Pembroke Dock Infrastructure

Underwater Noise Assessment

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Quality Management

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Tables

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1 Introduction

1.1 This report presents the results of a desktop appraisal considering the potential effects of underwater noise on the marine environment from construction of the proposed development at Pembroke Port, known as Pembroke Dock Infrastructure.

1.2 Noise is readily transmitted underwater and there is potential for sound emissions from the construction of the project to affect marine mammals and fish. It is considered that the key issues will be the effects of underwater noise on marine mammals and fish from the following activities:

- pre-construction dredging within the footprint of the new slipway using a back-hoe dredger; and
- construction of the new jetty structure including vibratory and impact piling of sheet piles.

1.3 This report provides an overview of the potential effects due to underwater noise from the project on the surrounding marine environment. The results from this underwater noise assessment will be used to inform the marine mammal and fish impact assessment within the Environmental Statement (ES) in order to determine the potential impact of underwater noise on marine life. Consequently, the primary purpose of the underwater noise assessment is to predict the likely range of onset for potential physiological and behavioural effects due to increased anthropogenic noise due to the construction of the project. The sensitivity of species, magnitude of impact and significance of impact from underwater noise associated with the project are dealt with in the ES (Chapter 6 Marine Ecology and Coastal Processes).

2 Acoustic Concepts and Terminology

2.1 Sound travels through water as vibrations of the fluid particles in a series of pressure waves. The waves comprise a series of alternating compressions (positive pressure variations) and rarefactions (negative pressure fluctuations). Because sound consists of variations in pressure, the unit for measuring sound is usually referenced to a unit of pressure, the Pascal (Pa). The unit usually used to describe sound is the decibel (dB) and, in the case of underwater sound, the reference unit is taken as 1 µPa, whereas 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, a sound pressure of 60 dB re 20 µPa is the same as 86 dB re 1 µPa, although care also needs to be taken when converting from in air noise to in water noise levels due to the different sound speeds and densities of the two mediums resulting in a conversion factor of 62 dB. All underwater sound pressure levels in this report are described in dB re 1 µPa. In water, the sound source strength is defined by its sound pressure level in dB re 1 µPa, referenced back to a representative distance of 1 m from an assumed (infinitesimally small) point source. This allows calculation of sound levels in the far-field. For large distributed sources, the actual sound pressure level in the near-field will be lower than predicted.

2.2 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 the peak to peak (or pk-pk) sound pressure level. The difference between the highest variation (either positive or negative) and the ambient 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. These descriptions are shown graphically in Figure 2.1.

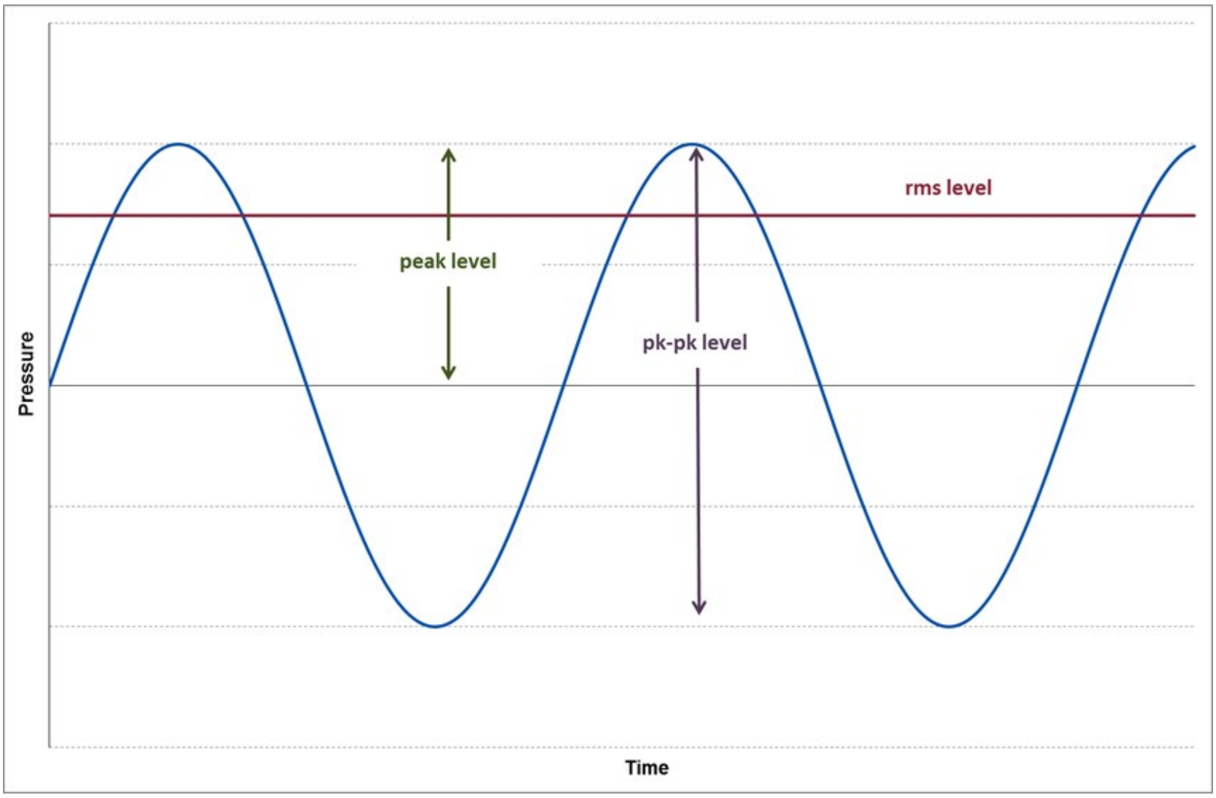

Figure 2.1: Graphical representation of acoustic wave descriptors

2.3 The rms sound pressure level (SPL) is defined as follows:

$$SPL_{rms} = 10log_{10}\left(\frac{1}{T}\int_{0}^{T}\left(\frac{p^2}{p_{ref}^2}\right)dt\right)$$

2.4 Another useful measure of sound used in underwater acoustics is the Sound Exposure Level, or 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. Historically, use was primarily made of rms and peak sound pressure level 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 over a 24 hour period to be taken into account. The SEL is defined as follows:

$$SEL = 10log_{10}\left(\int_{0}^{T}\left(\frac{p^2(t)}{p_{ref}^2 t_{ref}}\right)dt\right)$$

2.5 The frequency, or pitch, of the sound is the rate at which these oscillations occur 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 faculties of marine mammals and fish are not the same as humans, with marine mammals hearing over a wider range of frequencies, fish over a typically smaller range of frequencies and both with different sensitivities. It is therefore important to understand how an animal's hearing varies over the entire frequency range in order to assess the effects of sound on marine life. Consequently, use can be made of frequency weighting scales 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 2.2. 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. It is also worth noting that some fish are sensitive to particle velocity rather than pressure, although paucity of data relating to particle velocity levels for anthropogenic noise sources means that it is often not possible to quantify this effect.

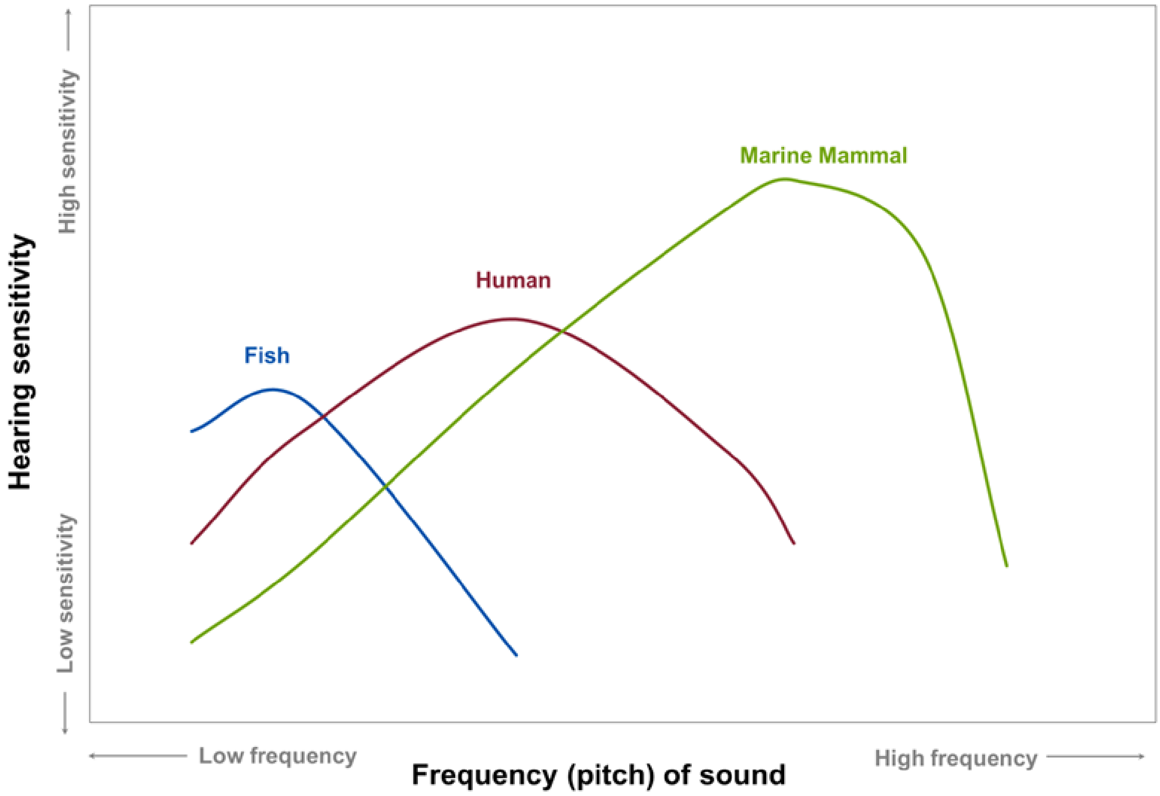

Figure 2.2: Comparison between hearing thresholds of different marine animals and humans.

3 Review of Sound Propagation Concepts

3.1 Increasing the distance from the noise source usually results in the level of noise getting lower, due primarily to the spreading of the sound energy with distance, analogous to the way in which the ripples in a pond spread after a stone has been thrown in.

3.2 The way that the noise spreads will depend upon several factors such as water column depth, pressure, temperature gradients, salinity, as well as water surface and 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.

3.3 In acoustically shallow waters[1] 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 2003, 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).

3.4 At the sea surface, the majority of sound is reflected back in to the water due to the difference in acoustic impedance (i.e. sound speed and density) between air and water. However, scattering of sound at the surface of the sea is an important factor with respect to the propagation of sound from a source. In an ideal case (i.e. for a perfectly smooth sea surface), the majority of sound wave energy will be reflected back into the sea. However, for rough waters, much of the sound energy is scattered (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.

3.5 Because surface scattering results in differences in reflected sound, its effect will be more important at longer ranges from the source sound and in acoustically shallow water (i.e. where

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[1] Acoustically, shallow water conditions exist whenever the propagation is characterised by multiple reflections with both the sea surface and seabed (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.

there are multiple reflections between the source and receiver). The degree of scattering will depend upon the water surface smoothness / wind speed, water depth, frequency of the sound, temperature gradient, grazing angle and range from source. Depending upon variations in the aforementioned factors, significant scattering could occur at sea state 3 or more for higher frequencies (e.g. 15 kHz or more). It should be noted that variations in propagation due to scattering will vary temporally (primarily due to different sea-states / wind speeds at different times) and that more sheltered areas (which are more likely to experience calmer waters) could experience surface scattering to a lesser extent and less frequently than less sheltered areas which are likely to encounter rougher waters. However, over shorter ranges (e.g. a few hundred meters or less) the sound will experience fewer reflections and so the effect of scattering should not be significant. Consequently, taking into account the sheltered location and likely distances over which injury will occur, this effect is unlikely to significantly affect the injury ranges presented in this report, although it is possible that disturbance ranges could vary depending on local and seasonal conditions.

3.6 When sound waves encounter the seabed, the amount of sound reflected will depend on the geoacoustic properties of the seabed (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, seabeds comprising primarily mud or other acoustically soft sediment will reflect less sound than acoustically harder seabeds such as rock or sand. This will also depend on the profile of the seabed (e.g. the depth of the sediment layer and how the geoacoustic properties vary with depth below the sea floor). The effect is less pronounced at low frequencies (a few kHz and below) and so might not be a significant factor to take into account with respect to piling noise (where most of the acoustic energy is at frequencies of a few hundred Hz). A scattering effect (similar to that which occurs at the surface) also occurs at the seabed (Essen, 1994; Greaves and Stephen, 2003; McKinney and Anderson, 1964; Kuo, 1992), particularly on rough substrates (e.g. pebbles).

3.7 Another phenomenon is the waveguide effect which means that 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. The cut-off frequency as a function of water depth is shown in Figure 3.1 for a range of seabed types. Thus, for a water depth of 10 m (i.e. shallow waters typical of coastal areas and estuaries) the cut-off frequency would be approximately 70 Hz for sand, 100 Hz for silt, 140 Hz for clayey silt and 40 Hz for bedrock.

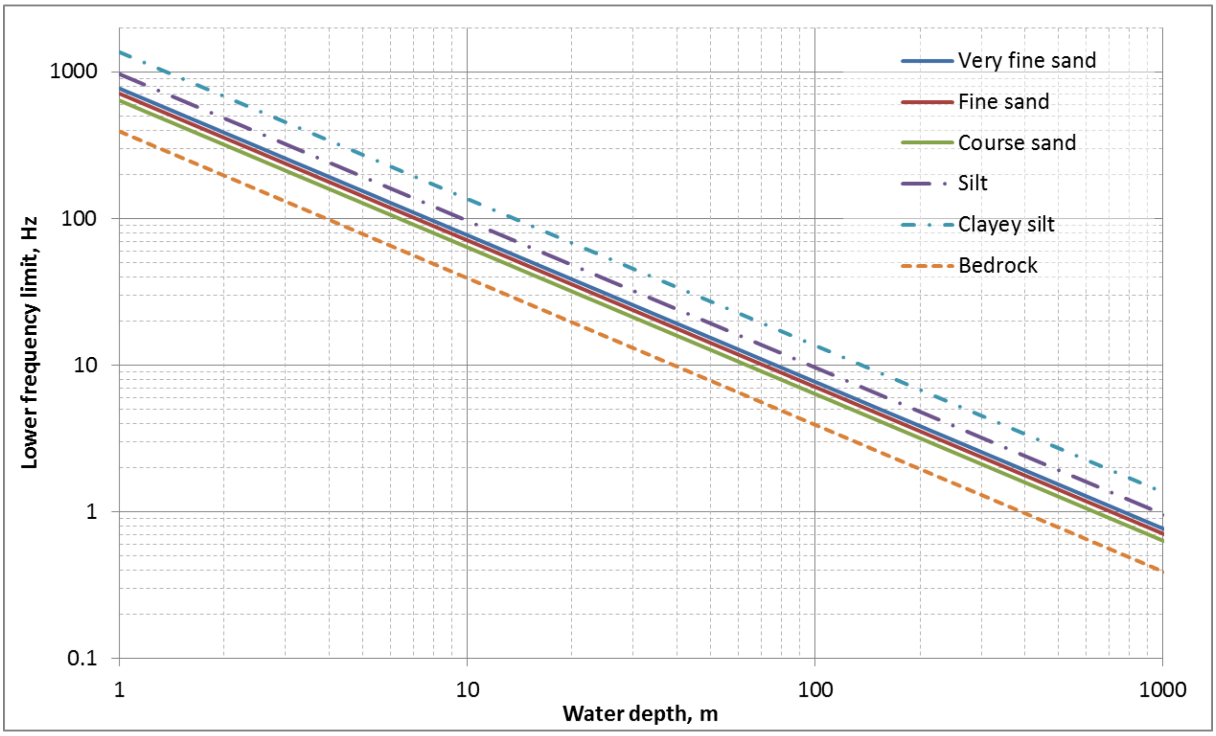

Figure 3.1: Lower cut-off frequency as a function of depth for a range of seabed types.

3.8 Sound energy can also be 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. This is shown in Figure 3.2. Although the effect of this absorption will be higher in cold water and with higher levels of MgSO4, these variations are relatively insignificant.

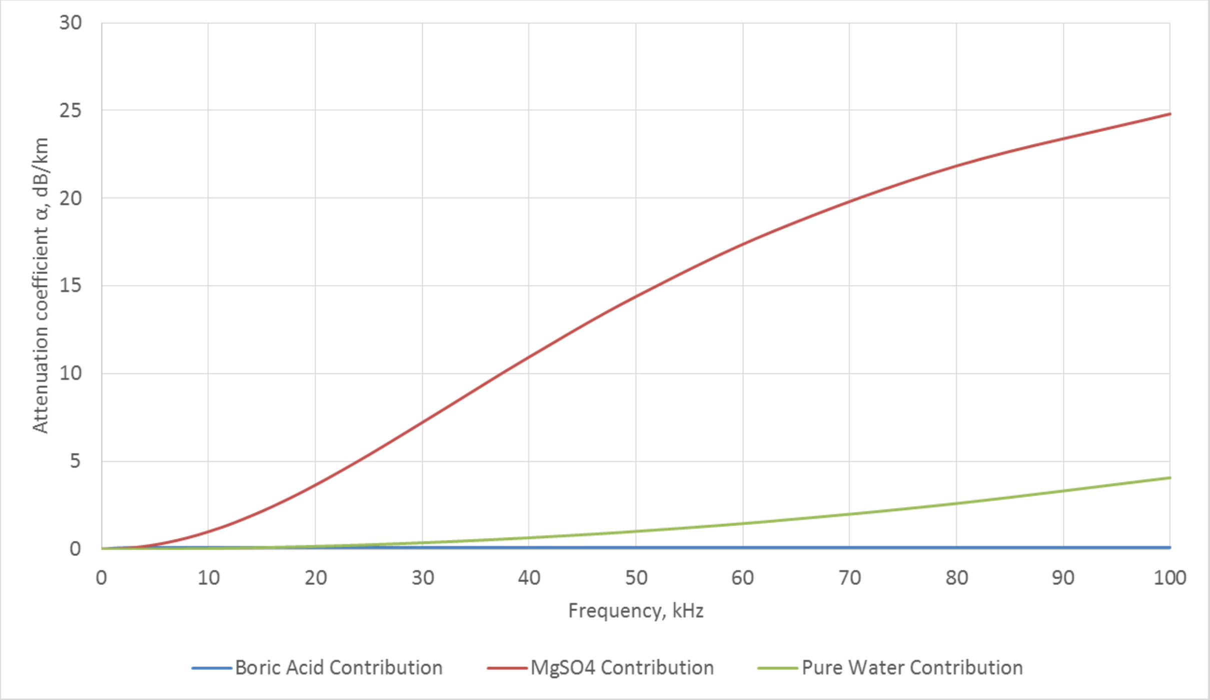

Figure 3.2: Absorption loss coefficient (α), dB/km (pH 8, 5 ºC, salinity 35 ppt).

4 Assessment Criteria

General

4.1 In order to determine the potential spatial range of injury and disturbance, assessment criteria have been developed based on a review of available evidence including national and international guidance and scientific literature. The following sections summarise the relevant criteria and describe the evidence base used to derive them.

4.2 Underwater noise has the potential to affect marine life in different ways depending on its noise level and characteristics. Assessment criteria generally separate sound into two distinct types, 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; NIOSH 1998; ANSI 2005). This category includes sound sources such as seismic surveys, impact piling and underwater explosions; and
- **Non-impulsive (continuous) 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 vibro-piling, running machinery, sonar and vessels.

4.3 The acoustic assessment criteria for marine mammals and fish in this report has followed the latest international guidance, (based on the best available scientific information), that are widely accepted for assessments in the UK, Europe and worldwide.

Injury and Disturbance to Marine mammals

4.4 Richardson *et al*. (Richardson and Thomson 1995) defined four zones of noise influence which vary with distance from the source and level as follows:

- injury/hearing loss;
- responsiveness;
- masking; and
- audibility.

4.5 For this study, it is the zones of injury and responsiveness (i.e. behavioural effects) that are of concern; there is insufficient evidence to properly evaluate masking.

4.6 The zone of injury in this study is classified as the distance over which a marine mammal can suffer a Permanent Threshold Shift (PTS) leading to non-reversible auditory injury. Injury thresholds are based on a dual criteria approach using both linear (i.e. un-weighted) peak SPL and marine mammal hearing-weighted SELs. 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 with an estimated functional hearing range between 7 Hz and 35 kHz);
- **Mid-frequency (MF) cetaceans** (i.e. marine mammal species such as dolphins, toothed whales, beaked whales and bottlenose whales with an estimated functional hearing range between 150 Hz and 160 kHz);
- **High-frequency (HF) cetaceans** (i.e. marine mammal species such as true porpoises, Kogia, river dolphins and cephalorhynchid with an estimated functional hearing range between 275 Hz and 160 kHz); and
- **Phocid pinnipeds (PW)** (i.e. true seals with an estimated functional hearing range between 50 Hz and 86 kHz); and
- **Otariid pinnipeds (OW)** (i.e. sea lions and fur seals with an estimated functional hearing range between 60 Hz and 39 kHz).

4.7 These weightings have therefore been used in this study and are shown in Figure 4.1. It should be noted that not all of the above categories of marine mammal will be present in the study area but criteria are presented in this report for completeness.

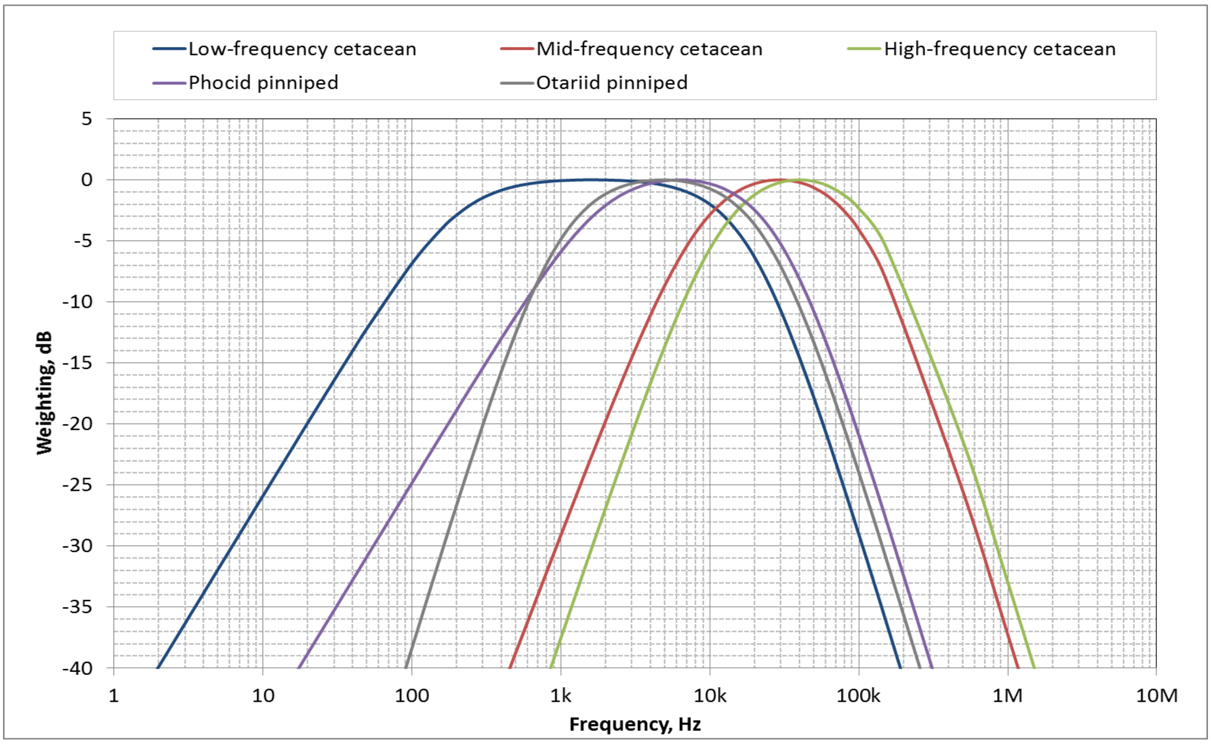

Figure 4.1 Hearing weighting functions for pinnipeds and cetaceans (NMFS, 2018).

4.8 Injury criteria are proposed in NOAA (NMFS, 2018) are for two different types of sound as follows:

- **Impulsive sounds** which are typically transient, brief (less than 1 second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay (ANSI 1986; NIOSH 1998; ANSI 2005). 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.

4.9 The relevant criteria proposed by NOAA are as summarised in Table 4.1 for impulsive sound (e.g. impact piling) and non-impulsive sound (e.g. vibro-piling and vessels). The SEL criteria are marine mammal hearing weighted whereas the peak criteria are unweighted.

Table 4.1: Summary of PTS onset acoustic thresholds (NMFS 2018).

Hearing Group	Parameter	Impulsive	Non-impulsive
Low-frequency (LF) cetaceans	Peak, dB re 1 µPa (unweighted)	219	-
	SEL, dB re 1 µPa^{2}s (LF weighted)	183	199
Mid-frequency (MF) cetaceans	Peak, dB re 1 µPa (unweighted)	230	-
	SEL, dB re 1 µPa^{2}s (MF weighted)	185	198
High-frequency (HF) cetaceans	Peak, dB re 1 µPa (unweighted)	202	-
	SEL, dB re 1 µPa^{2}s (HF weighted)	155	173
Phocid pinnipeds (PW)	Peak, dB re 1 µPa (unweighted)	218	-
	SEL, dB re 1 µPa^{2}s (PW weighted)	185	201
Otariid pinnipeds (OW)	Peak, dB re 1 µPa (unweighted)	232	-
	SEL, dB re 1 µPa^{2}s (OW weighted)	203	219

4.10 Beyond the area in which injury may occur, the effect on marine mammal behaviour is the most important measure of 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.

4.11 To consider the possibility of significant disturbance resulting from the project, 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.

4.12 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. JNCC guidance (JNCC, 2010) indicates that a score of 5 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 negative effects on life functions, which would constitute a disturbance under the relevant regulations.

4.13 Southall *et al.* (2007) present a summary of observed behavioural responses for various mammal groups exposed to different types of noise (single pulse, multiple pulse and non-pulse).

4.14 For non-pulsed sound (e.g. vessels etc.), the lowest sound pressure level at which a score of 5 or more occurs for low frequency cetaceans is 90 - 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 3 at a received level of 100 – 110 dB re 1 µPa (rms), with no higher severity score encountered for this species. For mid frequency cetaceans, a response score of 8 was encountered at a received level of 90 - 100 dB re 1 µPa (rms), but this was for one mammal (a sperm whale) and might not be applicable for the species likely to be encountered near this development. For Atlantic white-beaked dolphin, a response score of 3 was encountered for received levels of 110 – 120 dB re 1 µPa (rms), with no higher severity score encountered. For high frequency cetaceans, a number of individual responses with a response score of 6 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 6 once the received sound pressure level is greater than 140 dB re 1 µPa (rms).

4.15 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 6 (i.e. once the received rms sound pressure level is greater than 140 dB re 1 µPa). Taking into account 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.

4.16 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. Although these datasets contain much relevant data for low-frequency cetaceans, there are no strong data for mid-frequency or high-frequency cetaceans. Low frequency cetaceans, other than bow-head whales, were typically observed to respond significantly at a received level of 140 – 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 mid-frequency cetaceans indicate that some significant response was observed at a sound pressure level of 120 – 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 – 180 dB re 1µPa (rms). Furthermore, other mid-frequency cetaceans within the same study were observed to have no behavioural response even when exposed to a level of 170 – 180 dB re 1µPa (rms).

4.17 A more recent study is described in Graham *et al.* (2017). Empirical evidence from piling at the Beatrice offshore wind farm 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 SEL of 180 dB re 1μPa^{2}s, 50% at 155 dB re 1μPa^{2}s and dropping to approximately 0% at an SEL of 120 dB re 1μPa^{2}s.

4.18 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, bearded and spotted seals (Harris *et al*., 2001) found onset of a significant response at a received sound pressure level of 160 – 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 – 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 – 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.

4.19 Southall *et al*. (2007) also notes that, due to the uncertainty over whether high-frequency cetaceans may perceive certain sounds and due to paucity of data, it was not possible to present any data on responses of high frequency-cetaceans. However, Lucke *et al.* (2008) showed a single harbour porpoise consistently showed aversive behavioural reactions to pulsed sound at received sound pressure levels above 174 dB re 1 μPa (peak-to-peak) or a SEL of 145 dB re 1 μPa^{2}s, equivalent to an estimated[2] rms sound pressure level of 166 dB re 1 μPa.

4.20 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 cetaceans remain protected.

4.21 The High Energy Seismic Survey workshop on the effects of seismic (i.e. pulsed) sound on marine mammals ("Summary of Recommendations Made by the Expert Panel at the HESS Workshop on the Effects of Seismic Sound on Marine Mammals" 1997) concluded that mild behavioural

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[2] 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.

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.

4.22 This assessment adopts a conservative approach and uses the US National Marine Fisheries Service (NMFS 2005b) Level B harassment threshold of 160 dB re 1 µPa (rms) for impulsive sound. Level B Harassment is defined 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.

4.23 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.

Injury and Disturbance to Fish

4.24 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 spawn 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 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.

4.25 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). 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[3]. The criteria include a range of indices including SEL, rms and peak sound pressure levels. Where insufficient data exist to determine a quantitative guideline value, the risk is categorised in relative terms as “high”,

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[3] Guideline exposure criteria for explosions, seismic surveys, continuous sound and naval sonar are also presented though are not applicable to this Project.

"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.

4.26 The criteria used in this noise assessment for impulsive piling are given in Table 4.2. In the table, both peak and SEL criteria are unweighted.

Table 4.2: Criteria for onset of injury to fish due to impulsive piling (Popper et al., 2014).

Type of animal	Parameter	Mortality and potential mortal injury	Recoverable injury
Fish: no swim bladder (particle motion detection)	SEL, dB re 1 µPa^{2}s	>219	>216
	Peak, dB re 1 µPa	>213	>213
Fish: where swim bladder is not involved in hearing (particle motion detection)	SEL, dB re 1 µPa^{2}s	210	203
	Peak, dB re 1 µPa	>207	>207
Fish: where swim bladder is involved in hearing (primarily pressure detection)	SEL, dB re 1 µPa^{2}s	207	203
	Peak, dB re 1 µPa	>207	>207
Eggs and larvae	SEL, dB re 1 µPa^{2}s	>210	(*Near*) Moderate (*Intermediate*) Low (*Far*) Low
	Peak, dB re 1 µPa	>207	

4.27 The criteria used in this noise assessment for non-impulsive piling are given in Table 4.3.

Table 4.3: Criteria for onset of injury to fish due to non-impulsive sound (Popper et al., 2014).

Type of animal	Mortality and potential mortal injury	Recoverable injury
Fish: no swim bladder (particle motion detection)	(*Near*) Low (*Intermediate*) Low (*Far*) Low	(*Near*) Low (*Intermediate*) Low (*Far*) Low
Fish: where swim bladder is not involved in hearing (particle motion detection)	(*Near*) Low (*Intermediate*) Low (*Far*) Low	(*Near*) Low (*Intermediate*) Low (*Far*) Low
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
Eggs and larvae	(*Near*) Low (*Intermediate*) Low (*Far*) Low	(*Near*) Low (*Intermediate*) Low (*Far*) Low

4.28 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[4].

4.29 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.

4.30 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

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[4] 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.

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 4.4.

Table 4.4: Criteria for onset of behavioural effects in fish for impulsive and non-impulsive sound (Popper et al., 2014).

Type of animal	Relative risk of behavioural effects	
	Impulsive piling	**Non-impulsive sound**
Fish: no swim bladder (particle motion detection)	(*Near*) High (*Intermediate*) Moderate (*Far*) Low	(*Near*) Moderate (*Intermediate*) Moderate (*Far*) Low
Fish: where swim bladder is not involved in hearing (particle motion detection)	(*Near*) High (*Intermediate*) Moderate (*Far*) Low	(*Near*) Moderate (*Intermediate*) Moderate (*Far*) Low
Fish: where swim bladder is involved in hearing (primarily pressure detection)	(*Near*) High (*Intermediate*) High (*Far*) Moderate	(*Near*) High (*Intermediate*) Moderate (*Far*) Low
Eggs and larvae	(*Near*) Moderate (*Intermediate*) Low (*Far*) Low	(*Near*) Moderate (*Intermediate*) Moderate (*Far*) Low

4.31 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 impact, no matter the level of noise produced or the propagation characteristics.

4.32 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 Noise sources are usually described in dB re 1 µPa as if measured at 1 m from the source. In practice, it is not usually possible to measure at 1 m from a source, but this method allows different source levels to be compared and reported on a like-for-like basis. This method of specification involves assuming that the source is infinitesimally small so that at 1 m from this imagined point the sound pressure levels can be defined. In reality, for a large sound source such as a pile 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 actually occur for large sources, such as piles. In the acoustic near-field, the sound pressure level will be significantly lower than would be predicted using this method.

5.2 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 are 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; J. R. Nedwell *et al*. 2007; J. Nedwell and Howell 2004; Jeremy Nedwell *et al.,* 2003; CDoT 2001; Nehls *et al.*, 2007; Thomsen *et al.*, 2006).

5.3 For this project, the assessment has been carried out for a worst case scenario of installation of AU 25 piles using a combination of vibratory and impact piling methods. The hammer energy is not known at this time so it has been assumed that installation will utilise a 120 kJ hammer based on other similar projects. The assumption used for the modelling is that approximately 0.5% of the hammer energy is converted into sound in order to derive the SEL (based on a review of literature from Robinson *et al*., 2009, Robinson *et al*., 2013, Lepper, 2007, Lepper *et al.*, 2012 and Bailey *et al*., 2010). 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.

5.4 For vibro-piling, the source sound levels are based on those measured by Graham et al. (2017) during vibratory piling at Nigg Energy Park in Scotland. The study found source levels from vibratory piling to be higher than expected with a measured rms source level of 192 dB re 1 µPa re 1 m. For a continuous source, this is equivalent to a SEL per second of operation of 192 dB re 1 µPa^{2}s at 1 m.

Table 5.1: Piling noise source levels used in assessment (un-weighted).

Parameter	Source level at 1 m
Impact Piling	
SEL per blow @ 1 m, dB re 1 µPa^{2}s	192
Peak sound pressure level @ 1 m, dB re 1 µPa	210
rms$_{T90}$ sound pressure level @ 1 m, dB re 1 µPa	202
Vibratory Piling	
SEL per second of operation @ 1 m, dB re 1 µPa^{2}s	192
Peak sound pressure level @ 1 m, dB re 1 µPa	198
rms$_{T90}$ sound pressure level @ 1 m, dB re 1 µPa	192

5.5 The SEL exposure resulting from piling noise assumes that each hammer blow (or each second of operation for the vibro-piling) will contribute to the overall exposure of the marine mammal or fish, and that the piling operation has a fixed duration (12 hours per day) over which the number of blows per minute remains constant (assumed maximum speed 40 strikes per minute for impact piling and continuous operation for vibro-piling). Subsequently, the SEL exposure is calculated by considering the total number of blows likely to be experienced by a mammal moving away from the piling operation at a constant speed. It also assumes that there is no hearing recovery between hammer blows and therefore represents a worst case conservative assessment. Furthermore, this is considered overly pessimistic because in reality there will be breaks in activity in between installation of each pile.

5.6 For impact piling, 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 0.1 s.

5.7 Peak and rms sound pressure levels are not cumulative in the same way as SEL exposure, and assessments are made against levels for individual hammer blows.

5.8 Noise source data for construction vessels have been estimated using proxy data from publicly available data, as set out in Table 5.2.

Table 5.2: Source noise data for vessels.

Item	Description/assumptions	Data source	Source sound pressure level at 1 m	
			Rms, dB re 1 µPa	SEL(24h), dB re 1 µPa^{2}s
Backhoe dredger	Manu Pekka used as proxy	Nedwell *et al*. (2008)	163	212
Work / safety boat	Tug used as proxy	Richardson (1995)	172	221
Tug	Tug used as proxy	Richardson (1995)	172	221

6 Noise Propagation Modelling Methodology

6.1 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) 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 which lie somewhere in between these two extremes in terms of complexity.

6.2 In choosing which 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 and Farcas *et al.*, 2016). Thus, in some situations (e.g. low risk due to underwater noise, range dependent bathymetry is not an issue, non-impulsive sound) a simple (N log R) model will be sufficient, particularly where other uncertainties outweigh the uncertainties due to modelling. On the other hand, some situations (e.g. 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.

6.3 The first step in choosing a propagation model is therefore to examine these various factors, such as set out below:

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

6.4 For impulsive sound, such as that produced by impact piling, the sound propagation is rather more complex than can be modelled using a simple N log (R) relationship. For example, the rms sound pressure level of an impulsive sound wave will depend upon the integration window used or, in other words, the measurement time for the rms. Using a longer duration measurement would result in a lower rms sound pressure level than using a shorter one. An additional phenomenon occurs where the seismic waveform elongates with distance from the source due to a combination of dispersion and multiple reflections. This temporal “smearing” can significantly affect the peak pressure level and reduces the rms amplitude with distance (because the rms window is longer).

6.5 Sound propagation modelling for this assessment was therefore based on an established, peer reviewed sound propagation model which utilises the semi-empirical model developed by Rogers (1981). The model provides a robust balance between complexity and technical rigour over a wide range of frequencies, has been validated by numerous field studies and has been benchmarked against a range of other models. The following inputs are required for the model:

- third-octave band source sound level data;
- range (distance from source to receiver);
- water column depth (input as bathymetry data grid);
- sediment type;
- sediment and water sound speed profiles and densities;
- sediment attenuation coefficient; and
- source directivity characteristics.

6.6 The propagation loss is calculated using the formula:

$$TL = 15log_{10}R + 5\log_{10}(H\beta) + \frac{\beta R\theta_L^2}{4H} - 7.18 + \alpha_w R$$

Where R is the range, H the water depth, β the bottom loss, $\theta_L$the limiting angle and α_w the absorption coefficient of sea water (α_w is a frequency dependant term which is calculated based on Ainslie and McColm, 1998).

6.7 The limiting angle, θ_L is the larger of θ_g and θ_c where θ_g is the maximum grazing angle for a skip distance and θ_c is the effective plane wave angle corresponding to the lowest propagating mode.

$$\theta_g = \sqrt{\frac{2Hg}{c_w}} \qquad \theta_c = \frac{c_w}{2fH}$$

Where g is the sound speed gradient in water and f is the frequency.

6.8 The bottom loss β is approximated as:

$$\beta \approx \frac{0.477(\rho_s/\rho_w)(c_w/c_s)K_s}{[1-(c_w/c_s)^2]^{3/2}}$$

Where ρ_s is the density of sediment, ρ_w the density of water, c_s the sound speed in the sediment, c_w the sound speed in water and K_s is the sediment attenuation coefficient.

6.9 The propagation model also takes into account the depth dependent cut-off frequency for propagation of sound (i.e. the frequency below which sound does not propagate):

$$f_{cut-off} = \frac{c_w}{4h\sqrt{1 - \frac{c_w^2}{c_s^2}}}$$

Where c_s and c_w are the sound propagation speeds in the substrate and water.

6.10 The level of detail presented in terms of noise modelling needs to be considered in relation to the high 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.

6.11 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. Taking into account 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 an impact definitely will or will not occur. (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 - 10 dB depending on wind direction etc.).

6.12 As well as calculating the sound pressure levels at various distances from the source, it is also necessary to calculate the SEL for a mammal or fish using the relevant weightings described previously taking into account the amount of sound energy to which it is exposed over the course of a 24 hour period. In order to carry out this calculation, it has been assumed that a mammal will swim away from the noise source at an average speed of 1.5 ms^{-1} (or 0.5 ms^{-1} for fish). The calculation considers each pulse exposure separately resulting in a series of discrete SEL values of decreasing magnitude. As the mammal or fish swims away, the noise will become progressively quieter; the cumulative SEL is worked out 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 or fish 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 source is active continuously over a 12 hour period and that the animal will continue to swim away at a fairly constant relative speed. The real world situation is more complex and the noise source will vary in space and time and the animal is likely to move in a more complex manner[5].

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[5] Swim speeds of marine mammals have been shown to be up to 5 ms^{-1} (e.g. cruising minke whale 3.25 ms^{-1} (Cooper et al. 2008) and, harbour porpoise up to 4.3 ms^{-1} (Otani et al. 2000)). The more conservative swim speed of 1.5 ms^{-1} used in this assessment allows some headroom to account for the potential that the marine mammal might not swim directly away from the source, could change direction or does not maintain a fast swim speed over a prolonged period.

7 Baseline Noise

7.1 Background or “ambient” underwater noise is generated by a number of natural sources, such as rain, breaking waves, wind at the surface, seismic noise, biological noise and thermal noise. Biological sources include marine mammals (which use sound to communicate, build up an image of their environment and detect prey and predators) as well as certain fish and shrimp. Anthropogenic sources also add to the background noise, such as fishing boats, ships, industrial noise, seismic surveys and leisure activities. Generalised ambient noise spectra (Wenz, 1962) attributable to various noise sources including both natural and anthropogenic sources are shown in Figure 7.1.

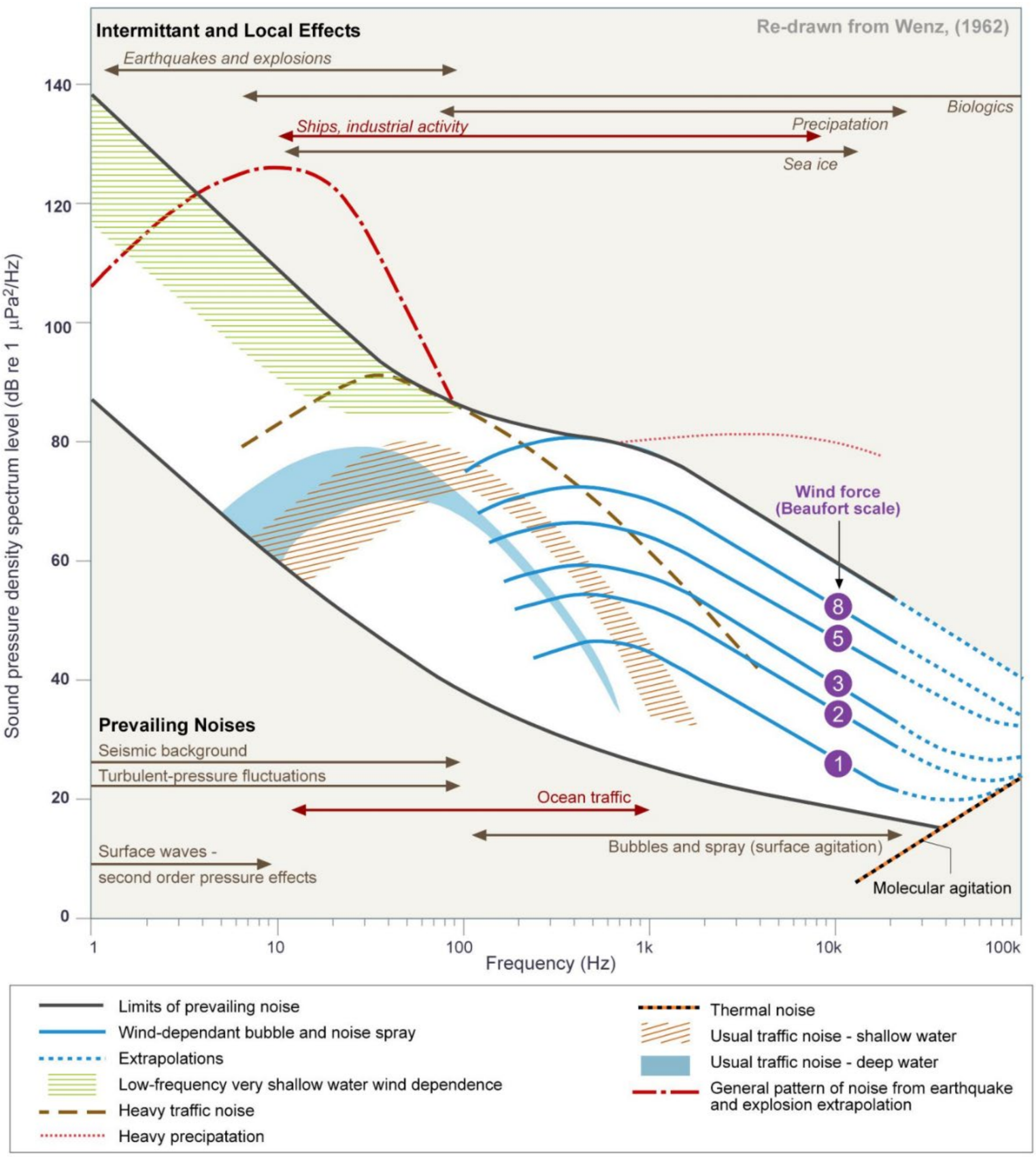

Figure 7.1: Generalised ambient noise spectra attributable to various noise sources (Wenz 1962).

7.2 The vast majority of research relating to both physiological effects and behavioural disturbance due to noise on marine species is based on determining the absolute noise level for the onset of that effect. As a result, criteria for assessing the effects of noise on marine mammals and fish tend to be based on the absolute noise criteria, as opposed to the difference between the baseline noise level and the specific noise being assessed (e.g. Southall *et al.*, 2007). Given the lack of evidence-based studies investigating the effects of noise relative to background on marine wildlife, the value of establishing the precise baseline noise level is somewhat diminished. It is important to understand that baseline noise levels will vary significantly depending on, amongst other factors, seasonal variations and different sea states, meaning that the usefulness of establishing such a value would be very limited. Nevertheless, it can be useful (though not essential) when undertaking an assessment of underwater noise, to have an understanding of the range of noise levels likely to be prevailing in the area, so that any noise predictions can be placed in the context of the baseline. It is important to note however, that even if an accurate baseline noise level could be determined, there is a paucity of scientific understanding regarding how various species distinguish anthropogenic sound relative to masking noise.

7.3 An animal’s perception of sound is likely to depend on numerous factors including the hearing integration time, the character of the sound, and hearing sensitivity. It is not known for example, to what extent marine mammals and fish can detect tones of lower magnitude than the background masking noise, or how they distinguish time varying sound. Therefore, it is necessary to exercise considerable caution if attempting any comparison between noise from the proposed development and the baseline noise level. For example, it does not follow that because the broadband sound pressure level due to the source being considered is below the numeric value of the baseline level, that this means that marine mammals or fish cannot detect that sound. This is particularly true where the background noise is dominated by low frequency sound which is outside the animal’s range of best hearing acuity. Until such a time as further research is conducted to determine a dose response relationship between the “signal-to-noise” level and behavioural response, a precautionary approach should be adopted.

7.4 For the reasons given above, it was considered that it would be disproportionate and unnecessary to undertake baseline noise measurements as part of this study. Alternatively, as detailed below, RPS has reviewed baseline noise studies carried out in UK waters for other projects in order to determine the likely magnitude of noise encountered in such waters.

7.5 A review of noise data relating to other sites in UK waters was undertaken for the Beatrice Wind Farm including a review of baseline underwater noise measurements in UK coastal waters

(Brooker *et al.,* 2012). These noise data are summarised in Table 7.1 and power spectral density levels are shown graphically in Figure 7.2 (Sea State 1) and Figure 7.3 (Sea State 3).

Table 7.1: Summary of average background levels of noise around the UK coast (Brooker *et al*., 2012).

	Overall (Un-Weighted) Average Background Noise Levels, dB re 1 µPa (rms)	
	Sea State 1	**Sea State 3**
Minimum	92	94
Maximum	126	132
Mean	111	112

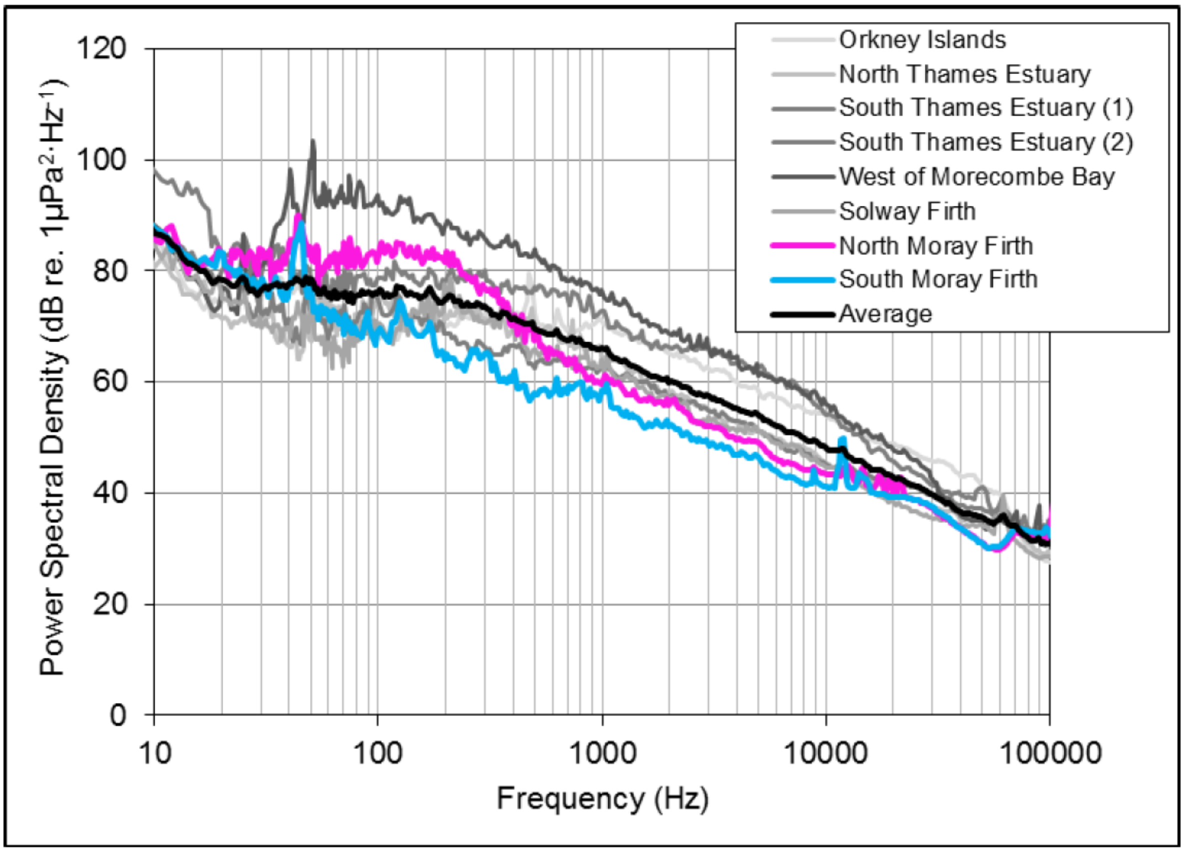

Figure 7.2: Summary of Power Spectral Density levels of background underwater noise at Sea State 1 at sites around the UK coast (Brooker, Barham, and Mason 2012).

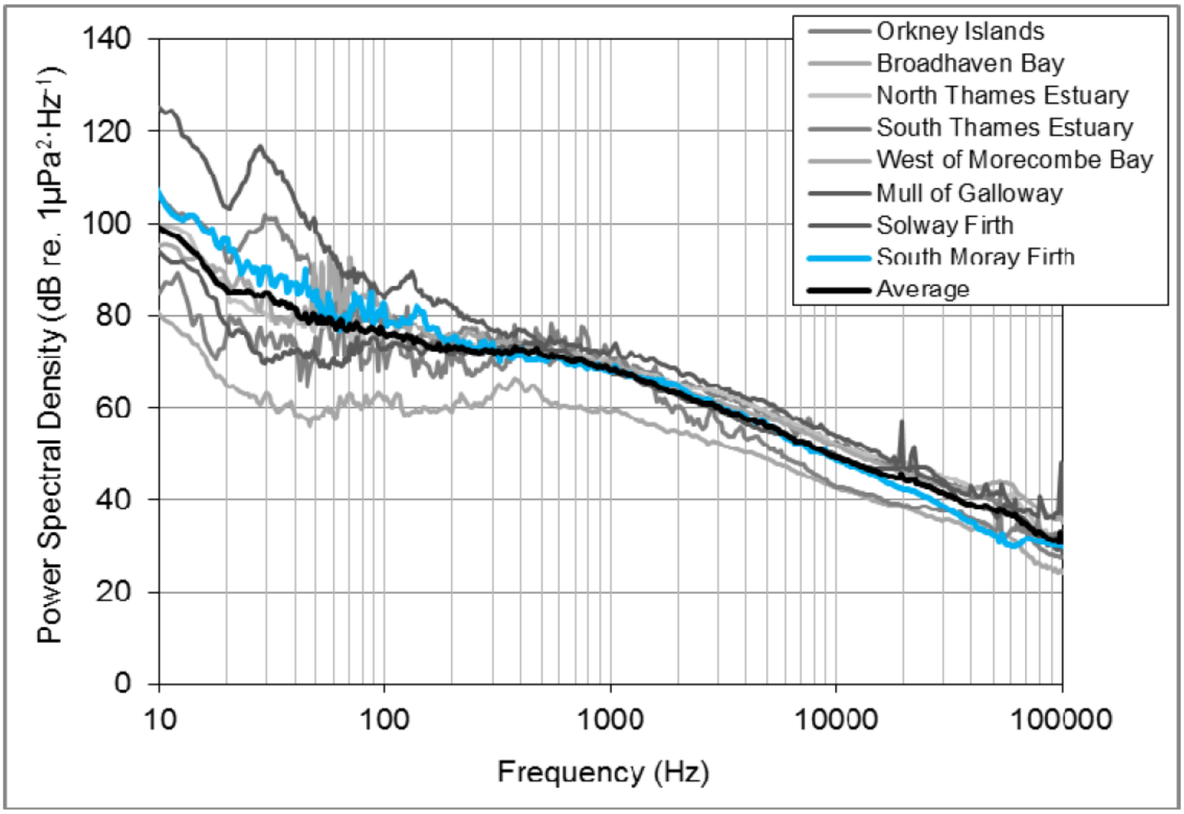

Figure 7.3: Summary of Power Spectral Density levels of background underwater noise at Sea State 3 at sites around the UK coast (Brooker *et al.*, 2012).

7.6 The measured power spectral density levels (maximum values in red, mean values in black and minimum values in green, in dB re 1 µPa^{2}Hz^{-1}) and third octave band sound pressure levels (light blue, in dB re 1 µPa) are shown in Figure 7.4 taken from Kongsberg (2012).

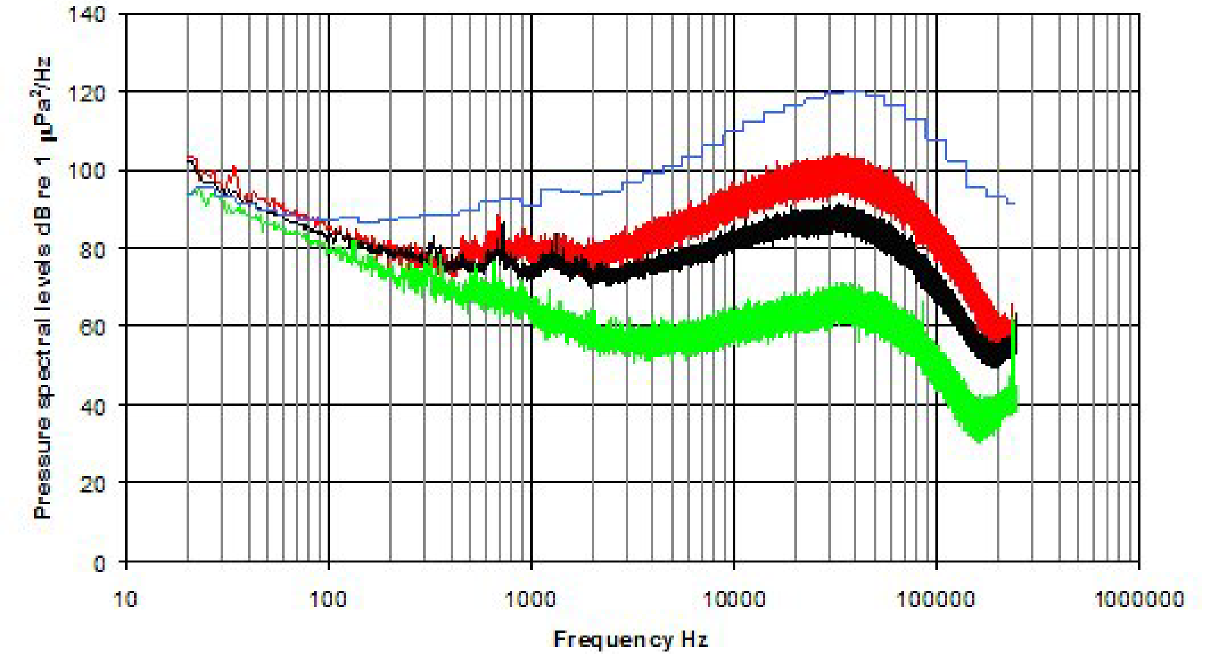

Figure 7.4: Summary of power spectral density levels and third octave band sound pressure levels of background underwater noise measured in the Inner Sound (Meygen), August 2011 (Kongsberg, 2012).

7.7 A "drifting-buoy" style assessment of background noise was undertaken by the Low Carbon Research Institute (LCRI) marine division in July 2014. Over an eleven-hour period, noise levels at the Inner Sound site were seen to vary from 91 dB re 1μPa during periods of low tidal flow speed to 121 dB re 1μPa at high tidal flow speeds.

7.8 In addition to natural ambient noise sources, Pembroke Port is within the vicinity of a heavily trafficked area. Significant vessel traffic occurs due to the hydrocarbon berths (South Hook LNG, Valero Refinery on the south bank, and Valero Oil Terminal & Dragon LNG) and Milford Haven Port. Consequently, the area will already experience elevated levels of anthropogenic noise in addition to elevated natural ambient noise.

7.9 Based on the review, it is concluded that baseline underwater noise levels in high-tidal coastal areas and estuaries are likely to be in the range 91 to 121 dB re 1 μPa (rms).

8 Results and Assessment

Piling Noise Modelling Results

8.1 Based on the modelling, the resultant PTS injury ranges for the proposed impact piling activities are summarised in Table 8.1.

Table 8.1: Summary of injury ranges for marine mammals due to impact piling (N/E = threshold not exceeded).

Species / Group	Threshold (Weighted SEL_{cum})	Range	Threshold (Peak SPL)	Range
Low frequency cetacean	183 dB re 1 µPa^{2}s	8 m	219 dB re 1 µPa (pk)	*N/E*
Mid frequency cetacean	185 dB re 1 µPa^{2}s	*N/E*	230 dB re 1 µPa (pk)	*N/E*
High frequency cetacean	155 dB re 1 µPa^{2}s	*N/E*	202 dB re 1 µPa (pk)	3 m
Phocid pinniped	185 dB re 1 µPa^{2}s	*N/E*	218 dB re 1 µPa (pk)	*N/E*
Otariid pinniped	203 dB re 1µ Pa^{2}s	*N/E*	232 dB re 1 µPa (pk)	*N/E*

8.2 PTS injury ranges for vibratory sheet piling are summarised in Table 8.2. It should be noted that only SEL criteria (and not peak levels) are used for assessing injury to marine mammals due to continuous sound.

Table 8.2: Summary of injury ranges for marine mammals due to vibratory piling (N/E = threshold not exceeded).

Species / Group	Threshold (Weighted SEL_{cum})	Range
Low frequency cetacean	199 dB re 1 µPa^{2}s	*N/E*
Mid frequency cetacean	198 dB re 1 µPa^{2}s	*N/E*
High frequency cetacean	173 dB re 1 µPa^{2}s	*N/E*
Phocid pinniped	201 dB re 1 µPa^{2}s	*N/E*
Otariid pinniped	219 dB re 1 µPa^{2}s	*N/E*

8.3 Maximum disturbance ranges for marine mammals are summarised in Table 8.3 based on the rms sound pressure level contours.

Table 8.3: Summary of disturbance ranges for marine mammals due to impact piling.

Effect	Threshold (SPL)	Range	Area
Mild disturbance	140 dB re 1µ Pa (rms)	2.8 km	5 km^2
Strong disturbance	160 dB re 1µ Pa (rms)	251 m	0.2 km^2

8.5 For vibro-piling, disturbance could occur within 4 km of the source based on the 120 dB re 1µ Pa (rms) threshold.

8.6 The single pulse unweighted SEL noise contours are shown in Figure 8.1, in steps of 5 dB.

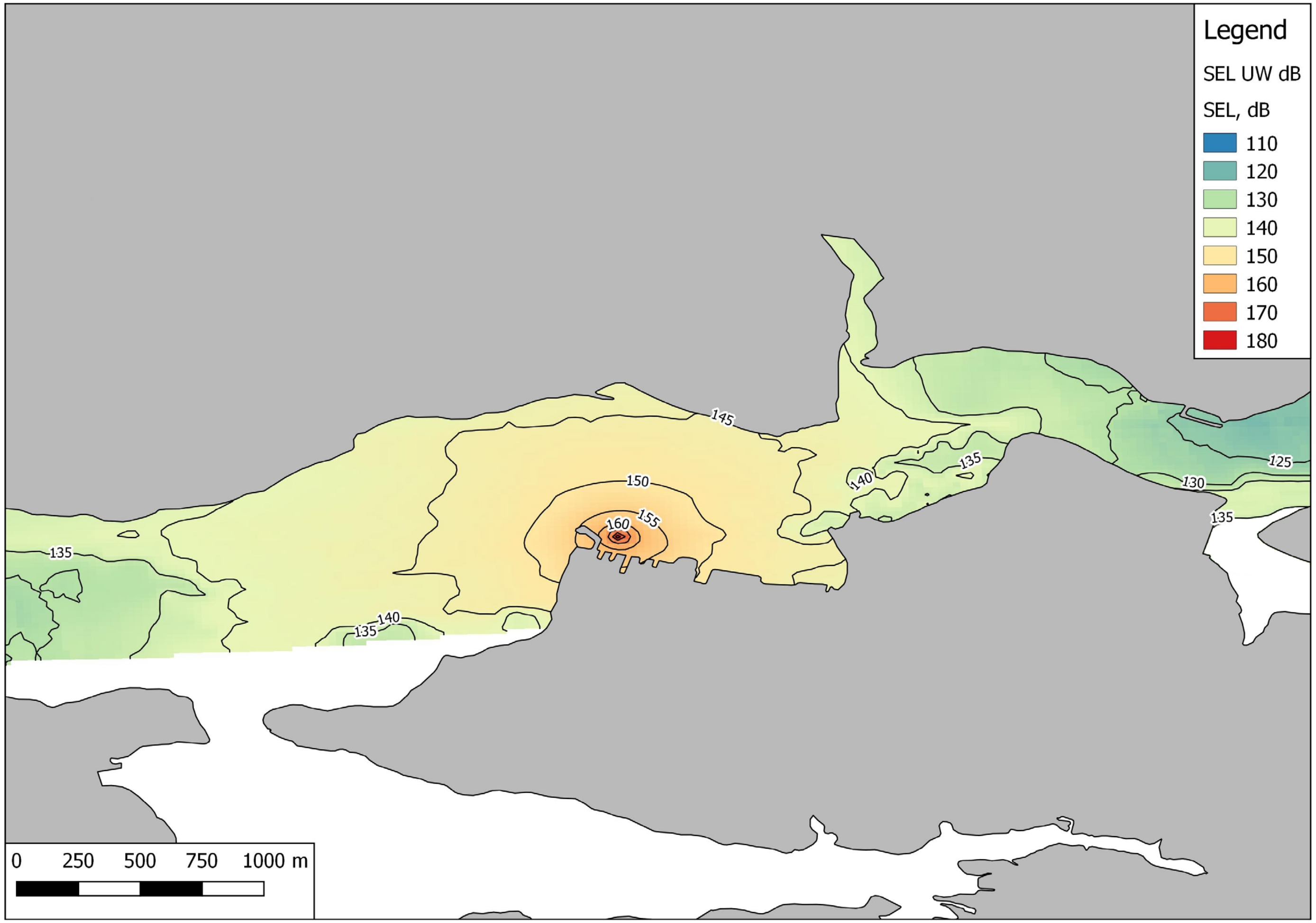

Figure 8.1: Unweighted single pulse SEL contours due to impact piling.

8.7 The results of the noise modelling for fish are shown in Table 8.4 based on the peak sound pressure and cumulative SEL thresholds.

Table 8.4: Summary of injury ranges for fish due to impact piling.

Class	Threshold	Range
Mortality No swim bladder (particle motion detection)	213 dB re 1 µPa (pk)	*N/E*
	219 dB re 1 $\mu Pa^2 s$	*N/E*
Impairment No swim bladder (particle motion detection)	213 dB re 1 µPa (pk)	*N/E*
	216 dB re 1 $\mu Pa^2 s$	*N/E*
Mortality Swim bladder not involved in hearing (particle motion detection)	207 dB re 1 µPa (pk)	*N/E*
	210 dB re 1 $\mu Pa^2 s$	*N/E*
Impairment Swim bladder not involved in hearing (particle motion detection)	207 dB re 1 µPa (pk)	*N/E*
	203 dB re 1 $\mu Pa^2 s$	*N/E*
Mortality Swim bladder involved in hearing (primarily pressure detection)	207 dB re 1 µPa (pk)	*N/E*
	207 dB re 1 $\mu Pa^2 s$	*N/E*
Impairment Swim bladder involved in hearing (primarily pressure detection)	207 dB re 1 µPa (pk)	*N/E*
	203 dB re 1 $\mu Pa^2 s$	*N/E*
Mortality Fish eggs and larvae	207 dB re 1 µPa (pk)	*N/E*
	210 dB re 1 $\mu Pa^2 s$	*N/E*
Behaviour	150 dB re 1 µPa (rms)	850 m

8.8 For fish where the swim bladder is involved in hearing the range for recoverable injury due to vibro-piling is 25 m. For all other effects, the qualitative criteria as set out in Table 4.3 (injury) and Table 4.4 (disturbance) are applicable.

Construction Vessel Noise Modelling Results

8.9 The results of the noise modelling for vessels on marine mammals are shown in Table 8.5. It should be noted that the SEL injury ranges are based on a marine mammal being within that range of the vessel continuously over a 24 h period. Consequently, it is considered that these ranges are over estimates and over precautionary.

Table 8.5: Summary of injury and disturbance ranges for marine mammals due to vessels (N/E = threshold not exceeded).

Activity / vessel	Radius of potential injury zone (assuming continuous exposure within that radius over 24 hour period)					Radius of potential disturbance – all marine mammals
	LF	MF	HF	PW	OW	
Backhoe dredger	*2 m*	*N/E*	*2 m*	*N/E*	*N/E*	*313 m*
Work / safety boat	*11 m*	*N/E*	*25 m*	*4 m*	*N/E*	*1.6 km*
Tug	*11 m*	*N/E*	*25 m*	*4 m*	*N/E*	*1.6 km*

8.10 The modelling results for the effect of vessels on fish is shown in Table 8.6. It should be noted that there are no numerical criteria for fish with no swim bladders contained in the ASA guidance and consequently no injury ranges for fish with swim bladders involved in hearing are included in the table.

Table 8.6: Summary of injury ranges for fish due to vessels (N/E = threshold not exceeded).

Activity / vessel	Recoverable injury
	Fish: swim bladder involved in hearing
Backhoe dredger	N/E
Work / safety boat	N/E
Tug	N/E

8.11 For all other effects, the qualitative criteria as set out in Table 4.3 (injury) and Table 4.4 (disturbance) are applicable.

9 Conclusions

9.1 Noise modelling has been undertaken to determine the range of potential effects on marine mammals and fish due to noise from the proposed piling activities and construction vessels.

9.2 Based on the assessment it is concluded that injury to high frequency cetaceans (harbour porpoise) could occur within 3 m of impact piling operations, for low frequency cetaceans within 8 m. The modelling shows that injury is unlikely to occur for mid frequency cetaceans and pinnipeds. Injury is unlikely to occur due to vibratory piling.

9.3 Results of the modelling show that strong disturbance to marine mammals could occur within a radius of up to 251 m from impact piling activities, with mild disturbance at up to 2.8 km. For vibro-piling, disturbance could occur within 4 km of the source, although the applicability of this threshold for vibro-piling is questionable so should be treated with caution.

9.4 Permanent impairment or injury is unlikely to occur to fish due to impact or vibratory piling. Disturbance to fish could occur within 850 from impact piling activities. No quantitative criteria are available for assessing the potential of vibratory piling to disturb to fish but it is likely that fish with swim bladders involved in hearing will experience significant disturbance within tens of metres from the source.

9.5 Injury could occur to marine mammals within a radius of up to 25 m from vessels, but only if they stay within that radius for a continuous period of 24 hours or more, which is considered a highly unlikely scenario. Disturbance to marine mammals could occur within 1.6 km, although it should be noted that operational noise levels will not be dissimilar to those already experienced in the area which is already heavily trafficked. Consequently, this is likely to be an over estimate of disturbance range for vessels.

9.6 The modelling shows that construction and operational vessels are unlikely to result in injury to fish. Disturbance to fish could occur up to 19 m from vessels.

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