor the marine mammal EIA took forward the predicted ranges from either the 4% reducing conversion factor or 1% constant conversion factor, whichever led to the greatest ranges using the relevant noise thresholds for injury and disturbance.

85. The justification for this assumption is provided in full in volume 3, appendix 10.1, annex A, and is summarised as follows:

- Measurements on piles using above water impact hammers show approximately linear SEL to hammer energy relationship (e.g. Bailey *et al*., 2010; Robinson *et al.,* 2007; Robinson *et al*., 2009; Lepper *et al*., 2012; Robinson *et al.*, 2013).
- Peer reviewed literature which considers theoretical concepts, concluded that a representative energy conversion factor is likely to be in the range β ≈ 0.3% to 1.5% (Zampolli *et al.,* 2013), whilst Dahl *et al.* (2015) concluded that β ≈ 0.5% based on a review of both theoretical considerations and measurement data by others.
- The theoretical upper limit of the energy conversion factor is therefore approximately 1.5%, although this is only likely to apply when the hammer is operating at the lower end of its power rating, with lower conversion factors being more likely throughout the remainder of the piling period (that are subject to higher hammer energies). An average hammer energy conversion factor of β ≈ 1% is therefore concluded to be representative and precautionary across the range of hammer energies used during a pile installation using an above water hammer.
- Peer reviewed studies based on measurements on above water piling hammers determined real world energy conversion factors of β = 0.8% (De Jong and Ainslie, 2008) and β ≈ 1% (Dahl and Reinhall, 2013). However, use of a submersible hammer can result in the conversion factor varying depending on pile penetration depth.
- Both measurement data and detailed source modelling presented for a partially submersible hammer in Lippert *et al*. (2017) supports a varying conversion factor of between β ≈ 2% and 0.5% depending on penetration depth and the length of pile above water.
- Thompson *et al*. (2020), whilst ostensibly indicating conversion factors ranging between β ≈ 10% and 1% for a fully submersible hammer, is considered to be a considerable overestimate of the true energy radiated into the water column caused by discrepancies between the noise modelling and real world propagation. True conversion factors are thought likely to be in the order of half these values, or less, as demonstrated by differences in the conversion factors derived at different ranges from each pile (a full analysis and explanation for this is provided in volume 3, appendix 10.1, annex A).
- Of the above two studies, the Lippert *et al*. (2017) study is considered scientifically robust because of the very strong correlation between the detailed finite element modelling and measured data.
- It is recognised that for the Lippert *et al*. (2017) study a significant proportion of the pile was above water at the start of the piling sequence which could have reduced the apparent conversion factor compared to a situation where the pile starts just above the water line. Assuming that the energy radiated into the water is approximately proportional to the length of pile which is exposed to the water then the conversion factor at the start of piling in the Lippert *et al.* (2017) study can be estimated to be approximately 3.5%.
- For the Proposed Development, although no detailed piling methodology is available at the point of Application, it is considered likely that in the deepest waters, piling will commence just above (or just below) the water line and will finalise with pile penetration just above the seafloor, in water depths of up to 70 m. Consequently, and in light of MSS and NatureScot's request, a conversion factor of β ≈ 4% has been used for the Proposed Development at the start of the piling sequence. This 4% conversion factor is higher than that derived in the Lippert *et al*. (2017) study and is therefore considered conservative.
- Furthermore, it should be noted that any piles installed in shallower waters within the Proposed Development array area, are likely to result in lower source levels than derived for the start of piling in deep waters as a significant proportion of the pile could penetrate above the water line, meaning much of the energy would radiate into the air rather than water therefore not affecting marine mammals under water.
- In Lippert *et al.* (2017) study, the piles remained approximately 17 m above the seabed floor at the end of the piling sequence which means that the β ≈ 1% conversion factor at the end of the piling sequence is likely to be an overestimate compared to the Proposed Development case where a greater proportion of the pile will penetrate the seabed. Since the final pile position in the Lippert *et al.* (2017) study was a little below mid-water depth (and since, when the pile is subsea, the fall-off in acoustic energy cited by Lippert *et al.* (2017) is ~2.5 dB per halving of exposed pile above the seabed) this infers a final conversion factor of 0.5% or less at the end of piling.
- Consequently, based on this review, the assumption that piling is likely to use a submersible hammer for the majority of the piling operation, best available scientific evidence, professional judgement, and taking into account the advice of MSS and NatureScot, it is proposed to utilise a varying energy conversion factor of β = 4% at the start of piling to 0.5% at the end of piling for underwater noise modelling at the Proposed Development.

86. A review of hammer energy conversion factors and further justification of the energy conversion factor assumptions is provided in volume 3, appendix 10.1, annex A. In addition, a sensitivity analysis using the

three different hammer energy conversion factors (i.e. 4% reducing to 0.5%, 1% constant throughout the piling period, and 10% reducing to 1%) is provided in volume 3, appendix 10.1, annex B. Furthermore, the various inputs and assumptions used in the modelling, including the conversion factors used to derive the source levels, has been subjected to an independent peer review which is provided in volume 3, appendix 10.1, annex H.

87. Figure 5.3 shows that due to the use of a reducing conversion factor, the highest sound exposure level no longer occurs during the period of maximum hammer energy (full power piling), but occurs during the period of piling that the maximum conversion factor is applied to (e.g. at the start of the piling sequence). This is consistent with the measurements taken by Lippert *et al.* (2017). Figure 5.4 shows the hammer energy over the same time period, for comparison, and illustrates the impact of conversion factor on the resultant noise level.

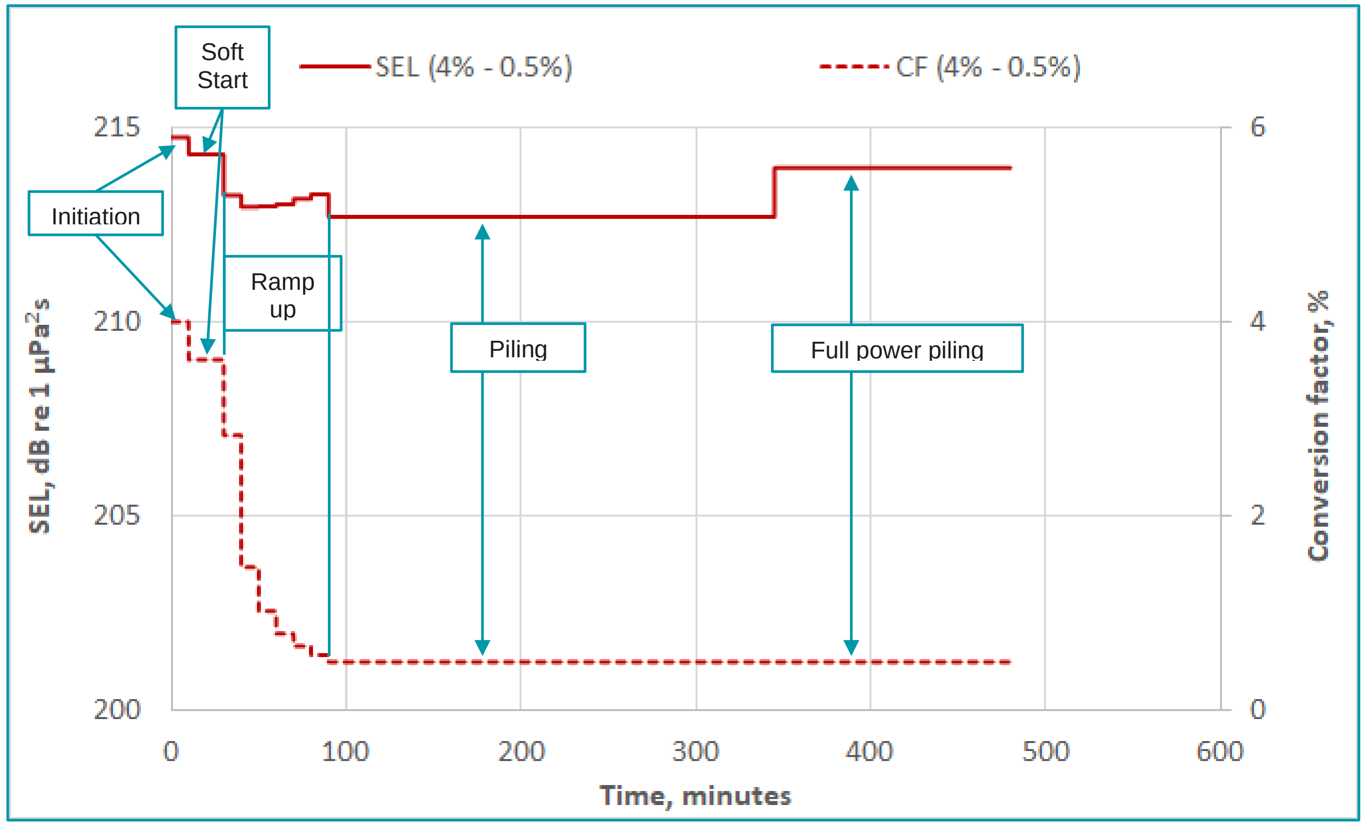

Figure 5.3: Representation of the Relationship Between the Varying Conversion Factor (4% to 0.5%) and SEL for the 4,000 kJ Scenario, Over the Piling Sequence as Indicated

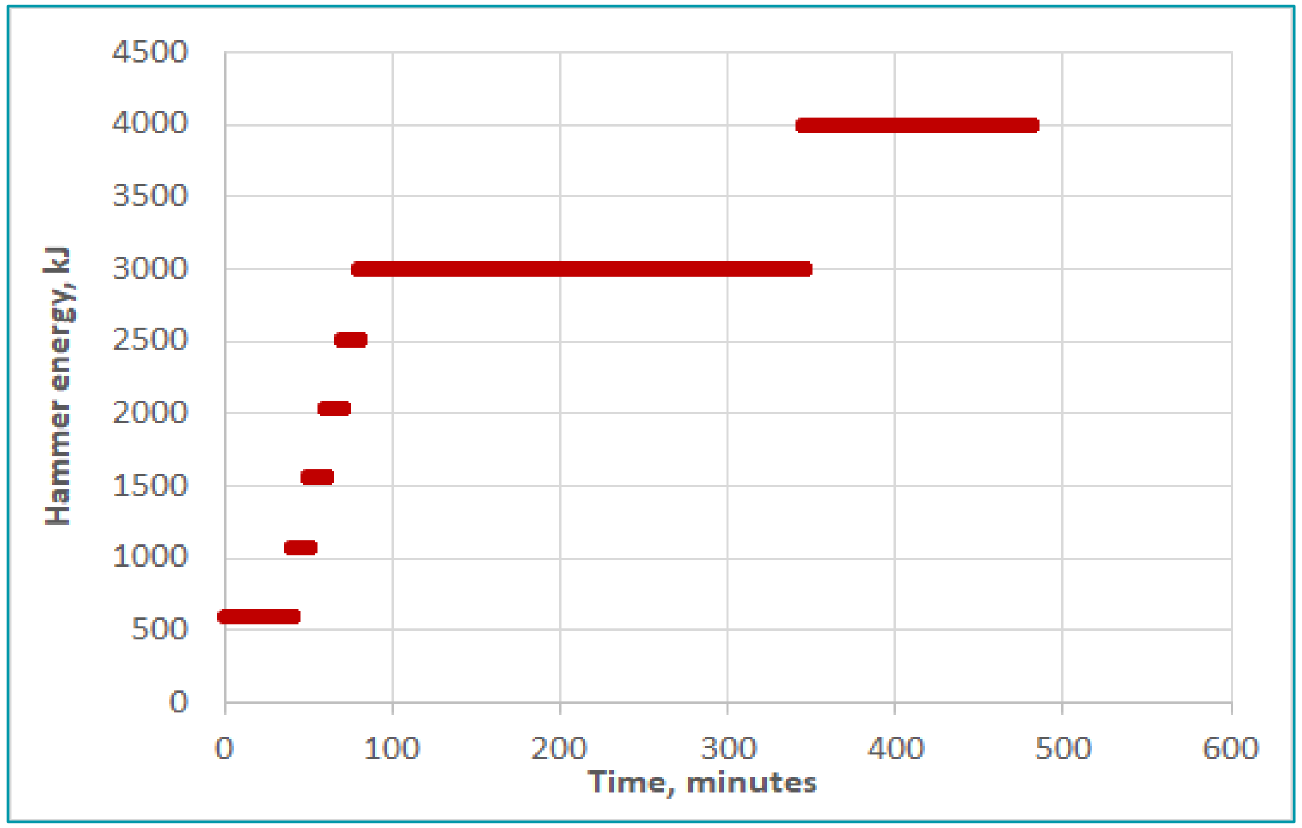

Figure 5.4: Hammer Energy Throughout the Piling Sequence, Maximum Design Scenario

88. The spectral distribution of the source SELs for impact piling were derived from the reference spectrum provided in De Jong and Ainslie (2008), reproduced in Figure 5.5.

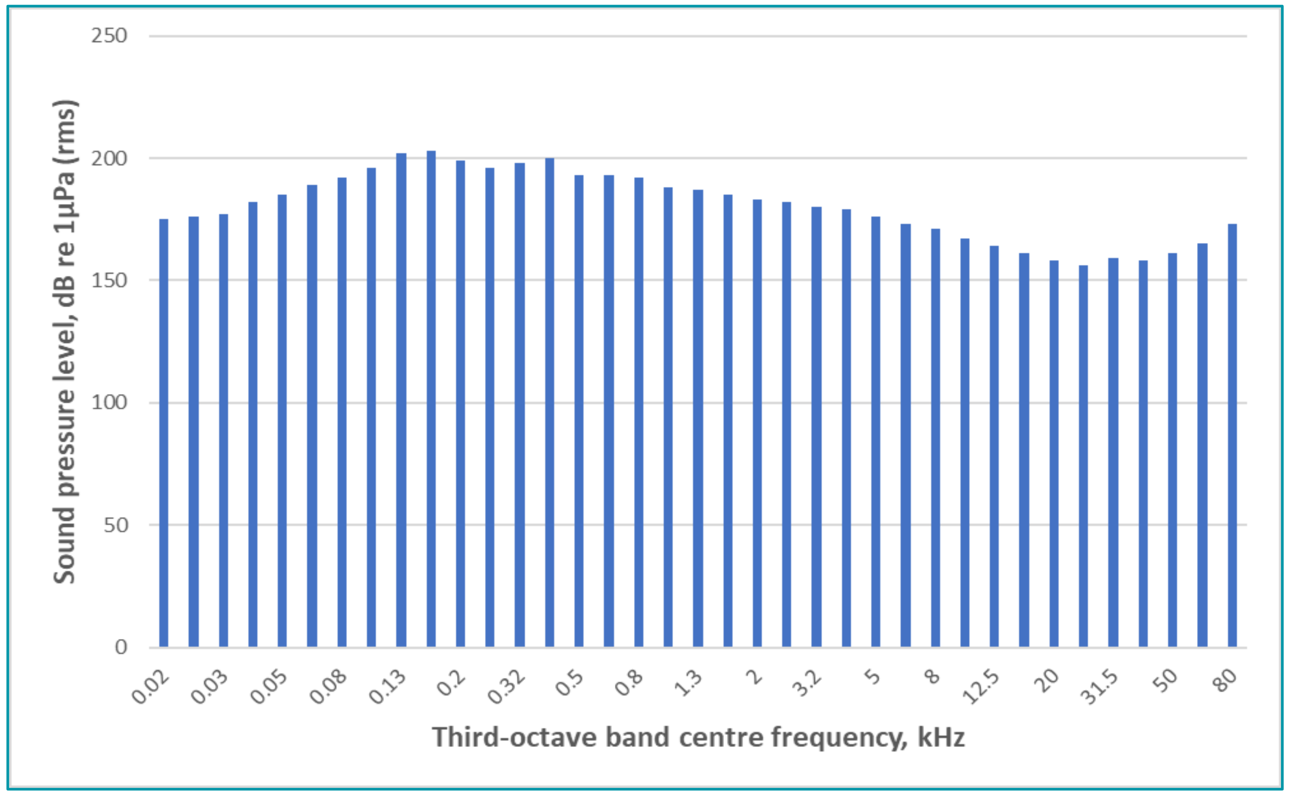

Figure 5.5: Impact Piling Source Frequency Distribution Used in the Assessment

89. The impact piling scenarios that have been modelled for the Proposed Development are:

- wind turbine foundations (Piled Jacket) Maximum design scenario–o - 24 MW wind turbines (largest wind turbine) using an absolute maximum hammer energy of 4,000 kJ for the longest possible duration (up to ten hours) (see Table 5.7);
- wind turbine foundations (Piled Jacket) realistic design scenario–o - 24 MW (see Table 5.8). Table 5.8 is based on the realistic average maximum hammer energy of 3,000 kJ for a realistic maximum duration (up to nine hours) and is included to provide context to the maximum hammer energy scenario; and
- OSP/Offshore convertor station platform foundations (jacket) maximum design scenario – using a maximum hammer energy of 4,000 kJ for a duration of up to eight hours (see Table 5.9).

Table 5.7: Impact Piling Schedule Used in Assessment - Wind Turbine Foundations (Maximum Design Scenario)

Activity/Stage	Duration (Minutes)	Hammer Energy (kJ)	Strike Rate (Strikes per Minute)	Number of Strikes	Notes
Pile self-weight penetration	N/A	N/A	N/A	N/A	Pile self-weight penetration where the pile will sink into the seabed under its own weight.
Initiation	10	600	5	50	Slow start to allow for alignment etc. and to allow marine mammals to leave area
Soft start	20	600	30	600	Soft start at low hammer energy for 20 minutes
Ramp up	60	600 – 3,000	30	1,800	Ramp up in hammer energy after soft start period
Piling	315	3,000	30	9,450	Steady driving using an energy level of approx. 3,000 kJ
Full power piling	195	4,000	30	5,850	Hard driving using an energy level of approx. 4,000 kJ

Table 5.8: Impact Piling Schedule Used in Assessment – Wind Turbine Foundations (Realistic Design Scenario)

Activity/Stage	Duration (Minutes)	Hammer Energy (kJ)	Strike Rate (Strikes per Minute)	Number of Strikes	Notes
Pile self-weight penetration	N/A	N/A	N/A	N/A	Pile self-weight penetration where the pile will sink into the seabed under its own weight.
Initiation	10	450	5	50	Slow start to allow for alignment etc. and to allow marine mammals to leave area
Soft start	20	450	30	600	Soft start at low hammer energy for 20 minutes
Ramp up	60	450 – 2,250	30	1,800	Ramp up in hammer energy after soft start period
Piling	315	2,250	30	9,450	Steady driving using an energy level of approx. 2,250 kJ
Full power piling	135	3,000	30	4,050	Hard driving using an energy level of approx. 3,000 kJ

Table 5.9: Impact Piling Schedule Used in Assessment - OSP/Offshore Convertor Station Platform Foundations

Activity/Stage	Duration (Minutes)	Hammer Energy (kJ)	Strike Rate (Strikes per Minute)	Number of Strikes	Notes
Pile self-weight penetration	N/A	N/A	N/A	N/A	Pile self-weight penetration where the pile will sink into the seabed under its own weight.
Initiation	10	600	5	50	Slow start to allow for alignment etc. and to allow marine mammals to leave area
Soft start	20	600	30	600	Soft start at low hammer energy for 20 minutes

Activity/Stage	Duration (Minutes)	Hammer Energy (kJ)	Strike Rate (Strikes per Minute)	Number of Strikes	Notes
Ramp up	60	600 – 3,000	30	1,800	Ramp up in hammer energy after soft start period
Piling	255	3,000	30	7,650	Steady driving using an energy level of approx. 3,000 kJ
Full power piling	135	4,000	30	4,050	Hard driving using an energy level of approx. 4,000 kJ

90. The peak sound pressure level 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:

$$SPL_{pk} = 1.43 \times SE- - 44.0$$

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

92. The piling of wind turbine foundations described in Table 5.8 was also modelled with the inclusion of an acoustic deterrant device (ADD) before commencement of piling. Use of an ADD was modelled for a duration of 30 minutes prior to commencement ofpiling, all other stages of piling remained the same, and the ADD itself was assumed to not contribute towards any animal injury.

5.4.2. DRILLED PILES

93. For drilled piling, source sound levels have been based on pile drilling for the Oyster 800 project (Kongsberg, 2011). The hydraulic rock breaking source sound levels are based on those measured by Lawrence (2016). The source levels used in the assessment are summarised in Table 5.10.

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

Table 5.10: 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 $\mu Pa^2 s$	163
Peak sound pressure level @ 1 m, dB re 1 μPa	166
rms_{T90} sound pressure level @ 1 m, dB re 1 μPa	163

95. 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 SEL based source levels are presented in Table 5.11.

Table 5.11: SEL Based Source Levels for Other Noise Sources

Sources	Data Source	RMS (dB re 1 µPa)	Frequency (Hz) 16	31.5	63	125	250	500	1k	2k	4k	8k	16k	31.5k
Cable laying	Wyatt (2008)	188	176	174	174	173	170	165	161	162	146	139	133	169
Cable trenching/ cutting	Nedwell *et al.* (2003)	178	135	135	148	161	167	169	167	162	157	148	142	141
Jack up rig	Nedwell and Edwards (2004)	163	120	132	141	148	148	152	149	143	148	152	145	139

5.4.3. VESSELS

96. Use of vessels is addressed in section 5.7 for all phases of the Proposed Development.

5.5. OPERATION AND MAINTENANCE PHASE

5.5.1. OPERATION NOISE FROM WIND TURBINES

97. A review of publicly available information on the potential for operation wind turbines to produce noise has been undertaken and is presented in section 7.3.

5.5.2. GEOPHYSICAL SURVEYS

98. Routine geophysical surveys will be similar to the geophysical surveys already discussed for the pre-construction phase (see section 5.3).

5.5.3. ROUTINE OPERATION AND MAINTENANCE

99. There are very few activities during the operation and maintenance phase that generate significant amounts of underwater noise. The source level for the general operations carried out in the operation and maintenance phase such as the jet cutting operation, which is considered to be the activity with the highest sound level, is presented in Table 5.12.

Table 5.12: SEL Based Octave Band Levels Used for Different Operations in this Phase

Source	SEL Broadband Level	Frequency (kHz) 0.016	0.0315	0.063	0.125	0.25	0.5	1	2	4	8	16	31.5
Jet cutting	195	167	170	173	176	179	182	185	185	181	175	166	157

5.5.4. VESSELS

100. The potential for vessels use to create underwater noise is presented in section 5.7 for all phases of the Proposed Development.

5.6. DECOMMISSIONING PHASE

5.6.1. VESSELS

101. As agreed with stakeholders during the pre-Application consultation phase, only the potential impact of noise from vessel activity has been scoped into the underwater noise assessment for the decommissioning phase of the Proposed Development. It should be noted that noise cavitation from the vessels themselves is likely to dominate the soundscape for other decommissioning activities (e.g. removal of subsea structures). The potential impact of vessels noise is addressed in section 5.7 for all phases of the Proposed Development.

5.7. VESSELS (ALL PHASES)

102. The noise emissions from the types of vessels that may be used for the Proposed Development are quantified in Table 5.13, based on a review of publicly available data. Sound from the vessels themselves (e.g. propeller, thrusters and sonar (if used)) primarily dominates the emission level, hence noise from activities such as seabed preparation, trenching and rock placement (if required) have not been included separately.

103. In Table 5.13, a correction of +3 dB has been applied to the rms sound pressure level to estimate the likely peak sound pressure level. SELs have been estimated for each source based on 24 hours continuous operation, although it is important to note that it is highly unlikely that any marine mammal or fish would stay at a stationary location or within a fixed radius of a vessel (or any other 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). 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 Proposed Development has been based on worst-case 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 was used as a proxy. This is considered an appropriate proxy because it is a similar size of vessel using dynamic positioning and therefore likely to have a similar acoustic footprint.

Table 5.13: Source Noise Data for Construction and Installation Vessels

Item	Description/Assumptions	Data Source	Source SPL at 1 m		
			RMS (dB re 1 µPa)	Peak (dB re 1 µPa)	SEL(24h) (dB re 1 µPa²s)
Main Installation Vessels (Jack-up Barge/DP vessel)	'Gerardus Mercator' trailer hopper suction dredger using DP as proxy	Wyatt (2008)	188	191	237
Tug/Anchor Handlers	Tug used as proxy	Richardson (1995)	172	175	221
Cable Installation Vessels	'Gerardus Mercator' trailer hopper suction dredger using DP as proxy	Wyatt (2008)	188	191	237
Guard Vessels	Tug used as proxy	Richardson (1995)	172	175	221
Survey Vessels	Offshore support vessel used as proxy	McCauley (1998)	179	182	228
Crew Transfer Vessels	Offshore support vessel used as proxy	McCauley (1998)	179	182	228
Scour/Cable Protection/Seabed Preparation/Installation Vessels	Offshore support vessel used as proxy	McCauley (1998)	179	182	228

6. PROPAGATION MODELLING

6.1. PROPAGATION OF SOUND UNDERWATER

104. As the distance from the sound source increases the level of sound recorded reduces, primarily due to the spreading of the sound energy with distance, in combination with attenuation due to absorption of sound energy by molecules in the water. This latter mechanism is more important for higher frequency sound than for lower frequencies.

105. The way that the sound 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 sound will propagate. However, in simple terms, the sound energy may spread out in a spherical pattern (close to the source) or a cylindrical pattern (much further from the source), although other factors mean that decay in sound energy may be somewhere between these two simplistic cases.

106. In acoustically shallow waters[6] in particular, the propagation mechanism is coloured by multiple interactions with the seabed and the water surface (Lurton, 2002; Etter, 2013; Urick, 1983; Brekhovskikh and Lysanov,

6 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 sound speed gradient, water depth, frequency of the sound and distance between the source and receiver.

2014; Kinsler *et al.*, 1999). Whereas in deeper waters, the sound will propagate further without encountering the surface or bottom of the sea, in shallower waters the sound may be reflected from either or both boundaries (potentially more than once).

107. At the sea surface, the majority of the sound is reflected into the water due to the difference in acoustic impedance (i.e. sound speed and density) between air and water. However, the scattering of sound at the surface of the sea can be an important factor in the propagation of sound. In an ideal case (i.e. for a perfectly smooth sea surface), the majority of sound energy will be reflected into the sea. However, for rough seas, much of the sound 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 life. Scattering is more pronounced for higher frequencies than for low frequencies and is dependent on the sea state (i.e. wave height). However, the various factors affecting this mechanism are complex.

108. Because surface scattering results in differences in reflected sound, its effect will be more important at longer ranges from the sound 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 sound, 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 sound will experience fewer reflections and so the effect of scattering should not be significant.

109. When sound waves encounter the bottom, the amount of sound reflected will depend on the geoacoustic properties of the bottom (e.g. grain size, porosity, density, sound speed, absorption coefficient and roughness) as well as the grazing angle and frequency of the sound (Cole, 1965; Hamilton, 1970; Mackenzie, 1960; McKinney and Anderson, 1964; Etter, 2013; Lurton, 2002; Urick, 1983). Thus, bottoms comprising primarily mud or other acoustically soft sediments will reflect less sound 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 bottom (Essen, 1994; Greaves and Stephen, 2003; McKinney and Anderson, 1964; Kuo, 1992), particularly on rough substrates (e.g. pebbles).

110. The waveguide effect should also be considered, which defines the shallow water columns do not allow the propagation of low frequency sound (Urick, 1983; Etter, 2013). The cut-off frequency of the lowest mode in a channel can be calculated based on the water depth and knowledge of the sediment geoacoustic properties. Any sound below this frequency will not propagate far due to energy losses through multiple reflections.

111. Changes in the water temperature and the hydrostatic pressure with depth mean that the speed of sound varies throughout the water column. This can lead to significant variations in sound propagation and can also lead to sound channels, particularly for high-frequency sound. Sound can propagate in a duct-like manner within these channels, effectively focussing the sound, and conversely, they can also lead to shadow zones. The frequency at which this occurs depends on the characteristics of the sound channel but, for example, a 25 m thick layer would not act as a duct for frequencies below 1.5 kHz. The temperature gradient can vary throughout the year and thus there will be potential variation in sound propagation depending on the season.

112. Sound energy is also absorbed due to interactions at the molecular level converting the acoustic energy into heat. This is another frequency-dependent effect with higher frequencies experiencing much higher losses than lower frequencies.

6.2. MODELLING APPROACH

113. There are several methods available for modelling the propagation of sound between a source and receiver ranging from very simple models which simply assume spreading according to a 10 log (R) or 20 log (R) relationship (as discussed above, 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, whose complexity and accuracy are somewhere in between these two extremes.

114. 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", NPL Guidance, (Dekeling *et al.*, 2014) and in Farcas *et al*. (2016). Thus, in some situations (e.g. low risk due to underwater noise, where range dependent bathymetry is not an issue, i.e. for non-impulsive sound) a simple (N log R) model might be sufficient, particularly where other uncertainties outweigh the uncertainties due to modelling. On the other hand, some situations (e.g. very high source levels, impulsive sound, complex source and propagation path characteristics, highly sensitive receivers, and low uncertainties in assessment criteria) warrant a more complex modelling methodology.

115. 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.

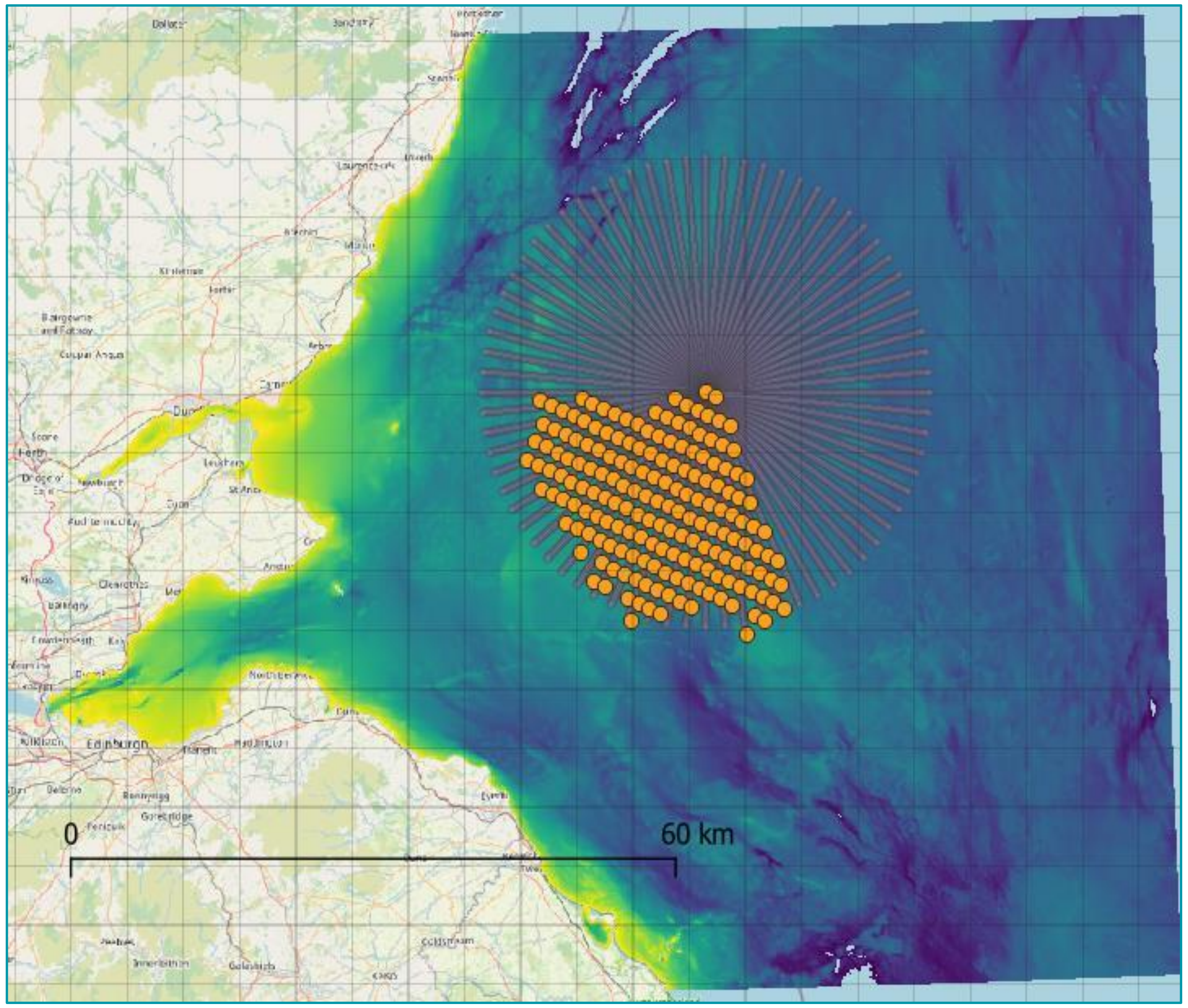

Figure 6.1: The Indicative Location of the Proposed Piles (Yellow Circles) in the Proposed Development, General Bathymetry Depth Around the Survey Region (Darker Is Deeper Water), and the Different Transects Employed for the Study Radiating out from one of the Modelled Source Locations

116. For the sound 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 see volume 3, appendix 10.1, annex C; 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 1,000 kHz (1 MHz), with different noise sources operating in different frequency bands. These frequencies overlap with the hearing sensitivities (as per Figure 4.1) of some of the marine mammals that are likely to be present in the survey area.

117. A more detailed justification for the choice of noise model is provided in a separate technical note in volume 3, appendix 10.1, annex A. A calibration of the Weston Flux Energy underwater noise model against other underwater noise models is provided in volume 3, appendix 10.1, annex C.

Table 6.1: Regions of Transmission Loss Derived by Weston (1971)

Region	Transmission Loss	Range of validity
Spherical	$TL = 10\log_{10}[R^2]$	$R < \frac{H_a}{2\theta_c}$
Channelling	$TL = 10\log_{10}\left[\frac{RH_aH_b}{2H_c\theta_c}\right]$	$\frac{H_a}{2\theta_c} < R < \frac{6.8H_a}{\alpha{\theta_c}^2}$
Mode stripping	$TL = 10\log_{10}\left[\frac{RH_aH_b}{5.22}\left(\alpha\int_0^R \frac{dR}{H^3}\right)^{1/2}\right]$	$\frac{6.8H_a}{\alpha{\theta_c}^2} < R < \frac{27k^2{H_a}^3}{(2\pi)^2\alpha}$
Single mode	$TL = 10\log_{10}\left[\frac{RH_aH_b}{\lambda}\right] + \frac{\lambda^2\alpha}{8}\int_0^R \frac{dR}{H^3}$	$R > \frac{27k^2{H_a}^3}{(2\pi)^2\alpha}$

118. The propagation loss is calculated using one for the four formulae detailed in the table above, 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.

119. In Table 6.1, H_a is the depth at the source, H_b is the depth at the receiver, H_c is the minimum depth along the bathymetry profile (between the source and the receiver), θ_c is the critical grazing angle (related to the speed of sound in both seawater and the seafloor material), λ and k are the wavelength and wavenumber as usual, and α is the seabed reflection loss gradient, empirically derived to be 12.4 dB/rad in Weston (1971).

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

121. 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 point (north-east point as marked in Figure 6.1 was extracted from the GEBCO database up to 80 km (where possible) in 72 different transects.
- A geoacoustic model of the different seafloor layers in the survey region was calculated.
- A calibrated Weston Energy model was employed to estimate the TL matrices for different frequencies of interest (from 25 Hz to 80 kHz) along the 72 different transects.
- The source level values calculated were combined with the TL results to achieve a frequency and range dependant RL of acoustic energy around the chosen source position.

- The recommended marine mammal weightings (m-weightings) were employed for injury and the TTS and PTS potential impact ranges for different marine mammal groups were calculated using relevant metrics (from Southall *et al.*, 2019) and by employing a fleeing marine mammal model where necessary.

122. The propagation and sound exposure calculations were conducted over a range of water column depths to determine the likely range for injury and disturbance. For the results shown in tables in section 7 a representative pile location in the middle of the site was chosen (wind turbine 96 for the 179T layout). For sound level contours, an additional five points were modelled, chosen as the extremities of the field (north, south, east and west), with the fifth being an additional point near the Firth of Forth. These six points are seen in Figure 6.2.

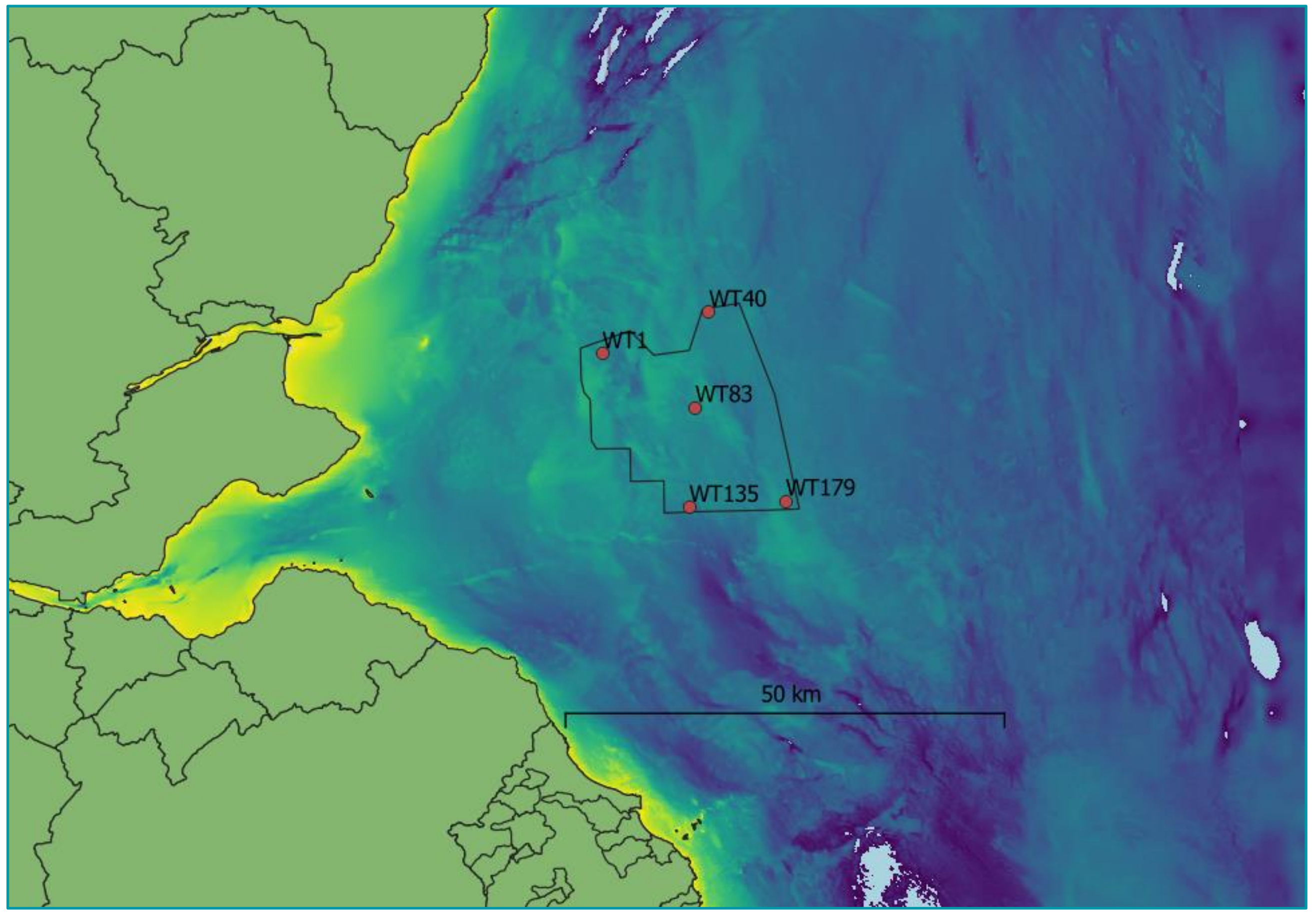

Figure 6.2: Six Representative Modelling Points within the Proposed Development. These Correspond to Indicative Foundation Locations 1, 40, 83, 135 and 179 from the 179T Layout. The Central Point (83) was Used for Potential Impact Ranges.

123. It should be borne in mind that noise levels (and associated range of effects) will vary depending on actual conditions at the time (day-to-day and season-to-season) and that the model predicts a typical worst-case scenario. Considering factors such as animal behaviour and habituation, any injury and disturbance ranges should be viewed as indicative and probabilistic ranges to assist in understanding potential impacts on marine life rather than lines either side of which a potential impact will or will not occur[7].

124. The Weston noise model used for this assessment has been calibrated against a range of other noise models showing good agreement (typically within +/- 1 dB to a range of 2.5 km). The results of this comparison are summarised in volume 3, appendix 10.1, annex C. The acoustical properties of different layers employed in the propagation modelling are presented in Table 6.2. This data is evaluated using recommendations by Hamilton (1980) based on the geological layers present in the survey region and the acoustic properties of the water column. Due to the relatively shallow nature of the area, only a single speed of sound in the water column was considered.

Table 6.2: Acoustical Properties of the Water Layer and Sediment Used for Propagation Modelling

Max Depth (m)		Speed of Sound (m/s)		Density	Attenuation (dB/λ)	
		Compressional	**Shear**	**kg/m³**	**Shear**	**Compressional**
Water column	65	1,475	0	1,024	0	0.1
Geological layer	NA	1,700	250	2000	10	0.5

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

6.3. BATCH PROCESSING

126. 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 sound field for the whole area around the source point. For more information on the methodology followed, see volume 3, appendix 10.1. 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

[7] This is a similar approach to that adopted for airborne noise where a typical worst case is taken, though it is known that day to day levels may vary to those calculated by 5 to 10 dB depending on wind direction etc.

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).

127. 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 2-D maps. 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 2-D RL maps centred around each source point.

6.4. EXPOSURE CALCULATIONS

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

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

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

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

132. In order to carry out the swimming mammal calculation, it has been assumed that a mammal will swim away from the noise source at the onset of activities. For impulsive sounds of piledriving the calculation considers each pulse to be established separately resulting in a series of discrete SEL values of decreasing magnitude (see Figure 6.3).

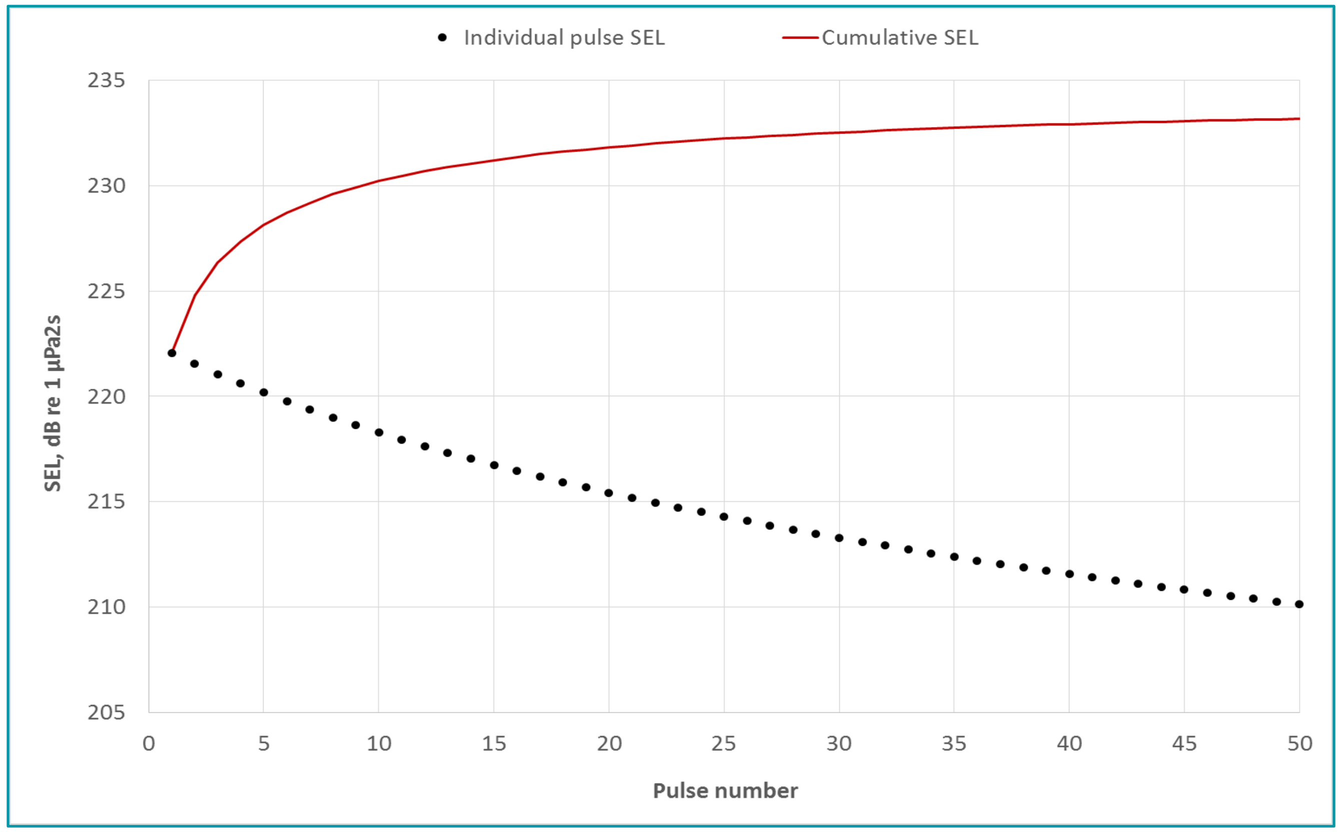

Figure 6.3: A Comparison of Discrete "Pulse" Based SEL and a Cumulative of SEL Values

133. As a marine mammal swims away from the sound source, the noise it experiences will become progressively more attenuated; the cumulative SEL is derived by logarithmically adding the SEL to which the mammal is exposed as it travels away from the source. This calculation was used to estimate the approximate minimum start distance for a marine mammal in order for it to be exposed to sufficient sound energy to result in the onset of potential injury. It should be noted that the sound exposure calculations are based on the simplistic assumption that the animal will continue to swim away at a fairly constant relative speed. The real-world situation is more complex, and the animal is likely to move in a more complex manner.

134. The swim speeds of marine mammals used in this assessment were presented during Marine Mammal Road Map Meeting 2 on 20 October 2021 (see volume 3, appendix 10.3) and no concerns were raised by NatureScot and MSS at the meeting or in subsequent correspondence. The swim speeds applied are summarised in Table 6.3 along with the source papers for the assumptions.

Table 6.3: Swim Speeds Assumed for Exposure Modelling

Species	Hearing Group	Swim Speed (m/s)	Source Reference
Harbour porpoise	VHF	1.5	Otani *et al.*, 2000
Harbour seal	PCW	1.8	Thompson, 2015
Grey seal	PCW	1.8	Thompson, 2015

Species	Hearing Group	Swim Speed (m/s)	Source Reference
Minke whale	LF	2.3	Boisseau et al., 2021
Bottlenose dolphin	HF	1.52	Bailey and Thompson, 2010
White-beaked dolphin	HF	1.52	Bailey and Thompson, 2010
Basking shark	Group 1 fish	1.0	Sims, 2000

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

136. In addition to the single-source pile driving, simplified situations of simultaneous pile driving from two piling rigs have been considered. The flight response has been approximated as fleeing straight away from the nearest point on a line 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.

6.5. UXO NOISE MODELLING

6.5.1. DETONATION

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

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

138. Where W is the equivalent TNT charge weight and R is the distance from source to receiver.

139. 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.

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

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

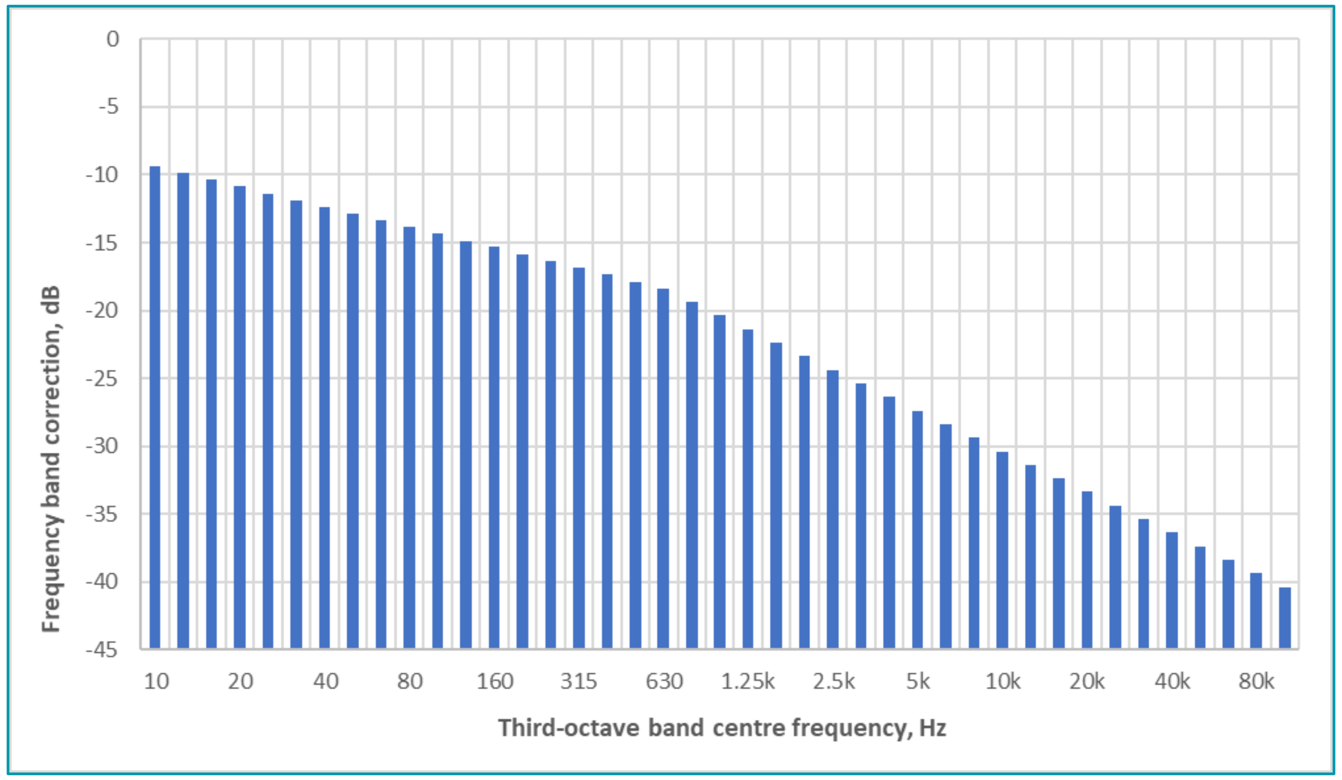

Figure 6.4: Assumed Explosive Spectrum Shape Used to Estimate Hearing Weighting Corrections to SEL

141. In order to compare to 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 (see Figure 6.4) 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.

6.5.2. LOW ORDER TECHNIQUES

142. According to Robinson *et al*. (2020), low order 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 as long as the size of the shaped charge is known.

143. Noise modelling for low order techniques (such as deflagration) has therefore been based on the methodology described in section 5.3 for detonations, using a smaller donor charge size.

7. SOUND MODELLING RESULTS

7.1. PRE-CONSTRUCTION PHASE

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

145. The potential ranges presented for injury and disturbance are not a hard and fast 'line' where an impact will occur on one side and not on the other. Potential impact is more probabilistic than that; dose dependency in PTS onset, individual variations and uncertainties regarding behavioural response and swim speed/direction all mean that it is much more complex than drawing a contour around a location. These ranges are designed to provide an understandable way in which a wider audience can appreciate the potential spatial extent of the impact.

7.1.2. GEOPHYSICAL SURVEYS

146. Geophysical surveying includes many sonar based operations and the resulting injury and disturbance ranges for marine mammals are presented in Table 7.1, based on a comparison to the non-impulsive thresholds set out in Southall *et al.* (2019). Table 7.2 presents the results for geotechnical investigations. CPT injury ranges are based on a comparison to the Southall *et al*. (2019) thresholds for impulsive sound (with the peak injury range presented in brackets if exceeded) 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.

147. 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-based surveys, many of the injury ranges are limited to approximately 65 m as this is the approximate water depth in the area. Sonar based systems have very strong directivity which effectively means that there is only potential for injury when a marine mammal is directly underneath the sound source. Once the animal moves outside of the main beam, there is no 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. For this reason, many of the TTS and PTS ranges are similar (i.e. limited by the depth of the water).

Table 7.1: 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	65	20	65	65	160	70	65	40	35	5	865
SSS	65	65	70	65	300	100	65	65	65	60	675
SBES	65	60	65	65	105	65	65	65	65	15	735
SBP (chirp/pinger)	70	65	245	65	1,190	360	75	65	65	65	2,045
UHRS	55	N/E	N/E	N/E	70	15	10	N/E	N/E	N/E	585

Table 7.2: Potential Impact Ranges for Geotechnical Site Investigation Activites 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	20 m
Core penetration testing	105	5	10	N/E	765 (26)	60 (12)	40	N/E	N/E	N/E	1.5 km (mild) 169 m (strong)
Vibro-coring	N/E	N/E	N/E	N/E	310	N/E	N/E	N/E	N/E	N/E	7,459 m

7.1.3. VESSELS

148. The potential impact ranges for vessels are included in section 7.4, which summarises the vessel modelling results for all phases of the development.

7.1.4. UXO CLEARANCE

Low order disposal

149. The Applicant has committed to using low order techniques for UXO clearance. The predicted injury ranges for low order disposal are presented in Table 7.3 and Table 7.4 whereas the predicted ranges for the clearance shot to remove any residual explosive material from the seabed are shown in Table 7.5 and Table 7.6.

150. All UXO injury and disturbance ranges are based on a comparison to the relevant impulsive sound thresholds as set out in section 4.

Table 7.3: Injury Ranges for Marine Mammals due to Detonation of 0.08 kg Donor Charge (Low Order Disposal)

Group	PTS Range				TTS Range			
	SPL Peak		SEL (Weighted)		SPL Peak		SEL (Weighted)	
	Threshold	Range (m)	Threshold	Range (m)	Threshold	Range (m)	Threshold	Range (m)
LF	*219*	120	*183*	80	*213*	225	*168*	1,110
HF	*230*	40	*185*	5	*224*	75	*170*	40
VHF	*202*	685	*155*	310	*196*	1,265	*140*	2,015
PCW	*218*	135	*185*	15	*212*	250	*170*	210
OCW	*232*	30	*203*	N/E	*226*	60	*188*	10

Table 7.4: Injury Ranges for Fish due to Detonation of 0.08 kg Donor Charge (Low Order Disposal)

Group	Mortality		Recoverable Injury	TTS
	Threshold	Range (m)		
Group 1 fish	*229 - 234*	30 - 45	(*Near*) High (Intermediate) Low (*Far*) Low	(*Near*) High (Intermediate) Moderate (*Far*) Low
Group 2 fish	*229 - 234*	30 - 45	(*Near*) High (Intermediate) High (*Far*) Low	(*Near*) High (Intermediate) Moderate (*Far*) Low
Group 3 and 4 fish	*229 - 234*	30 - 45	(*Near*) High (Intermediate) High (*Far*) Low	(*Near*) High (Intermediate) High (*Far*) Low
Sea turtles	*229 - 234*	30 - 45	(*Near*) High (Intermediate) Low (*Far*) Low	(*Near*) High (Intermediate) Moderate (*Far*) Low

Table 7.5: Injury Ranges for Marine Mammals due to Detonation of 0.5 kg Clearance Shot

Group	PTS Range				TTS Range			
	SPL Peak		SEL (Weighted)		SPL Peak		SEL (Weighted)	
	Threshold	Range (m)	Threshold	Range (m)	Threshold	Range (m)	Threshold	Range (m)
LF	*219*	225	*183*	195	213	415	168	2,645
HF	*230*	75	*185*	5	224	135	170	95
VHF	*202*	1,265	*155*	650	196	2,325	140	3,110
PCW	*218*	250	*185*	40	212	455	170	505
OCW	*232*	60	*203*	5	226	110	188	25

Table 7.6: Injury Ranges for Fish due to Detonation of 0.5 kg Clearance Shot

Group	Mortality		Recoverable Injury	TTS
	Threshold	Range (m)		
Group 1 fish	*229 - 234*	50 - 80	(*Near*) High (Intermediate) Low (*Far*) Low	(*Near*) High (Intermediate) Moderate (*Far*) Low
Group 2 fish	*229 - 234*	50 - 80	(*Near*) High (Intermediate) High (*Far*) Low	(*Near*) High (Intermediate) Moderate (*Far*) Low
Group 3 and 4 fish	*229 - 234*	50 - 80	(*Near*) High (Intermediate) High (*Far*) Low	(*Near*) High (Intermediate) High (*Far*) Low
Sea turtles	*229 - 234*	50 - 80	(*Near*) High (Intermediate) Low (*Far*) Low	(*Near*) High (Intermediate) Moderate (*Far*) Low

Detonation – high order disposal

151. There is a small chance that the use of low order techniques (such as deflagration) could end up resulting in a high order detonation event. The predicted injury ranges for marine mammals and fish are shown in Table 7.7 and Table 7.8 for a realistic worst case 300 kg UXO detonation. It should be noted that, due to a combination of dispersion (i.e. where the waveform elongates), multiple reflections from the sea surface and bottom and molecular absorption of high frequency energy, the sound 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 7.7: Potential Injury Ranges for Marine Mammals due to High Order Detonation of 300 kg UXO

Group	PTS Range				TTS Range			
	SPL Peak		SEL (Weighted)		SPL Peak		SEL (Weighted)	
	Threshold	Range (m)	Threshold	Range (m)	Threshold	Range (m)	Threshold	Range (m)
LF	*219*	1,885	*183*	4,175	*213*	3,470	*168*	34,135
HF	*230*	615	*185*	150	*224*	1,130	*170*	1,370
VHF	*202*	10,630	*155*	3,805	*196*	19,590	*140*	8,900
PCW	*218*	2,085	*185*	790	*212*	3,840	*170*	6,430
OCW	*232*	505	*203*	40	*226*	925	*188*	500

Table 7.8: Potential Injury Ranges for Fish due to High Order Detonation of 300 kg UXO

Group	Mortality		Recoverable Injury	TTS
	Threshold	Range (m)		
Group 1 fish	*229 - 234*	410 - 680	(*Near*) High (Intermediate) Low (*Far*) Low	(*Near*) High (Intermediate) Moderate (*Far*) Low
Group 2 fish	*229 - 234*	410 - 680	(*Near*) High (Intermediate) High (*Far*) Low	(*Near*) High (Intermediate) Moderate (*Far*) Low
Group 3 and 4 fish	*229 - 234*	410 - 680	(*Near*) High (Intermediate) High (*Far*) Low	(*Near*) High (Intermediate) High (*Far*) Low
Sea turtles	*229 - 234*	410 - 680	(*Near*) High (Intermediate) Low (*Far*) Low	(*Near*) High (Intermediate) Moderate (*Far*) Low

7.2. CONSTRUCTION PHASE

152. The construction phase of operations contains some of the loudest possible types of noise sources (including impact piling operations) and a range of vessels to support these activities.

153. Results are provided for piling of wind turbine foundations including maximum energy piling, a realistic maximum energy piling and piling of OSP/Offshore convertor station platform foundations, simultaneous pile installation by two vessels of wind turbine foundations at maximum energy piling and realistic maximum energy, and construction vessel noise (see section 5.7).

7.2.1. IMPACT PILING

154. The impact piling scenarios modelled were as follows:

- single piling rig – Wind turbine foundations - Maximum design scenario (4,000 kJ);
- single piling rig – Wind turbine foundations - Realistic design scenario (3,000 kJ);
- single piling rig - OSP/Offshore convertor station platform foundations - Maximum design scenario (4,000 kJ);
- two rigs concurrent piling – Wind turbine foundations - Maximum design scenario (4,000 kJ); and
- two rigs concurrent piling – Wind turbine foundations - Realistic design scenario (3,000 kJ).

155. As described in section 5.4.1, all source sound levels have been calculated based on a conversion factor of 4% reducing to 0.5%.

156. There is a possibility that during the piling operations it will be necessary for two pile installation vessels to operate concurrently. For the concurrent piling scenarios, two separate maximum adverse case assumptions were identified, as follows:

- separation distance of 1 km (the minimum distance between foundations) as a maximum adverse scenario for injury; and
- separation distance of 42.9 km as a maximum adverse scenario for disturbance.

157. The reason the maximum adverse scenario assumptions for injury and disturbance differ is that the scenario which results in the greatest potential for injury is when two rigs are operating in close proximity, meaning that the animal is exposed to sound from both rigs at relatively high levels. Conversely, the maximum area of disturbance occurs when both rigs are operating at a further distance apart in the AfL and their disturbance ranges are just overlapping. For the latter case, the maximum adverse scenario is not necessarily the greatest possible separation distance and piles wind turbine 1 and wind turbine 179 and piles wind turbine 40 and wind turbine 135 were chosen as representative as the combined maximum adverse scenario in terms of separation distance and bathymetry.

158. All impact piling injury and disturbance ranges are based on a comparison to the relevant impulsive sound thresholds as set out in section 4.

159. The injury ranges for peak sound pressure are based on the first strike the animal experiences at the closest point during each phase of the pile installation. Consequently, the peak pressure ranges for simultaneous piling do not differ from the peak injury ranges identified for single rigs.

160. Injury ranges for marine mammals due to impact pile driving for the “realistic” and “maximum” pile driving schedule for the 24 MW option, and for the piling of the OSP/Offshore convertor station platform are summarised in Table 7.9.

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

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

points out that *"…it should be recognized that the use of impulsive exposure criteria for receivers at greater ranges (tens of kilometers) is almost certainly an overly precautionary interpretation of existing criteria"*.

163. Consequently, great caution should be used when interpreting any results with predicted injury ranges in the order of tens of kilometres. Further discussion on this topic is provided in the technical note in volume 3, appendix 10.1, annex D.

Table 7.9: Injury and Disturbance Ranges Based on the Cumulative SEL Metric for Marine Mammals due to Impact Pile Driving for the "Realistic" and "Maximum" Pile Driving for Wind Turbine Jacket Foundations, and for the Piling of the OSP/Offshore Convertor Station Platform Jackets

Species/Group	Threshold (Weighted SEL)	Range (m)		
		Wind Turbine - Max Energy	Wind Turbine - Realistic Energy	OSP/Offshore Convertor Station Platform
LF	PTS - 183 dB re 1 µPa²s	1,000	707	1,000
	TTS - 168 dB re 1 µPa²s	28,700	23,400	27,500
HF	PTS - 185 dB re 1 µPa²s	N/E	N/E	N/E
	TTS - 170 dB re 1 µPa²s	33	26	33
VHF	PTS - 155 dB re 1 µPa²s	286	223	285
	TTS - 140 dB re 1 µPa²s	8,500	6,900	8,300
PCW	PTS - 185 dB re 1 µPa²s	47	35	47
	TTS - 170 dB re 1 µPa²s	3,200	2,200	2,800
OCW	PTS - 203 dB re 1 µ Pa²s	N/E	N/E	N/E
	TTS - 188 dB re 1 µPa²s	18	N/E	18
Behavioural disturbance	Mild - 140 dB re 1 µPa (rms)	43,000	38,000	43,000
	Strong - 160 dB re 1 µPa (rms)	5,100	4,400	5,100

164. All ranges presented are the 95th percentile across the bearings modelled. These results are identical to the given accuracy for the "maximum" and the "realistic" pile driving schemes. The schemes only differ by the final full power section, which is one hour longer in the "maximum" scenario. This identical result is due to the flight model, with the pile driving period being six hours after the start of piling.

165. The injury ranges for marine mammals based on peak pressure are summarised in Table 7.10. These ranges represent the potential zone for instantaneous injury. The injury ranges are based on the first strike the animal experiences, and is therefore highly dependent upon the hammer energy, but independent of piling duration. As such, the ranges are presented for both PTS and TTS by each stage of the piling, but as piling energies are consistent across all three scenarios (wind turbine maximum energy, realistic energy and OSP/Offshore convertor station platform) the peak pressure ranges will also be the same across all three scenarios. It is therefore assumed that, although the piling and full power piling phases have larger injury ranges, the animal would have moved out of the ranges at the time those hammer energies are used. It should be noted that the peak SPLs were calculated on a 20 m grid spacing meaning that the results are presented to the nearest 20 m. Since the reported distance is the first "bin" where the peak SPL is below the threshold, any ranges of 20 m are in reality likely to be lower than this and possibly not exceeded. In this respect it is important to understand that a pile is a large and distributed source and therefore reporting injury ranges that are smaller than the physical size of the pile based on a point source sound level assumption (i.e. assumption of an infinitesimally small source size) could result in an overestimation of injury range.

Table 7.10: Summary of Peak Pressure Injury Ranges for Marine Mammals due to the Phase of Impact Piling Resulting in the Maximum Peak Sound Pressure Level, for Wind Turbine Foundations ("Maximum" and "Realistic" Scenarios) and OSP/Offshore Convertor Station Platform Foundations

Species/Group	Threshold (Unweighted Peak)	Range (m)	
		Wind Turbine - Max Energy and OSP/Offshore Convertor Station Platform	Wind Turbine - Realistic Energy
LF	PTS - 219 dB re 1 µPa (pk)	83	72
	TTS - 213 dB re 1 µPa (pk)	138	119
HF	PTS - 230 dB re 1 µPa (pk)	33	29
	TTS - 224 dB re 1 µPa (pk)	55	47
VHF	PTS - 202 dB re 1 µPa (pk)	346	298
	TTS - 196 dB re 1 µPa (pk)	568	490
PCW	PTS - 218 dB re 1 µPa (pk)	91	78
	TTS - 212 dB re 1 µPa (pk)	150	129
OCW	PTS - 232 dB re 1µ Pa (pk)	28	24
	TTS - 226 dB re 1 µPa (pk)	46	40

166. The results of the noise modelling for fish and turtles are shown in Table 7.11 based on the cumulative sound exposure level thresholds, and in Table 7.12 based on the peak sound pressure thresholds. The tables show two results for Group 1 Fish, one based on the 0.5 m/s and another (in square brackets) showing the range for basking sharks using a higher swim speed of 1 m/s. Similarly, sea turtles have been assumed to swim at a speed of 0.5 m/s whereas fish eggs and larvae have been assumed to be static, resulting in a different potential impact range to reach the same numerical SEL criteria.

Table 7.11: Injury Ranges for Fish Based on the Cumulative SEL Metric due to Impact Pile Driving for the "Realistic" and "Maximum" Pile Driving for Wind Turbine Jacket Foundations, and for the Piling of the OSP/Offshore Convertor Station Platform Jackets based on the Cumulative SEL Metric

Hearing Group	Response	Threshold (SEL, dB re 1 µPa²s)	Range (m)		
			Wind turbine Max Energy	Wind turbine Realistic Energy	OSP/Offshore Convertor Station Platform
Group 1 Fish: No swim bladder (particle motion detection) – [*basking shark ranges shown in square brackets*].	Mortality	219	N/E	N/E	N/E
	Recoverable injury	216	N/E	N/E	N/E
	TTS	186	4,161 [2,219]	3,183 [1,609]	3,943 [2,165]
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	19	N/E	19
	Recoverable injury	203	67	53	67
	TTS	186	4,161	3,183	3,943
	Mortality	207	33	26	33
	Recoverable injury	203	67	53	67

Hearing Group	Response	Threshold (SEL, dB re 1 µPa²s)	Range (m)		
			Wind turbine Max Energy	Wind turbine Realistic Energy	OSP/Offshore Convertor Station Platform
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	TTS	186	4,161	3,183	3,943
Sea turtles	Mortality	210	19	N/E	19
Fish eggs and larvae (static)	Mortality	210	495	400	439

Table 7.12: Summary of Peak Pressure Injury Ranges for Fish due to the Phase of Impact Piling Resulting in the Maximum Peak Sound Pressure Level, for Both Wind Turbine Foundations and OSP/Offshore Convertor Station Platform Foundations Based on the Peak Pressure Metric

Hearing Group	Response	Threshold (SPL_{pk}, dB re 1 µPa)	Range (m)	
			Wind Turbine - Max Energy and OSP/Offshore Convertor Station Platform	Wind Turbine - Realistic Energy
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	213	138	119
	Recoverable injury	213	138	119
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	207	228	196
	Recoverable injury	207	228	196
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	228	196
	Recoverable injury	207	228	196
Sea turtles	Mortality	207	228	196
Fish eggs and larvae	Mortality	207	228	196

167. The disturbance range for fish, given by the 150 dB re 1 µPa SPL_{rms} contour is 17 km for single pile driving.

168. The maximum design scenario was also modelled with the use of and ADD for 30 minutes prior to commencement of piling, the results of which are provided in Table 7.13 for cumulative SEL, and in Table 7.14 for peak sound level.

Table 7.13: Injury Ranges Based on the Cumulative SEL Metric for Marine Mammals due to Impact Pile Driving for the "Maximum" Pile Driving for Wind Turbine Jacket Foundations with and without 30 Minutes of ADD

Species/Group	Threshold (Weighted SEL)	Range (m)	
		Without ADD	With ADD
LF	PTS - 183 dB re 1 µPa²s	1,000	N/E
	TTS - 168 dB re 1 µPa²s	28,700	24,500
HF	PTS - 185 dB re 1 µPa²s	N/E	N/E
	TTS - 170 dB re 1 µPa²s	33	N/E
VHF	PTS - 155 dB re 1 µPa²s	286	N/E
	TTS - 140 dB re 1 µPa²s	8,500	5,800
PCW	PTS - 185 dB re 1 µPa²s	47	N/E
	TTS - 170 dB re 1 µPa²s	3,200	N/E
OCW	PTS - 203 dB re 1 µ Pa²s	N/E	N/E
	TTS - 188 dB re 1 µPa²s	18	N/E

169. As can be seen from Table 7.13, the use of an ADD is effective in reducing all PTS injury ranges to a level not exceeding the thresholds, but has less beneficial benefit in reducing potential TTS ranges. This is because for the longer ranges associated with TTS, the distance the animal can swim during the 30 minutes of ADD activation is small compared to the overall potential range of TTS from the piling location.

170. The potential injury ranges due to the peak sound level metric will remain the same regardless of whether an ADD is used. However, if the animal is able to swim outside of the peak injury range during the period of ADD activation, the peak thresholds will not be exceeded.

Table 7.14: Summary of Peak Pressure Injury Ranges for Marine Mammals due to Each Phase of Impact Piling for Wind Turbine Foundations "Maximum" Scenario: Showing Whether the Key Mammal Species can Flee the Injury Range During the Period of ADD

Species/ Group	Threshold (Unweighted Peak)	Range (m) Wind Turbine Max Energy	Swim Speed (m/s)	Swim Distance (m)	Flee
LF	PTS - 219 dB re 1 µPa (pk)	83	2.3	4,140	Yes
	TTS - 213 dB re 1 µPa (pk)	138			Yes
HF	PTS - 230 dB re 1 µPa (pk)	33	1.52	2,736	Yes
	TTS - 224 dB re 1 µPa (pk)	55			Yes
VHF	PTS - 202 dB re 1 µPa (pk)	346	1.5	2,700	Yes
	TTS - 196 dB re 1 µPa (pk)	568			Yes
PCW	PTS - 218 dB re 1 µPa (pk)	91	1.8	3,240	Yes
	TTS - 212 dB re 1 µPa (pk)	150			Yes
OCW	PTS - 232 dB re 1µ Pa (pk)	28	1.5	2,700	Yes
	TTS - 226 dB re 1 µPa (pk)	46			Yes

171. From Table 7.14 it can be seen that although the peak injury ranges do not change due to the use of an ADD, the use does give animals time to swim out with the potential injury range prior to the commencement of piling.

Noise contours

172. The potential noise contours (every 5 dB) for single strike SEL for a single piling event at all locations shown in Figure 6.2 are provided in volume 3, appendix 10.1, annex E.

173. The areas contained within the 140 and 160 dB re 1 µPa (rms) contours (equating to the NMFS mild and strong disturbance ranges) are shown in Table 7.15.

Table 7.15: Disturbance Areas for Marine Mammals due to Impact Pile Driving at One Location

Species/Group	Threshold (Weighted SEL)	Area (km^2)
		Wind Turbine – Maximum Scenario
Marine Mammal Behavioural Disturbance	Mild - 140 dB re 1 µPa (rms)	6,735
	Strong - 160 dB re 1 µPa (rms)	135

Two piling vessels operating concurrently

174. There is a possibility that during the piling operations it will be necessary for two pile installation vessels to operate concurrently. The potential cumulative SEL injury ranges for marine mammals due to impact pile driving for the "realistic" and "maximum" pile driving schedule are summarised in Table 7.16, along with the mild and strong disturbance ranges based on rms sound pressure levels. Here the piles are modelled as following the same piling plans with all phases starting at the same time. For injury a worse case is considered to be that of two adjacent piles, separated by a distance of 2.2 km due to the maximal overlap of sound propagation contours leading to the maximum generated sound 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.

Table 7.16: Injury and Disturbance Ranges Based on the Cumulative SEL Metric for Marine Mammals due to Impact Pile Driving at Two Locations Concurrently, for the "Realistic" and "Maximum" Pile Driving for Wind Turbine Jacket Foundations

Species/Group	Threshold (Weighted SEL)	Range (m)	
		Wind Turbine – Maximum Scenario	Wind Turbine - Realistic Scenario
LF	PTS - 183 dB re 1 µPa²s	2,300	1,600
	TTS - 168 dB re 1 µPa²s	42,900	36,000
HF	PTS - 185 dB re 1 µPa²s	N/E	N/E
	TTS - 170 dB re 1 µPa²s	35	27
VHF	PTS - 155 dB re 1 µPa²s	439	307
	TTS - 140 dB re 1 µPa²s	13,300	11,000
PCW	PTS - 185 dB re 1 µPa²s	53	38
	TTS - 170 dB re 1 µPa²s	6,700	5,000
OCW	PTS - 203 dB re 1 µ Pa²s	N/E	N/E
	TTS - 188 dB re 1 µPa²s	20	14
Mammal Behavioural Disturbance	Mild - 140 dB re 1 µPa (rms)	54,800	49,000
	Strong - 160 dB re 1 µPa (rms)	6,900	6,000

175. The ranges for mortality and recoverable injury for the groups of fish and sea turtles do not change between single and double pile driving. This is because the injury range at distances close to the pile are dominated by energy from the closest pile, with little influence from the pile which is further away. For example, if the pulse SEL due to the nearest pile was 200 dB re 1 µPa²s and the SEL from the further pile was 190 dB re 1 µPa²s (i.e. 10 dB difference), then the cumulative SEL from both piles would only be 200.4 dB re 1 µPa²s. If the difference between SEL levels was 20 dB then the cumulative SEL of both pulses would only be 200.04 dB re 1 µPa²s. Consequently, it is only for injury ranges which are of a similar or greater magnitude to the separation distance between piles that a significant change in injury range will be derived for the simultaneous piling scenario. It should be noted that this assumes that the animal does not swim directly towards the furthest pile in order to end up at a close range to that pile having left the injury range of the original pile.

176. The TTS range for fish and basking sharks for simultaneous pile driving for close foundations is given in Table 7.17. The disturbance range for fish, given by the 150 dB re 1 µPa SPL RMS contour is 23 km for simultaneous pile driving.

Table 7.17: TTS Injury Ranges based on the Cumulative SEL Metric for Fish due to Impact Pile Driving at Two Locations Concurrently, for the "Realistic" And "Maximum" Pile Driving for Wind Turbine Jacket Foundations Based on the Cumulative SEL Metric

Hearing group	Response	Threshold (SEL, dB re 1 µPa²s)	Range (km)	
			Wind Turbine Max Energy	Wind Turbine Realistic Energy
Group 1 Fish: No swim bladder (particle motion detection) – [*basking shark ranges shown in square brackets*].	TTS	186	7.1 [4.3]	5.6 [3.3]
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	TTS	186	7.1	5.6
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	TTS	186	7.1	5.6

177. Contours for single strike SEL for simultaneous piling at two piling locations (adjacent wind turbines 1 and 179 and wind turbines 40 and 135) are provided in volume 3, appendix 10.1, annex F.

178. The maximum design scenario was also modelled for concurrent piling in the presence of 30 minutes of ADD use, the results of which are shown in Table 7.18 for the potential impact of cumulative SEL. The potential impact of peak sound level on marine mammals will remain the same as the single piling case, as it did for the scenarios without ADD.

Table 7.18: Injury Ranges for Marine Mammals due to Impact Pile Driving at Two Locations Concurrently for the "Maximum" Pile Driving for Wind Turbine Jacket Foundations with and Without 30 Minutes of ADD

Species/ Group	Threshold (Weighted SEL)	Range (m)	
		Without ADD	With ADD
LF	PTS - 183 dB re 1 µPa²s	2,300	N/E
	TTS - 168 dB re 1 µPa²s	42,900	38,800
HF	PTS - 185 dB re 1 µPa²s	N/E	N/E
	TTS - 170 dB re 1 µPa²s	35	N/E
VHF	PTS - 155 dB re 1 µPa²s	439	N/E
	TTS - 140 dB re 1 µPa²s	13,300	10,600
PCW	PTS - 185 dB re 1 µPa²s	53	N/E
	TTS - 170 dB re 1 µPa²s	6,700	3,500
OCW	PTS - 203 dB re 1 µ Pa²s	N/E	N/E
	TTS - 188 dB re 1 µPa²s	20	N/E

179. As can be seen from Table 7.13, the use of ADD is useful for reducing all PTS injury ranges to a level not exceeding the thresholds, but has little impact on many of the TTS levels. This is because for these long distances the distance the mammal can swim during these 30 minutes is short compared to the overall distance from the piling.

7.2.2. DRILLED PILING

180. The potential impact ranges for drilled piling are small (or not exceeded) for all marine mammal species groups, due to the low broadband SEL levels expected from these operations, at 160 dB re 1 µPa²s (see Table 7.19). The behavioural threshold range for all marine mammal groups is also report.

Table 7.19: Potential Impact Ranges (m) for Marine Mammal Exposed to Drilled Piling

Source	Potential Impact Ranges (m)										
	LF		HF		VHF		PCW		OCW		All
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Behaviour
Drilled piling	N/E	N/E	N/E	N/E	10	N/E	N/E	N/E	N/E	N/E	1,900

181. The ranges for recoverable injury and TTS for Group 3 and 4 Fish are presented in Table 7.20 based on the thresholds contained in Popper *et al.* (2014). It should be noted that fish would need to be exposed within these potential impact ranges for a period of 48 hours continuously in the case of recoverable injury and 12 hours continuously in the case of TTS for the effect to occur. It is therefore considered that these ranges are highly precautionary, and injury is unlikely to occur in reality.

Table 7.20: Median Potential Impact Ranges (m) for Group 3 and 4 Fish Exposed to Drilled Piling

Source	Recoverable Injury	TTS
	170 dB rms for 48 hrs	158 dB for 12 hrs
Drilled piling	<20	100

7.2.3. OTHER OPERATIONS

182. 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 7.21. The potential impact ranges for fish are presented in Table 7.22.

Table 7.21: 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	2,580
Cable laying	N/E	N/E	45	N/E	740	N/E	N/E	N/E	N/E	N/E	4,389
Jack-up rig	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	300

Table 7.22: Median Potential Impact Ranges (m) for Group 3 and 4 Fish Exposed to Other Construction Related Operations

Source	Injury Zone Radius (m)	
	Recoverable Injury	TTS
	170 dB rms for 48 hrs	158 dB rms for 12 hrs
Cable trenching	<20	1,260
Cable laying	40	400
Jack-up rig	<20	150

7.2.4. VESSELS

183. The potential impact ranges for vessels are included in section 7.4, which summarises the vessel modelling results for all phases of the development.

7.3. OPERATION AND MAINTENANCE PHASE

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

185. 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.

186. The distances and exposures of mammals and fish reported by studies that investigate the potential 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 7.23. The authors found a slight increase in SPL compared to the ambient noise measured before the construction of the wind farms. They concluded that even the highest increases found within the dataset (20 to 25 dB re 1µ Pa) are unlikely to cause a significant potential 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 potential long-term impacts to aquatic life.

Table 7.23: Desktop Study of Operational Noise from Wind Turbines

Paper	Wind Turbine	Foundation Type	Location	Notes
Betke, 2006	Vestas V80-2 MW 70 m hub height	Monopiles	Horns Rev	118 dB re 1 µPa @ 150 Hz
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 V80-2MW 68 m hub height	Steel monopiles 4.8 m diameter	Scroby Sands	Inside wind farm 130 dB re. 1 µPa Outside 132 dB re. 1 µPa States that the background level is higher inside the wind farm, perhaps due to shallow water No tonal component
	Vestas V90-3 MW 70 m hub height	Monopiles	Kentish Flats	Inside wind farm 114 dB re. 1 µPa Outside 113 dB re. 1 µPa Clear tonal components dependent upon separation
	Vestas V90-3 MW 75 m hub height	Steel monopiles 4.75 m diameter	Barrow	Inside wind farm 124 dB re. 1 µPa Outside 122 dB re. 1 µPa No tonal components. No consistent relationship between distance and level, thought due to wind noise
Norro *et al*., 2011	Senvion (Repower) 5 MW 95 m hub height	Gravity base	Thorntonbank	Increase of 8 dB above background
	Vestas V90-3 MW 72 m hub height	Steel monopile foundations	Belwind Bligh Bank	Increase of 20 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

187. The potential impact ranges for the maintenance noise source are reported in Table 7.24 and Table 7.25.

Table 7.24: Potential Impact Ranges (m) for Marine Mammal Groups from other Maintenance Operations

Source	Potential Impact Range (m)										
	LF		HF		VHF		PCW		OCW		All
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
Jet cutting	80	N/E	N/E	N/E	735	N/E	N/E	N/E	N/E	N/E	24,965
Anchor handling vessel	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	1,100
Installation vessel, construction vessel (DP)	N/E	N/E	N/E	N/E	625	N/E	N/E	N/E	N/E	N/E	4,320
Rock placement vessel	N/E	N/E	N/E	N/E	625	N/E	N/E	N/E	N/E	N/E	4,320
Survey vessel and support vessels	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	2,980
Misc. small vessel (e.g. tugs, vessels carrying ROVs, crew transfer vessels, dive boats, barges and RIBs)	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	1,100

Source	Potential Impact Range (m)										
	LF		HF		VHF		PCW		OCW		All
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
Excavator, Backhoe dredger, Pipe laying, Geophysical survey vessel, jack up vessel	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	300

Table 7.25: Median Potential Impact Ranges (m) for Groups 3 and 4 Fish

Source	Injury Zone Radius (m)	
	Recoverable Injury	TTS
	170 dB rms for 48 hrs	158 dB rms for 12 hrs
Jet cutting	80	140

7.3.1. VESSELS

188. Vessels employed during the operation and maintenance phase are likely to be similar in size and noise signature to those employed in the construction phase. This includes for operations such as jack-up vessels, cable installation (repair) vessels and Crew Transfer Vessels (CTVs). Jack-up vessels and cable repair vessels will be used to facilitate any component replacement works or cable repair/remediation works. CTVs are likely to be required on a day to day basis for routine inspection and maintenance activities. Vessel noise associated with operation and maintenance activities is likely to similar in nature to activities at other parts of the survey.

189. The potential impact ranges for vessels are included in section 7.4, which summarises the vessel modelling results for all phases of the development.

7.4. VESSEL NOISE

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

191. 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.

192. 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 7.26. The exposure metrics for different marine mammal and flee speeds (as detailed in section 6.4) were employed.

Table 7.26: Estimated PTS and TTS Ranges from Different Vessels for Marine Mammals

Source/Vessel	Range (m)										
	LF		HF		VHF		PCW		OCW		All
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
Anchor handling vessel	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	1,100
Installation vessel, construction vessel (DP)	N/E	N/E	N/E	N/E	625	N/E	N/E	N/E	N/E	N/E	4,320
Rock placement vessel	N/E	N/E	N/E	N/E	625	N/E	N/E	N/E	N/E	N/E	4,320
Survey vessel and support vessels	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	2,980
Misc. small vessel (e.g. tugs, vessels carrying ROVs, crew transfer vessels, dive boats, barges and RIBs)	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	1,100
Excavator, Backhoe dredger, Pipe laying, Geophysical survey vessel, jack up vessel	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	300

193. The ranges for recoverable injury and TTS for Groups 3 and 4 Fish are presented in Table 7.27 based on the thresholds contained in Popper *et al.* (2014). It should be noted that fish would need to be exposed within these potential impact ranges for a period of 48 hours continuously in the case of recoverable injury and 12 hours continuously in the case of TTS for the effect to occur. It is therefore considered that these ranges are highly precautionary, and injury is unlikely to occur in reality.

Table 7.27: 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 rms for 48 hrs	158 dB rms for 12 hrs
Anchor handling vessel, Survey vessel, Support vessels	<20	<20
Installation vessel, construction vessel (DP)	30	40
Rock placement vessel	30	40
Misc. small vessel (e.g. tugs, vessels carrying ROVs, crew transfer vessels, dive boats, barges and RIBs)	<20	<20
Excavator, Backhoe dredger, Pipe laying, Geophysical survey vessel, jack up vessel	<20	<20

8. SUMMARY

194. Noise modelling has been undertaken to determine the range of potential effects on marine mammals, fish, and sea turtles due to noise from piling activities associated with construction of the Proposed Development. The results are summarised in Table 8.1 which shows the maximum injury range for each group of mammals, fish, and sea turtles, for individual and simultaneous piling (the worst-case scenario of cumulative SEL or peak). The potential PTS impact range is typically dominated by nearest pile, so these ranges don't change for single or simultaneous pile driving (except for LF cetaceans).

Table 8.1: Summary of Maximum PTS Injury Ranges for Marine Mammals, and Mortality for Fish, and Turtles due to Impact Piling of a Single Pile Based on Highest Range of Peak Pressure or SEL (N/E = Threshold Not Exceeded)

Species Group	Range (m)				
	Wind Turbine - Max Energy	Wind Turbine - Realistic Energy	OSP/Offshore Convertor Station Platform	Concurrent Piling - Wind Turbine - Max Energy	Concurrent Piling - Wind Turbine - Realistic Energy
Marine Mammals					
Low frequency cetacean	1,030	707	1,023	2,319	1,556
High frequency cetacean	33	29	33	33	29
Very high frequency cetacean	346	298	346	439	307
Phocid carnivores	91	78	91	91	78
Other carnivores	28	24	28	28	24
Fish, Eggs/Larvae, Turtles					
Group 1 Fish: no swim bladder	138	119	138	138	119
Group 2 Fish: where swim bladder is not involved in hearing	228	196	228	228	196
Group 3 to 4 Fish: where swim bladder is involved in hearing	228	196	228	228	196
Sea turtles	228	196	228	228	196
Eggs and larvae	495	542	439	708	571

195. Underwater noise emissions from the wind turbines, other relevant operational noises, and vessels during the operation and maintenance phase are unlikely to be at a level sufficient to cause injury or behavioural changes to marine mammals, fish, or sea turtles.

196. The use of ADD means that no PTS injury thresholds are exceeded for marine mammals.

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