Contents

List of Tables

List of Figures

Glossary

Acoustic particle velocity The rate of change of the displacement of fluid particles created by the forces exerted on the fluid by acoustic pressure in the presence of a sound wave. The units of velocity are metres per second (m/s).

Acoustic Pressure The force per unit area exerted by a sound wave above and below the ambient or static equilibrium pressure is called the acoustic pressure or sound pressure. The units of pressure are pounds per square inch (psi) or, in the SI system of units, Pascals (Pa). In underwater acoustics the standard reference is one-millionth of a Pascal, called a micro-Pascal (1 µPa).

Ambient sound Normal background noise in the environment, which has no distinguishable sources.

Bandwidth The range of frequencies over which a sound is produced or received.

Decibel (dB) A customary scale most commonly used (in various ways) for reporting levels of sound. Due to the logarithmic nature of the measurement, a difference of 10 dB corresponds to a factor of 10 in sound power. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be 10 log10,(actual/reference), where (actual/reference) is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is 20 log10 (actual pressure/reference pressure). As noted above, the standard reference for underwater sound pressure is 1 micro-Pascal (µPa). The dB symbol is followed by a second symbol identifying the specific reference value (i.e., re 1 µPa).

dB_{ht}(*Species*) The dB_{ht}(*Species*) metric (Nedwell *et al.* (2007b)) has been developed as a means for quantifying the potential for a behavioural impact of a sound on a species in the underwater environment. It is similar to the dB(A) in that it uses a species' audiogram in its calculation. The dB_{ht}(*Species*) metric can be understood as the level above the minimum audible sound (threshold of hearing) which a species can hear. A level of 0 dB_{ht}(*Species*) represents the minimum audible sound.

Far field A region far enough away from a source that the sound pressure behaves in a predictable way, and the particle velocity is related to only the fluid properties and exists only because of the propagation sound wave (see Near field).

Hertz The units of frequency where 1 hertz = 1 cycle per second. The abbreviation for hertz is Hz.

Impulse sound Transient sound produced by a rapid release of energy. Impulse sound has extremely short duration and extremely high peak sound pressure.

Near field	A region close to a sound source that, depending on the size of the source relative to the wavelength of the sound, has either irregular sound pressure or exponentially increasing sound pressure towards the source, and a high level of acoustic particle velocity because of kinetic energy added directly to the fluid by motion of the source. This additional kinetic energy does not propagate with the sound wave. The extent of the near field depends on the wavelength of the sound and/or the size of the source.
Peak pressure	The highest pressure above or below ambient that is associated with a sound wave.
Permanent threshold shift (PTS)	A total or partial permanent loss of hearing caused by some kind of acoustic or drug trauma.
Pulse	A transient sound wave having finite time duration. A pulse may consist of one to many sinusoidal cycles at a single frequency, or it may contain many frequencies and have an irregular waveform.
Resonance frequency	The frequency at which a system or structure will have maximum motion when excited by sound or an oscillatory force.
Shock wave	A propagating sound wave that contains a discontinuity in pressure, density, or particle velocity.
Sound attenuation	Reduction of the level of sound pressure. Sound attenuation occurs naturally as a wave travels in a fluid or solid through dissipative processes (e.g., friction) that convert mechanical energy into thermal energy and chemical energy.
Sound exposure	The integral over all time of the square of the sound pressure of a transient waveform.
Sound exposure level (SEL)	The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level, or the accumulated exposure to sound by a receptor over a period of time. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.
Sound exposure spectral density	The relative energy in each narrow band of frequency that results from the Fast Fourier Transform (FFT - a mathematical operation that is used to express data recorded in the time domain as a function of frequency) of a transient waveform. It is a measure of the frequency distribution of a transient signal.
Sound pressure level (SPL)	The sound pressure level is an expression of the sound pressure using the decibel (dB) scale and the standard reference pressures of 1 µPa for water and biological tissues, and 20 µPa for air and other gases.
Spectrum	A graphical display of the contribution of each frequency component contained in a sound.

Temporary threshold shift (TTS)	Temporary loss of hearing as a result of exposure to sound over time. Exposure to high levels of sound over relatively short time periods is thought to cause the same amount of TTS as exposure to lower levels of sound over longer time periods. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory cells. The duration of TTS varies depending on the nature of the stimulus, but there is generally recovery of full hearing over time.
Threshold	The threshold generally represents the lowest signal level an animal will detect in some statistically predetermined per cent of presentations of a signal. Most often, the threshold is the level at which an animal will indicate detection 50 per cent of the time. Auditory thresholds are the lowest sound levels detected by an animal at the 50 per cent level.
Total energy dose	The total cumulative energy received by an organism or object over time in a sound field.
Unweighted sound levels	Sound levels which are ‘raw’ or have not been adjusted in any way, for example to account for the hearing ability of a species.
Weighted sound levels	A sound level which has been adjusted with respect to a ‘weighting envelope’ in the frequency domain, typically to make an unweighted level relevant to a particular species. Examples of this are the dB(A), where the overall sound level has been adjusted to account for the hearing ability of humans, or dB_{ht}(*Species*) for fish and marine mammals.

Abbreviations and Acronyms

dB	Decibel
dB(A)	decibel (a weighted sound pressure level)
dB(ht)	decibel (hearing threshold)
FoF	Firth of Forth Phase 1
FTOWDG	Firth and Tay Offshore Wind Developers Group
Hz	Hertz
INSPIRE	Impulse Noise Sound Propagation and Impact Range Estimator
JNCC	Joint Nature Conservation Committee
kHz	Kilohertz
kJ	Kilojoules (unit of energy)
MS-LOT	Marine Scotland Licensing Operations Team
NnG	Neart na Gaoithe
PTS	Permanent Threshold Shift
SEL	Sound Exposure Level
SL	Source Level
SPEAR	Simple Propagation Estimator and Ranking
TS	Transmission Loss
TTS	Temporary Threshold Shifts

11 Underwater Noise

11.1 Introduction

1 This chapter describes the approach taken to the modelling of underwater noise fields generated during the construction, operation and decommissioning activities at the Inch Cape Offshore Wind Farm and the associated Offshore Transmission Works (OfTW). It also describes the noise modelling undertaken to inform the cumulative impact assessments of the Project with other projects. The results of the noise modelling have been used to inform impact assessments on natural fish and shellfish and marine mammals which are found in *Chapter 13: Natural Fish and Shellfish* and *Chapter 14: Marine Mammals*.

2 The full and detailed model outputs for all construction and operation activities are provided in *Appendix 11A: Underwater Noise*.

3 As described above, the modelled noise fields from construction and operation activities have been used by marine ecologist specialists to predict potential noise related impacts exerted upon fish and marine mammal receptors. The predicted impacts on marine ecology species are not presented within this chapter, but instead within the following chapters (and relevant technical appendices):

- *Chapter 13: Natural Fish and Shellfish;* and
- *Chapter 14: Marine Mammals.*

11.2 Consultation

4 A Scoping Opinion issued by the Marine Scotland Licensing Operations Team (MS-LOT), which included feedback from statutory and non-statutory consultees, was received by Inch Cape Offshore Limited (ICOL). The Opinion included responses from Marine Scotland and Scottish Natural Heritage (SNH) with regards to underwater noise, as summarised below in Table 11.1. In addition to the formal Scoping Opinion, further informal consultation has been undertaken in relation to the assessment of the impacts of the Wind Farm and OfTW with relevant stakeholders. The information received through this consultation, together with the formal Scoping Opinion and recognised best practice, has informed the methodology and scope for the noise modelling, the outputs of which are presented in this chapter.

5 In summary, both organisations required a detailed consideration of the effects of underwater noise from various sources during the construction, operation and decommissioning of the Wind Farm and OfTW. The assessment of effects was also required to take into account potential cumulative effects arising from the construction of other proposed wind farms off the Firth of Forth and Firth of Tay occurring concurrently.

Table 11.1: Scoping Responses and Actions

Consultees	Scoping Response	Project Response
Scottish Natural Heritage	Environmental Impact Assessment should consider underwater noise impacts on fish in respect of construction and decommissioning work, based on existing knowledge. The levels of noise production that can be expected during construction should be set-out and, using published literature, the impact, if any, this will have on fish movements and behaviour should be considered. The levels of noise that are expected to be generated during operation should be set-out, and the impact this may have on fish should be considered.	Underwater noise modelling has been undertaken to estimate the level of noise likely to be produced during construction. The outputs of this modelling have been used to undertake an impact assessment of likely effects on key species of fish in the region with respect to injury and behavioural criteria. The results of this impact assessment are presented in *Chapter 13: Natural Fish and Shellfish*. The potential levels of noise during operational activities have also been considered (see *Section 11.6.1)*. As described in *Section 11.6.4*, the potential effects of decommissioning are considered to be lower than the worst case effects assessed for the construction phase (piling). General impact assessments have been undertaken for likely activities within *Chapter 13: Natural Fish and Shellfish*.
Marine Scotland	Noise assessments should take into consideration sources of noise during construction and their potential impact on cetaceans/pinnipeds/fish. Within the non-site specific data gaps, the potential for cumulative effects on species whose range encompasses other potential wind farm development sites should be assumed to accumulate linearly, unless the developer has evidence to the contrary.	In conjunction with the modelling of noise levels from the Project, the cumulative levels of noise resulting from potentially simultaneous construction at Firth of Forth Phase 1 and Neart na Gaoithe wind farms have also been included in this chapter (see *Section 11.7*).

11.3 Design Envelope and Embedded Mitigation

6 The potential development parameters and scenarios are defined as a Design Envelope and presented in *Chapter 7: Description of Development.* The assessment of potential impacts from underwater noise on receptors is carried out in *Chapters 13 and 14.* This chapter provides modelled outputs which quantify the magnitudes and ranges of noise levels when considered in context of the species identified in *Chapters 13 and 14*. These quantified magnitudes are based on the worst case scenario as identified from this Design Envelope, which is specific to the potential scenarios modelled in this chapter.

7 Key parameters for the worst case scenario for each potential impact are detailed in Tables 11.2 and 11.4 below.

Table 11.2: Worst Case Scenario - Development Area

Potential Impact	Design Envelope Scenario Assessed
Construction Noise	The steel jacket foundation option has been identified as representing the worst case scenario for noise impacts, as pile driving is accepted as producing the largest potential source of noise. Piling noise modelled considers the following sources: • 213 WTG with four piles per foundation; • three met mast with four piles per foundation; and • five OSPs with 16 piles per foundation. Further detail on the piling energy sources and temporal aspects modelled are detailed in table 11.3. Dredging operations also relate to Gravity Base Substructure (GBS) installation have been considered and are presented in this chapter. However, it is recognised that this noise source presents a significantly lower noise output to the steel jacket foundation options and do not represent the worst case. In addition to foundation piling there are a number of other construction activities that are potential sources of noise which may occur simultaneously to piling. These include: • Drilling (if required for steel jacket installation); • Construction vessels; • Cable installation (both trenching and cable laying); and • Cable protection (rock placement).
Operation Noise	Operational noise resulting from the works in the Development Area include: • Operation vessels; • Cable installation (both trenching and cable laying); and • WTG operation.

8 As described in *Chapter 7*, pile drivability assessments, which utilised data from geotechnical survey, were undertaken for representative foundation locations within the Development Area. These assessments provided the number of blows and associated blow energy likely to be required to pile drive 2438 mm diameter piles to the required depth during the installation of WTG foundations at the Development Area. Due to the varying ground conditions across the Development Area, two representative pile drivability assessments were undertaken. The first, representing the most likely ground conditions to be encountered, estimated that pin piles could be installed in approximately 2.1 hours with a 1200 kJ hammer. The second, representing the worst case in which harder substrate could be encountered, estimated piling could take up to 4.2 hours using the same sized hammer. The blow energy profile and duration of the piling activity for these two scenarios are provided below in Table 11.3 below.

Table 11.3: Results of Pile Drivability Assessments for the Most Likely and Worst Case Scenarios

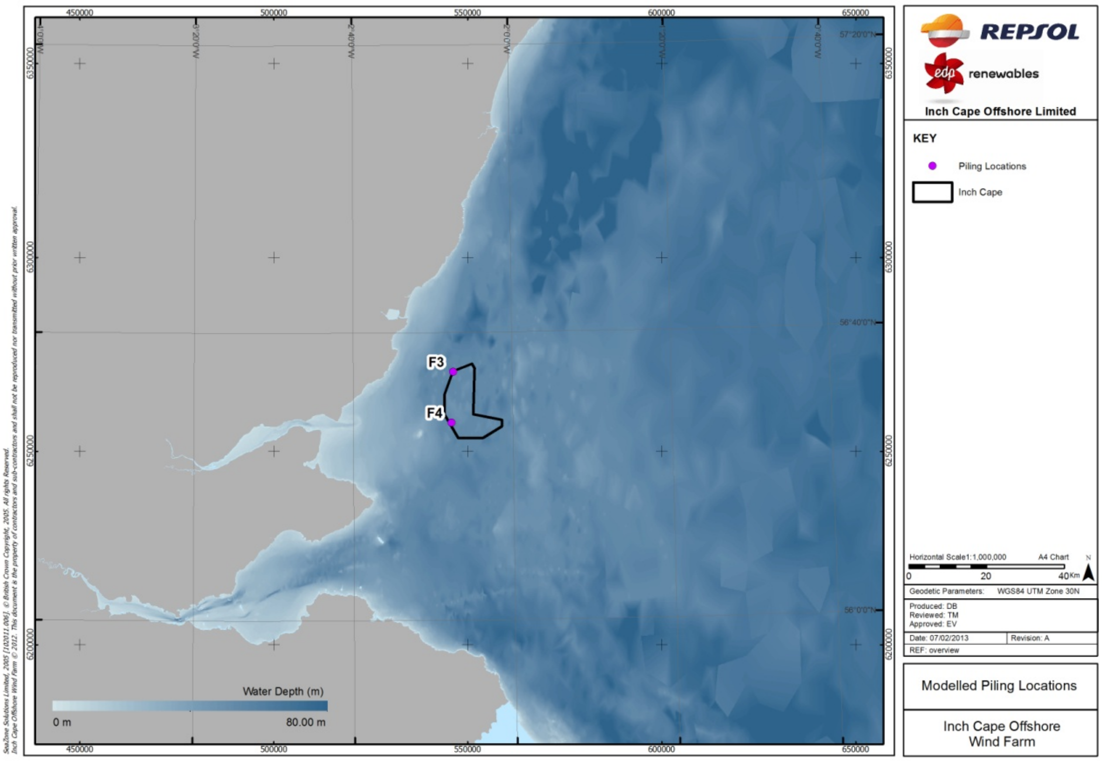
Scenario	Most Likely (ML)		Worst Case (WC)	
Pile Diameter (mm)	2438		2438	
Hammer Capacity (kJ)	1200		1200	
Max blow energy (90% of hammer capacity, kJ)	1080		1080	
Total Piling Duration (hours per pile)	2.1		4.2	
Ramp-up Details	Time	Efficiency	Time	Efficiency
	(minutes at % efficiency)	(% of max blow energy)	(minutes at % efficiency)	(% of max blow energy)
	20	15	20	15
	20	40	20	40
	10	60	10	60
	75	90	201	90
Average strike rate during soft start (per s)	0.3		0.3	
Average strike rate (per s)	2		2	

9 The most likely ground conditions are estimated to represent 70 per cent of the Development Area, with worst case constituting an estimated 30 per cent. The above blow energy profiles have been utilised to model predicted underwater noise arising from the pile driving activities associated with Wind Farm foundations. Although the piles required for the offshore substations may be larger than those required for the WTGs and met masts (up to three metres rather than 2438 mm), it is likely that the equivalent hammer will be used to install them on site. Because they will be installed during the same period as the WTGs and similar blow energies will be required, it is considered that their installation can be considered within the Design Envelope assessed (see *Chapter 7*). Installation of two pin piles per 24 hour period is considered to be most representative of likely construction activity at the Development Area. The majority of currently available construction vessels would drive two piles from one location and then be required to mobilise and reposition in order to pile the remaining two pin piles of each foundation. Thus, for the most likely scenario, modelling has been carried out using the example of two pin piles being installed consecutively per 24 hour period. While it is highly unlikely that four pin piles, requiring 4.2 hours per pin to drive,

could be installed from one vessel within a single 24 hour period with current technology, this eventuality was included within the worst case scenario.

10 In addition to the noise arising from piling utilising a single construction vessel deployed at the Development Area, modelling has also been undertaken to represent two piling vessels in operation simultaneously at the Development Area. This modelling has used both most likely and worst case piling scenarios described above in Table 11.3, and the locations for which noise modelling was undertaken are shown in Figure 11.1 below.

Figure 11.1: Map Showing Locations of the Piles Whose Driving has been Modelled at the Development Area



11 The modelling was undertaken at sites with a focus on receptors that could be most affected by the construction and operation at those sites. With respect to the Development Area, Position F3 (as shown in Figure 11.1 above) is most relevant for bottlenose dolphin, harbour porpoise, minke whale and migratory fish. Position F4 is most relevant for seal haul-outs and predicted 'at sea' distributions and white-beaked dolphin. Worst case and most likely scenarios were modelled for construction activities occurring at both positions individually and occurring at F3 and F4 together. The justifications for the selection of locations are found in *Section 13.6.1* and *Section 14.7.*

Table 11.4: Worst Case Scenario Definition – Offshore Export Cable Corridor

Potential Impact	Design Envelope Scenario Assessed
Installation Phase	
Installation Noise	Noise sources relating to installation activities in the Offshore Export Cable Corridor include: • Construction vessels; • Cable installation (both trenching and cable laying); and • Cable protection (rock placement).
Operation Phase	
Operation Noise	Noise sources relating to operation activities in the Offshore Export Cable Corridor include: • Operation vessels; and • Cable installation (both trenching and cable laying), if cable reburial is required.

12 The modelling outputs described in this chapter include the effects of embedded mitigation of 'soft start' of piling activities as recommended by Joint Nature Conservation Committee (JNCC)(2010). Further embedded mitigation relating to noise impacts cannot be reflected within the noise modelling outputs. They are, however, included as embedded mitigation within the assessment of the impacts of anthropogenic noise on sensitive receptors within *Chapter 13* and *Chapter 14*.

11.4 Baseline Environment

13 A large database, containing measurements of underwater noise taken during offshore construction projects in United Kingdom (UK) territorial waters, has been used to provide information on the background noise. The measurements, which were taken in a large range of different geographical locations and sea states, cover a broad frequency range from one Hertz (Hz) to 120 kHz, and have a dynamic range in excess of 70 dB.

14 Recordings of underwater noise taken at 10 different sites, all of which are between one kilometre and 20 km from the UK coast, have been analysed to yield typical spectra for underwater coastal background sound.

15 Background noise levels underwater often arise from distant shipping, industrial activities and other anthropogenic noise, ocean turbulence, wind, rain and biological sources (such as snapping shrimp) as well as other marine life. The measurements were analysed over the frequency range from 1 Hz to 120 kHz. All of the measurements used were taken in the absence of precipitation, with no other noticeable sources of underwater noise, such as presence of nearby shipping, present, and at Sea States from 1 to 3, with the hydrophone at half water depth (typically 10 m to 15 m below the surface).

16 There is no data available specifically for locations in the Development Area or the Offshore Export Cable Corridor, but detail for the nearest location where data is available (the Moray Firth) has been provided as an example. Figure 11.2 and Figure 11.3 below present summaries of the Power Spectral Density levels and describe how the power of the measured sound level is distributed across the frequency range. They also present the data from the nearest location (Moray Firth) as highlighted, and an average of all the data shown. Figure 11.2 presents data for measurements during Sea State 1 conditions and Figure 11.3 presents data for slightly rougher Sea State 3 conditions.

Figure 11.2: Summary of Power Spectral Density Levels of Background Underwater Noise at Sea State 1 at Sites around the UK Coast

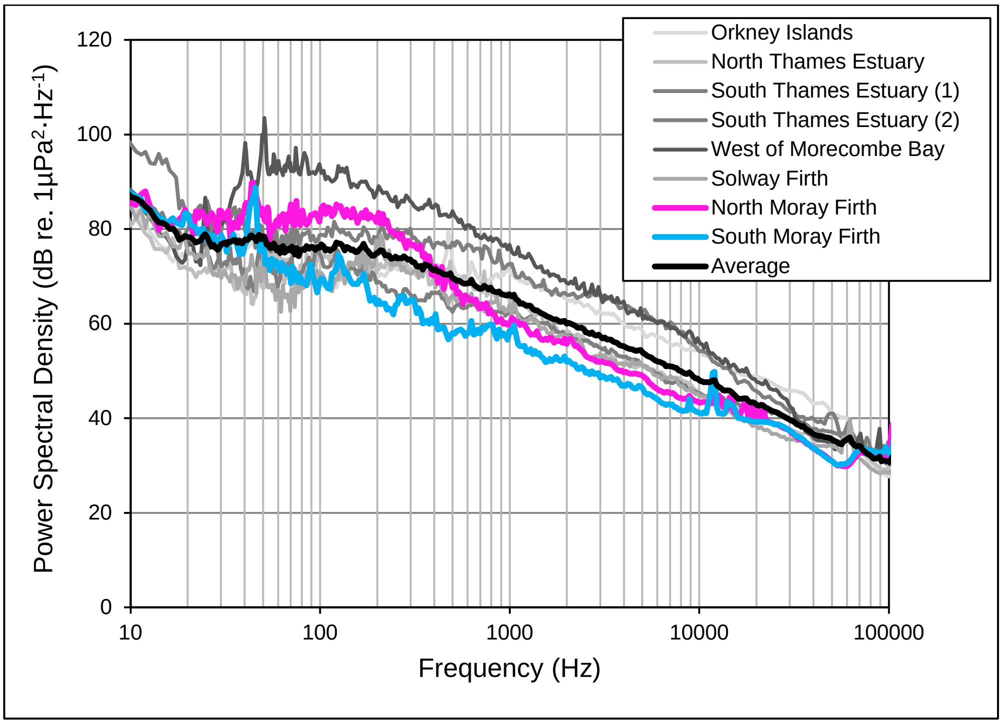
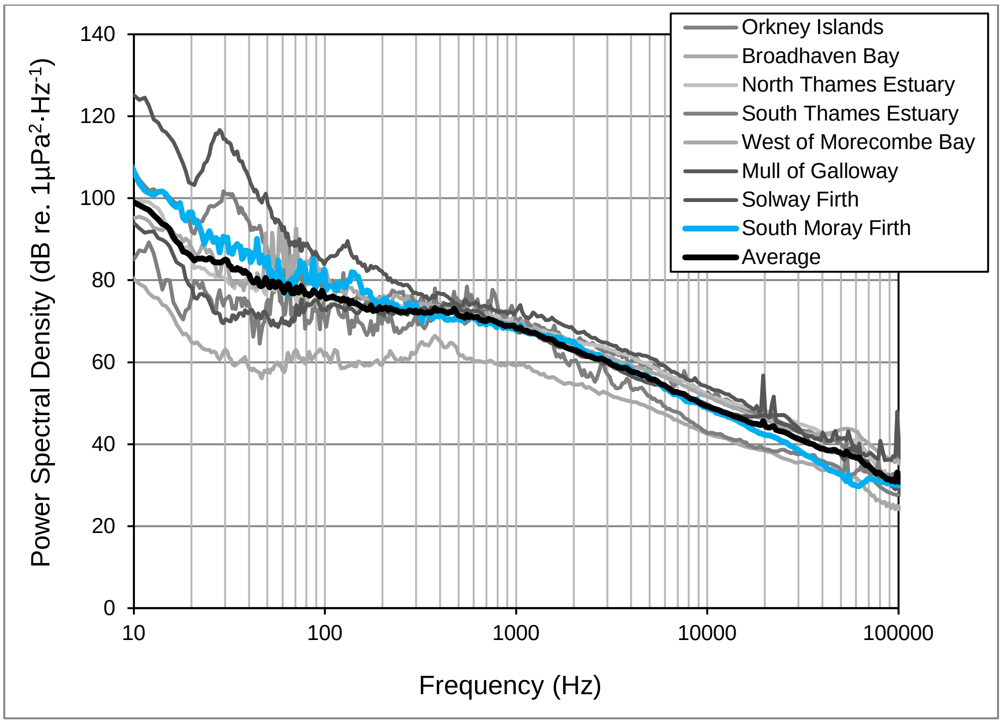


Figure 11.3: Summary of Power Spectral Density Levels of Background Underwater Noise at Sea State 3 at Sites around the UK Coast



17 Figures 11.2 and 11.3 illustrate that the unweighted values for background noise show a trend of increased background noise with an increased (rougher) sea state. This increase in background noise, however, should be seen in context with the variation of noise in each sea state and may not constitute a substantial change in noise environment. This is further illustrated in Table 11.5 and Table 11.6, which suggest that unlike fish, marine mammals perceive the noise environment of the sea state 3 as slightly quieter than sea estate 1. This is a consequence of variation in frequencies that are audible to marine mammals (higher frequency component) as opposed to fish species (lower frequency component).

Table 11.5: Summary of Average Background Levels of Noise Around the UK Coast at Sea State 1

	Unweighted dB re. 1µPa	**Bass dB_{ht}(*Micropterus salmoides*)**	**Cod dB_{ht}(*Gadus morhua*)**	**Dab dB_{ht}(*Limanda limanda*)**	**Herring dB_{ht}(*Clupea harengus*)**	**Salmon dB_{ht}(*Salmo salar*)**	**Bottlenose dolphin dB_{ht}(*Tursiops*)**	**Harbour porpoise dB_{ht}(*Phocoen phocoena*)**	**Harbour seal dB_{ht}(*Phoca vitulina*)**	**Killer whale dB_{ht}(*Orcinus orca*)**
Overall Average Background Noise Levels – Sea State 1										
Max	126	15	39	26	42	17	66	74	43	66
Min	92	0	1	0	9	0	36	44	21	37
Mean	111	5	23	10	28	5	44	54	31	47

Table 11.6: Summary of Average Background Levels of Noise Around the UK Coast at Sea State 3

	Unweighted dB re. 1µPa	**Bass dB_{ht}**	**Cod dB_{ht}**	**Dab dB_{ht}**	**Herring dB_{ht}**	**Salmon dB_{ht}**	**Bottlenose dolphin dB_{ht}**	**Harbour porpoise dB_{ht}**	**Harbour seal dB_{ht}**	**Killer whale dB_{ht}**
Overall Average Background Noise Levels – Sea State 3										
Max	132	15	42	31	47	19	50	60	38	53
Min	94	0	3	0	11	0	30	42	7	29
Mean	112	4	22	11	28	5	41	52	27	43

11.5 Methodology

18 A number of species of marine mammals, fish and shellfish use sound for prey detection, communication and navigation. Anthropogenic noise, which falls within the audible range of these species and exceeds natural background levels, has the potential to disturb and in extreme cases cause auditory injury. In recent years, the study of underwater noise associated with the construction of offshore wind farms has been a topic of substantial research (e.g. Tougaard *et al*., 2003a and 2003b; Nedwell *et al*., 2004; Bailey *et al*., 2006; Thomsen *et al*., 2006; and Nedwell *et al*., 2007a and 2007b). In the context of offshore wind farm construction activities, it is widely accepted that piling operations are likely to be the principal source of noise with the potential to harm or displace marine life. Other construction activities, such as cable laying, rock placement and the transit of vessels to and from the Development Area and the Offshore Export Cable Corridor will also increase the level of anthropogenic noise to a lesser degree, and thus potentially illicit behaviour responses in the form of avoidance of the vicinity of the activity.

19 The impacts of noise considered in the assessments in *Chapter 13 and Chapter 14* are intrinsically linked to the species under consideration, as the perception of the received sound depends on the physiological characteristics of the receptor. As such noise modelling is carried out considering the received sound for the species in question. Modelling has been undertaken for two sets of criteria:

- *dB_{ht}(Species) have been used to predict potential behavioural impacts (displacement); and*
- *dB Sound Exposure Level (SEL) have been used to predict potential auditory injury (Permanent Threshold Shift (PTS) onset).*

20 The dB_{ht}(*Species*) criteria represent noise levels that are audible to each relevant species and reflect an instantaneous noise level. The dB SEL criteria account for the duration of noise production as it reflects the total sound exposure of an animal as it swims away from the noise source throughout the duration of a pile driving event. The SEL will therefore be affected by the increased duration of noise associated with the worst case scenario compared to the most likely pile drivability scenario described in Table 11.3, and the number of piles installed within a 24 hour period.

11.5.1 Underwater Noise and Marine Species

21 The impact of sound on underwater life can have a variety of effects depending on the level of the noise. At one extreme the loudest noise can generate a substantial pressure that is sufficient to injure or kill an animal in the same way as an explosion. Noise at a lower level can have less extreme effects: damage to an animal's auditory sense will occur before any physical injury occurs. At the other end of the scale a quieter noise will not cause any harm to an animal but may trigger a behavioural response, which, at sufficient volume, will cause the animal to flee the area to escape the high noise levels. The term "flee" is a term used synonymously with "move away" and the actual modelled speed of movement is stated separately.

22 Over the past 20 years it has become increasingly evident that noise from human activities in and around underwater environments may have an impact on the marine species in the area. The extent to which intense underwater sound might cause an adverse environmental impact on a particular species is dependent upon the level of the incident sound, its frequency content, its duration and/or its repetition rate (see, for example Hastings and Popper (2005)). As a result scientific interest in the hearing abilities of aquatic animal species has increased.

23 The sound pressures required for physical injury or mortality are universal across species. However, other effects noted above, for example the noise level required to elicit a behavioural response, are species dependent. The following sections describe the criteria which will be used to assess the likelihood of an adverse impact on marine fauna within *Chapter 13* and *Chapter 14*.

11.5.2 Lethality and Physical Injury

24 The following criteria have been applied in this study for levels of noise likely to cause physical effects to marine mammals and fish:

- *lethal effect may occur where peak-to-peak levels exceed 240 dB re 1 µPa, or an impulse of 100 Pa.s;* and
- *physical injury may occur where peak-to-peak levels exceed 220 dB re 1 µPa, or an impulse of 35 Pa.s.*

11.5.3 Audiological Injury

25 At a high enough level of sound, traumatic hearing injury may occur even where the duration of exposure is short. Injury also occurs at lower levels of noise where the duration of exposure is long. In this case the degree of hearing damage depends on both the level of the noise and the duration of exposure to it. These effects can be classed as either Temporary Threshold Shifts (TTS), where a temporary loss of hearing ability occurs but there is no permanent damage, or Permanent Threshold Shift (PTS), where there is a permanent adverse impact to the threshold of hearing.

26 A set of criteria to assess auditory damage has been proposed by Southall *et al.* (2007). That study considers the likelihood of permanent hearing damage (PTS) caused by accumulated noise exposure, rather than occurring as a result of a single event. Their auditory injury criteria, for various groups of marine mammals, are based on M-weighted Sound Exposure Levels (dB re 1 µPa^2.s (M)). The M-weighting weights the incident sound according to the audiological sensitivity of marine mammal species groups, and so goes some way to reflect auditory damage being more apparent within the frequencies that the animal group can actually hear. The criteria are given in Table 11.7, and consider an accumulated sound exposure over a 24-hour period. The equivalent M-weighted SEL criteria for fish are not sufficiently developed and as such are not considered further.

27 The measures of sound quoted here (peak level, peak-to-peak level, Sound Pressure Level , Sound Exposure Level, and the M-weighting concept) are fully described in *Appendix 11A, Section 11A.2.3 and 11A.3.5*.

Table 11.7: Proposed PTS Auditory Injury Criteria for Various Cetacean Groups

Marine Mammal Group	**Sound Type** (Single and multiple pulses)
Low Frequency Cetaceans (e.g. Minke Whale)	
Sound Exposure Level	198 dB re 1 µPa^2.s (M_{lf})
Mid Frequency Cetaceans (e.g. Bottlenose Dolphin)	
Sound Exposure Level	198 dB re 1 µPa^2.s (M_{mf})
High Frequency Cetaceans (e.g. Harbour Porpoise)	
Sound Exposure Level	198 dB re 1 µPa^2.s (M_{hf})
Source: Southall *et al*. (2007)	

28 Southall also notes suggested criteria for pinnipeds, given in Table 11.8.

Table 11.8: Proposed PTS Auditory Injury Criteria for Various Pinniped Groups

Marine Mammal Group	**Sound Type** (Single and multiple pulses)
Pinnipeds (in water) (e.g. Harbour Seal)	
Sound Exposure Level	186 dB re 1 µPa^2.s (M_{pw})
Source: Southall *et al.* (2007)	

29 These figures suggest that pinnipeds are significantly more sensitive to potential PTS onset than cetaceans. However, recent research by Thompson and Hastie (2011) suggests that pinnipeds may respond to similar noise levels to cetaceans and thus the 186 dB SEL to induce PTS onset in pinnipeds may be overly conservative. However, until agreement is reached with stakeholders, the 186 dB criterion has been used to model noise doses sufficient to induce PTS onset in pinnipeds (assessed in *Chapter 14)*.

30 In order to allow the visual contextualisation of the M-Weighted SEL criteria between the 198 and 186 dB re 1 µPa^2, modelling using the M-Weighted SEL criteria has been carried out

over several increments between the two criteria for all cetaceans and pinnipeds. More detail on this is provided within *Appendix 14B: Marine Mammals Piling Impact Assessment*.

11.5.4 Behavioural Impacts

31 At levels lower than those that cause auditorial physical injury, PTS or TTS, noise may nevertheless have important behavioural effects on a species. The most significant effect is likely to be some degree of avoidance of the insonified area (the region within which noise from the source of interest is above ambient underwater noise levels).

32 The dB_{ht}(*Species*) metric (Nedwell *et al.* (2007b)) has been developed as a means for quantifying the likely audibility of a sound on a species in the underwater environment. It is similar in concept to the dB(A) in humans in that it uses a species' audiogram in its calculation. As any given sound will be perceived differently by different species (since they have differing hearing abilities) an absolute noise level will produce a different dB_{ht} value depending on what species is under consideration. Consequently the species name must be appended when specifying a level using this metric.

33 If the level of sound is sufficiently high on the dB_{ht}(*Species*) scale, it is likely that an avoidance reaction will occur. The response from a species will be probabilistic in nature (e.g. at 75 dB_{ht}(*Species*) one individual from a species may react, whereas another individual may not: the metric indicates 'loudness' of the noise and this can be related to a probability of an individual reacting). The probability of a behavioural response may also vary depending upon the type of signal.

34 A level of 0 dB_{ht}(*Species*) represents a sound that is at the hearing threshold for that species and is, therefore, at a level at which sound will start to be 'heard'. At this, and lower perceived sound levels, no response occurs as the receptor cannot hear the sound.

35 The dB_{ht} levels provided in Nedwell *et al.* (2007b) and used in the modelling are described below in Table 11.9. *Chapter 14* expands this assessment criteria to dB_{ht} levels in 5 dB_{ht} increments from 130 to 50 dB_{ht} *(Species)*. Details can be found in the *Chapter 14* and associated appendices.

Table 11.9: Criteria that can be used to Assess the Potential Effect of Underwater Noise on Marine Species.

Level in dB_{ht}(*Species*)	Effect as Provided in Nedwell *et al.* (2007b)
75 and above	Mild avoidance reaction by the majority of individuals.
90 and above	Strong avoidance reaction by virtually all individuals.

11.5.5 Species Considered

36 Table 11.10 below presents a summary of the species of interest to this study, along with some information regarding the availability of data concerning their sensitivity to underwater sound. Full references are given in *Appendix 11A*, *Section 11A.4.5*.

37 Note on lamprey (sea lamprey (*Petromyzon marinus*) and river lamprey (*Lampetra fluviatilis*)): Little data is available for lamprey of any species with respect to hearing, and no audiograms are understood to exist that provide an indication as to their sensitivity to noise, or indeed a confirmation as to whether they are able to detect sound at all (Popper, 2005). In common with cephalopods, lamprey have statolith organs, and so it is thought that they may also have a sensitivity to low frequency sound (Lenhardt M.L. and Sismour E., 1995), or particle velocity rather than sound pressure as species of 'hearing generalist' fish.

38 Table 11.10 below also includes species that were also considered, but for which no specific audiological data exists. In order to include these species a surrogate species, for which audiogram data is available, was selected. These surrogate species are considered representative of the species of interest and were selected based on their family and hearing morphology.

Table 11.10: Summary of Marine Species Included in Modelling

Species common to area	Audiogram available?	Surrogate used	Comments	Reference
Cod	Yes	-	-	Chapman and Hawkins (1973)
Herring	Yes	-	-	Enger (1967)
Salmon	Yes	-	-	Hawkins and Johnstone (1976)
Trout	Yes	-	-	Nedwell *et al* (2006)

Species common to area	Audiogram available?	Surrogate used	Comments	Reference
Bottlenose dolphin	Yes	-	-	Johnson (1967)
Harbour porpoise	Yes	-	-	Kastelein (2002)
Common (Harbour) seal	Yes	-	No single audiogram dataset covering full audiometric range available. Data from two studies used.	Kastak and Schusterman (1998) Mohl (1968)
Grey seal	Partial – only upper frequencies	Harbour seal	No single audiogram dataset covering full audiometric range available. Data from two studies used.	Kastak and Schusterman (1998) ; Mohl (1968)
Plaice	No	Dab	-	Chapman and Sand (1974)
Minke whale	No	Humpback whale	No surrogate data available for large mysticetes.	Erbe (2002)
Sandeel	No	Japanese sand lance	-	Suga et al (2005)
White beaked dolphin	No	Bottlenose dolphin	Audiogram data suggest bottlenose dolphin are most sensitive dolphin species to sound so may provide conservative indication of impacts	Johnson (1967)

11.5.6 Introduction to Noise Modelling

39 The estimation of the levels of underwater noise resulting from the development of the Wind Farm and OfTW has been undertaken in two phases:

- In the first, a broad-brush modelling approach has been used to rank order a wide range of offshore wind farm-related sources of underwater noise. This was completed using the proprietary Simple Propagation Estimator and Ranking (SPEAR) model. The information used to validate this model has come from a very substantial database of recordings of various noise sources that has been compiled by Subacoustech Ltd over the last 20 years. The model uses estimates from this database of the typical frequency content, source level and transmission losses associated with each type of noise source to calculate the variation of noise level with range from the source. The rank ordering showed that piling was the activity that generated the highest noise levels. Details of this SPEAR modelling are provided below in *Section 11.6.1*.

- As a consequence of the SPEAR modelling outputs, piling was modelled in detail using the Impulse Noise Sound Propagation and Impact Range Estimator (INSPIRE) model to provide an assessment of the levels of noise predicted to occur at various ranges from the piling operations. The results of this modelling were then used by marine ecologists to inform the assessment of impacts on fish (to be found in *Chapter 13*) and marine mammals (*Chapter 14*).

11.6 Underwater Noise Modelling

11.6.1 Initial Noise Modelling using the SPEAR model

40 The SPEAR model has been used to make noise predictions for a number of representative scenarios for the various activities related to offshore wind farms and offshore transmission works. A summary is provided in Table 11.11.

41 With the exception of impact piling durations, detailed information relating to the amount of time that construction activities will require to be carried out, for example duration of time a vessel will be on site, the type of vessel or how long dredging may take, is not available at this stage. It has therefore been necessary to take a worst case estimation in terms of noise generation which considers all the activities will be carried out continuously for a 24 hour period.

Table 11.11: Summary of Parameters Taken into Account in the SPEAR Modelling

Activity	Parameters used for SPEAR Modelling
Dredging	Suction dredger required for any seabed preparation for cables and foundations.
Drilling	Potentially required for pin pile installation.
Piling Parameters	4.2 hours (worst case) or 2.1 hours (most likely) driving per pile. 2438 mm diameter piles. 4 piles (worst case) or 2 piles (most likely) installed per day. Up to two piling vessels operating in the area simultaneously.
Operational noise	Proposed 213 WTGs Assumed 24 hours a day for operational WTGs.
Cable laying	Required during inter-array and export cable installation.
Rock placement (including concrete mattressing)	Required during inter-array and export cable installation. Part of the scour protection process for foundations.

Activity	Parameters used for SPEAR Modelling
Trenching (including Jetting and Rock Cutting)	Required during inter-array and export cable installation.
Vessel Noise	Large vessels required for piling and wind turbine generator (WTG) installation. Other large and medium sized vessels will be on site to carry out construction jobs and anchor handling.

42 The results of the SPEAR modelling for herring and the harbour seal are given in Figure 11.4 and Figure 11.5 respectively, where a 2438 mm pile is modelled for the impact piling. Herring are considered to be the most sensitive fish species, and seal a representative marine mammal species, with regards to noise sensitivity. Results for other species are given in *Appendix 11A*, *Section 11A.5*.2. The relative effects of impact piling on species considered in this assessment are shown in Figure 11.6.

Figure 11.4: Modelled Noise Ranges of Various Activities (90 dB_{ht} (*Herring*)

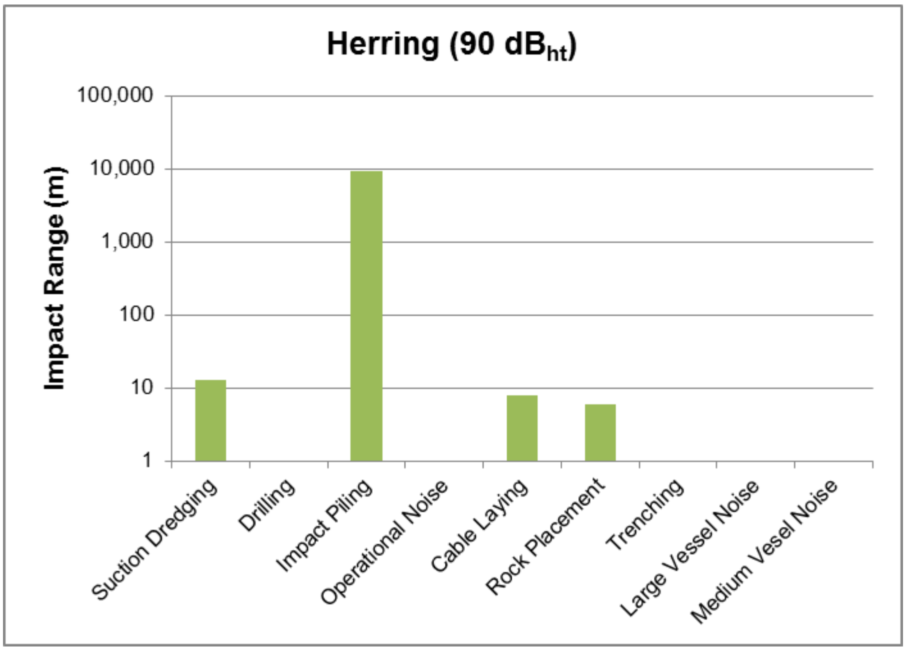


Figure 11.5: Modelled Noise Ranges of Various Activities (90 dB_{ht}(*Harbour Seal*)

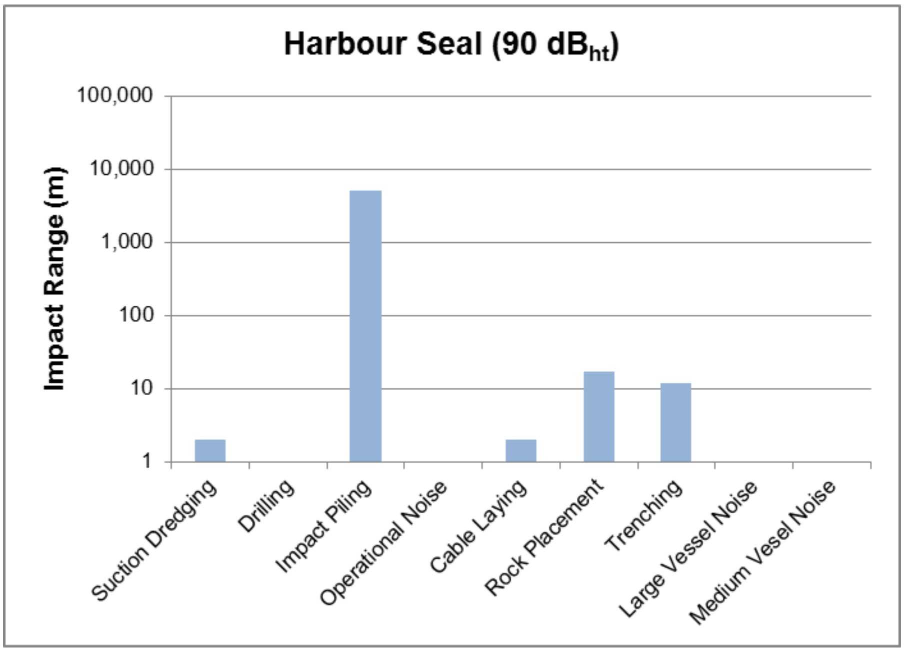
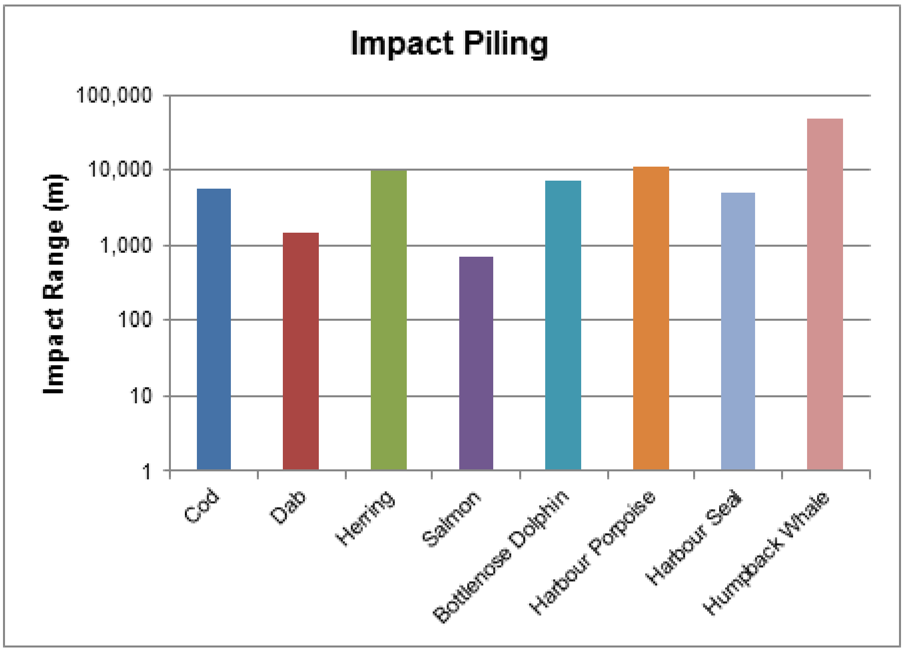


Figure 11.6: Modelled Noise Ranges for Various Species Resulting from Piling Activities 90 dB_{ht}(*Species*), using a 2438 mm Diameter Pile



43 Table 11.12 to Table 11.18 below, give the maximum perceived noise ranges and areas of sea affected for a variety of underwater noise sources other than piling. These are calculated using the SPEAR model, for the key species of fish and marine mammal using the dB_{ht}(*Species*) metric. From these results it can be seen that the largest noise range is estimated for the harbour porpoise during trenching, with a 90 dB_{ht} range of 140 m.

44 The Tables 11.12 to 11.18 show that the estimated noise ranges are greater for species of marine mammal than they are for fish. This is most likely to be because of the greater sensitivity to sound pressure of marine mammals and the substantial high frequency component of the noise. Marine mammals can perceive higher frequencies of noise than fish, and the noise sources involved for these operations are primarily in the higher frequencies. More detail of the modelling outputs using the SPEAR model is given in *Appendix 11A*, *Section 11A.5*.2.

Table 11.12: Maximum Ranges from Suction Dredging Noise using the dB_{ht}(*Species*) Metric

Activity: Suction dredging	90 dB_{ht}(*Species*) range (m)	75 dB_{ht}(*Species*) range (m)
Cod	7	39
Dab	1	7
Herring	13	65
Salmon	1	5
Bottlenose Dolphin	7	72
Harbour Porpoise	21	200
Harbour Seal	2	26
Humpback Whale	16	180

Table 11.13: Maximum Ranges from Drilling Noise using the dB_{ht}(*Species*) Metric

Activity: Drilling	90 dB_{ht}(*Species*) range (m)	75 dB_{ht}(*Species*) range (m)
Cod	2	14
Dab	<1	1
Herring	1	12
Salmon	<1	1
Bottlenose Dolphin	4	27
Harbour Porpoise	4	35
Harbour Seal	1	9
Humpback Whale	6	54

Table 11.14: Maximum Ranges from Cable Laying Noise using the dB_{ht}(*Species*) Metric

Activity: Cable laying	90 dB_{ht}(*Species*) range (m)	75 dB_{ht}(*Species*) range (m)
Cod	1	20
Dab	<1	1
Herring	8	66
Salmon	<1	1
Bottlenose Dolphin	9	75
Harbour Porpoise	29	220
Harbour Seal	2	29
Humpback Whale	18	180

Table 11.15: Maximum Ranges from Rock Placement Noise using the dB_{ht}(*Species*) Metric

Activity: Rock placement	90 dB_{ht}(*Species*) range (m)	75 dB_{ht}(*Species*) range (m)
Cod	2	25
Dab	<1	4
Herring	6	62
Salmon	<1	4
Bottlenose Dolphin	31	170
Harbour Porpoise	99	550
Harbour Seal	17	99
Humpback Whale	70	390

Table 11.16: Maximum Ranges from Trenching Noise using the dB_{ht}(*Species*) Metric

Activity: Trenching	90 dB_{ht}(*Species*) range (m)	75 dB_{ht}(*Species*) range (m)
Cod	1	16
Dab	<1	<1
Herring	<1	27
Salmon	<1	2
Bottlenose Dolphin	81	350
Harbour Porpoise	140	640
Harbour Seal	12	87
Humpback Whale	59	390

Table 11.17: Maximum Ranges from Medium Vessel Noise using the dB_{ht}(*Species*) Metric

Activity: Vessel Noise	90 dB_{ht}(*Species*) range (m)	75 dB_{ht}(*Species*) range (m)
Cod	<1	1
Dab	<1	<1
Herring	<1	3
Salmon	<1	<1
Bottlenose Dolphin	4	45
Harbour Porpoise	11	110
Harbour Seal	<1	4
Humpback Whale	2	58

Table 11.18: Maximum Ranges from Large Vessel Noise using the dB_{ht}(*Species*) Metric

Activity: Vessel Noise	90 dB_{ht}(*Species*) range (m)	75 dB_{ht}(*Species*) range (m)
Cod	<1	8
Dab	<1	<1
Herring	1	10
Salmon	<1	<1
Bottlenose Dolphin	12	110
Harbour Porpoise	22	200
Harbour Seal	<1	11
Humpback Whale	6	130

45 From measured data on operational wind farms, WTG noise is not estimated to exceed 75 dB_{ht}(*Species*) at the point of emission at the WTG tower for any of the species noted above.

46 SPEAR modelling outputs predict noise levels from trenching activity to be the loudest noise source other than piling. Table 11.20 below summarises the results of the SPEAR modelling for trenching activity in terms of the M-weighted SELs that (Southall *et al*. (2007)) propose are sufficient to induce PTS in marine mammal species. Assuming that an animal moves away from the noise source at a rate of 1.5 m/s (considered to be a typical cruising speed for a marine mammal), the SPEAR modelling outputs show it is unlikely that a marine mammal will receive a level of noise sufficient to induce auditory injury from any construction and operation activities other than piling.

Table 11.19: Summary of the Maximum Ranges from Trenching using the M-weighted SEL Metrics

Marine Mammal Group	Fleeing animal (1.5 m/s) Auditory injury range (m)
Low frequency Cetaceans (198 dB re. 1µPa/s^2(Mlf)	< 1
Mid frequency Cetaceans (198 dB re. 1µPa/s^2(Mmf)	< 1
High frequency Cetaceans (198 dB re. 1µPa/s^2(Mhf)	< 1
Pinniped (in water) (186 dB re. 1µPa/s^2(Mpw)	< 1

11.6.2 Detailed Underwater Noise Modelling using the INSPIRE Model

47 Figure 11.4 and Figure 11.5 above show that the noise associated with piling is greater than that of any other likely noise source expected during construction of the Wind Farm and OfTW. It is therefore important to make an accurate estimation of the likely noise levels so that its impact can be comprehensively assessed. There are a variety of acoustic models for the estimation of underwater noise propagation in coastal and offshore regions, mainly developed as a result of military interests. However, Subacoustech Ltd is not aware of any other underwater broadband noise propagation models suitable for the much shallower environments typical of offshore wind farm construction, or for the highly impulsive time histories encountered from impact piling. In these environments and with these source types there is a greater capacity for underwater sound to be affected by absorptive processes in the seabed, resulting in propagation losses which typically increase with frequency but decrease with depth.

48 The INSPIRE model has been developed specifically to model the propagation of impulsive broadband underwater noise in shallow waters. It uses a combined geometric and energy flow/hysteresis loss model to conservatively predict propagation in relatively shallow coastal water environments, and has been tested against measurements from a large number of other offshore wind farm piling operation[1]. The following section describes the methodology used for modelling of the propagation of underwater noise produced during impact piling.

11.6.3 Modelling of Sound Propagation

49 Sound levels underwater are usually described in terms of the Source Level (SL), which is a measure of the radiated sound at the noise's source, and the Transmission Loss (TL), which describes the way in which the radiated sound decays. The Sound Pressure Level at a specific range from the source is found from the difference between the SL and TL. For a constant depth and frequency the calculation of TL is relatively simple. In relatively shallow coastal waters, where offshore wind farms are typically situated, the depth may rapidly fluctuate between water of a few metres and deeper water of tens of metres. In these circumstances the TL becomes a more complex function of depth that depends heavily on the local bathymetry and hence must be calculated using a more sophisticated model. *Appendix 11A* gives a more detailed explanation of how sound propagation is modelled through the INSPIRE model.

50 Transmission losses are calculated by the INSPIRE model on a fully range and depth dependent basis. The model imports bathymetry data as a primary input to allow it to calculate the transmission losses along transects extending from the pile location. Other simple physical data are also supplied as input to the model. The model is able to provide a wide range of outputs, including the peak pressure, dB_{ht}(*Species*) and M-weighted Sound Exposure Level (SEL) of the noise. These quantities are fully described in *Appendix 11A*. For the purposes of predicting noise related impacts, the dB_{ht}(*Species*) and M-Weighted SEL

[1] For example, see Thompson *et al.* (2013) for the results of modelling against measured noise from the piling of the Beatrice Demonstrator foundations.

values are of relevancy to the marine ecologists and have been described in *Section 11.5.6* above.

51 As well as calculating the SEL variation with range, the model incorporates a "fleeing animal receptor" extension which enables the calculation of the noise dose an animal receives as it moves away from a piling operation. This feature permits the calculation of the nearest distance from a pile from which an animal must start fleeing such that its noise dose just reaches the criterion value at the cessation of the piling operation. In the work reported here a typical 'cruising speed' of 1.5 m/s was assigned to the mammals under consideration. Stakeholder agreement was obtained to apply fleeing animal models only and that no modelling of noise doses for stationary animals were required. It should be noted that the M-Weighted SEL criteria are designed for species of marine mammal and not fish. As a consequence no SEL modelling has been possible for fish species.

52 'Single strike' SEL noise modelling outputs were provided to inform the modelling of the exposure of marine mammals to noise. Although not represented graphically within *Appendix 11A*, outputs were provided to SMRU Ltd for all marine mammal species to populate the SAFESIMM model. SAFESIMM was then run by SMRU Ltd to predict potential numbers of individual animals that could be exposed to sufficient noise to induce PTS onset for all the scenarios described below in Table 11.21 and 11.22. Further details of this are provided in *Chapter 14*.

53 The species and criteria modelled at each location to inform the assessment of noise related impacts from piling at the Development Area and the parameters detailed in table 11.3 are provided below in Tables 11.20 and 11.21.

Table 11.20: Summary of Scenarios Modelled for Piles Driven at a Single Location in the Development Area

Pile Diameter (mm)	Number of piles/location	Piling duration (per pile)	Species/Filter	Results shown
2438	Position F3	N/A	Cod, Dab (as a surrogate for Plaice), Herring, Salmon, Sand Lance (as a surrogate for Sandeel), Trout, Bottlenose Dolphin, Humpback Whale (as a surrogate for Minke Whale), Harbour Porpoise.	90 and 75 dB_{ht} contours
2438	2 piles sequentially at Position F3	Most likely (2.1 hours)	Low Frequency Cetacean. Mid Frequency Cetacean. High Frequency Cetacean.	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M) for an animal fleeing at 1.5 m/s

Pile Diameter (mm)	Number of piles/location	Piling duration (per pile)	Species/Filter	Results shown
2438	4 piles sequentially at Position F3	Worst case (4.2 hours)	Low Frequency Cetacean. Mid Frequency Cetacean. High Frequency Cetacean.	198, 193, 188 and 186 dB re 1 μPa^2s (M) for an animal fleeing at 1.5 m/s
2438	2 piles sequentially at Position F3	Most likely (2.1 hours)	Low Frequency Cetacean. Mid Frequency Cetacean. High Frequency Cetacean. Pinnipeds (in Water).	SEL outputs for input into SAFESIMM by SMRU Ltd.
2438	4 piles sequentially at Position F3	Worst case (4.2 hours)	Low Frequency Cetacean. Mid Frequency Cetacean. High Frequency Cetacean. Pinnipeds (in Water).	SEL outputs for input into SAFESIMM by SMRU Ltd.
2438	Position F4	N/A	Cod, Dab (as a surrogate for Plaice), Herring, Salmon, Sand Lance (as a surrogate for Sandeel), Trout, Harbour Seal, Bottlenose dolphin (as a surrogate for White-beaked dolphin).	90 and 75 dB_{ht} contours
2438	2 piles sequentially at Position F4	Most likely (2.1 hours)	Mid Frequency Cetacean. Pinnipeds (in water).	198, 193, 188 and 186 dB re 1 μPa^2s (M) for an animal fleeing at 1.5 m/s
2438	4 piles sequentially at Position F4	Worst case (4.2 hours)	Mid Frequency Cetacean. Pinnipeds (in water).	198, 193, 188 and 186 dB re 1 μPa^2s (M) for an animal fleeing at 1.5 m/s

Table 11.21: Summary of Conditions Modelled for Piles Driven at Two Locations in the Development Area

Pile Diameter (mm)	Number of piles/location	Piling duration	Species/Filter	Results shown
2438	Positions F3 and F4	N/A	Cod, Dab (as a surrogate for Plaice), Herring, Salmon, Sand Lance (as a surrogate for Sandeel), Trout, Bottlenose Dolphin, Harbour Porpoise, Harbour Seal, Humpback Whale (as a surrogate for Minke Whale), Bottlenose dolphin (as a surrogate for White-beaked dolphin).	90 and 75 dB_{ht} contours
2438	2 piles sequentially at Positions F3 and F4	Most likely (2.1 hours)	Low Frequency Cetacean, Mid Frequency Cetacean, High Frequency Cetacean, Pinnipeds (in water).	198, 193, 188 and 186 dB re 1 μPa^2s (M) for an animal fleeing at 1.5 m/s
2438	4 piles sequentially at Positions F3 and F4	Worst case (4.2 hours)	Low Frequency Cetacean, Mid Frequency Cetacean, High Frequency Cetacean, Pinnipeds (in water).	198, 193, 188 and 186 dB re 1 μPa^2s (M) for an animal fleeing at 1.5 m/s

11.6.4 Decommissioning Activities

54 The potential effects of decommissioning are considered to be equivalent to and potentially lower than the worst case effects assessed for the construction phase activities. The approach to decommissioning is described in *Section 7.12*. A decommissioning plan will be prepared in accordance with the requirements of the *Energy Act 2004* (see *Section 3.2.5*) and will be subject to approval from the Department of Energy and Climate Change prior to implementation.

55 It should be noted, however, that piling will not be required during decommissioning and hence, effects associated to noise during this phase will be significantly smaller than those assessed for the construction phase above.

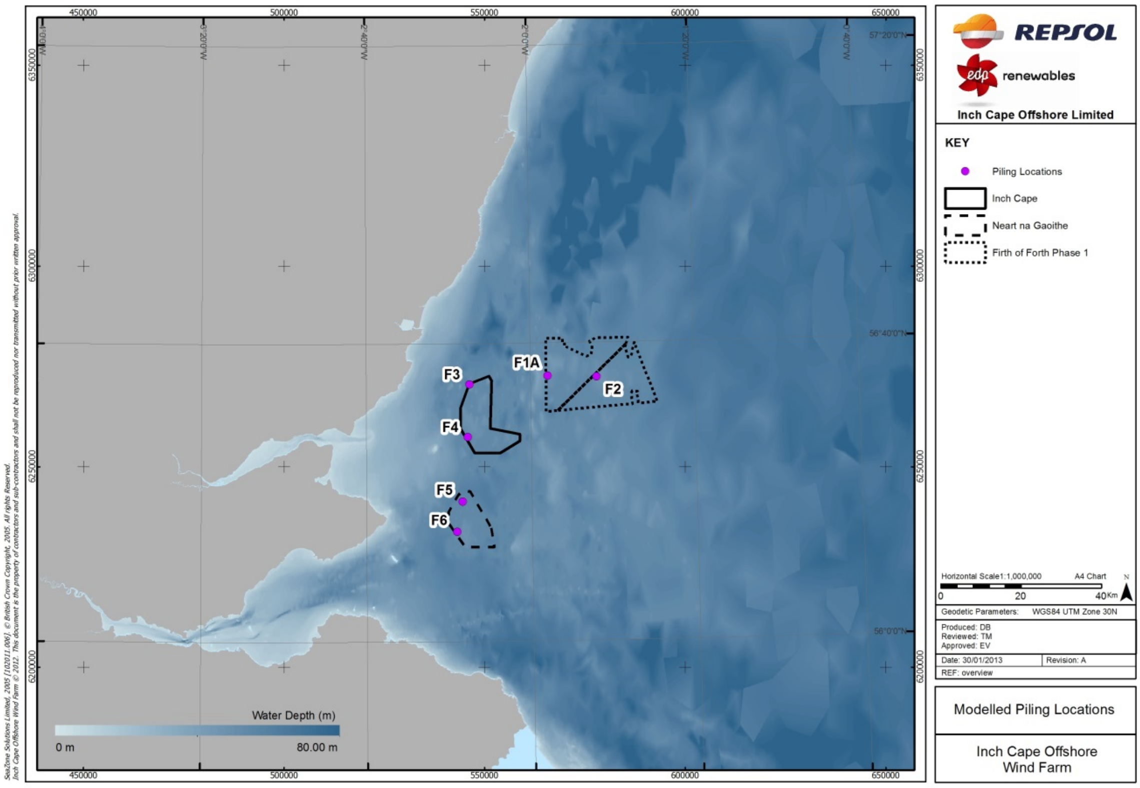
11.7 Cumulative Modelling

11.7.1 FTOWDG Modelling

56 Underwater noise modelling has been undertaken as a collaborative effort by Firth of Forth and Tay Offshore Developers Group (FTOWDG), which represents ICOL as well as the developers of the Neart na Gaoithe (NnG) (Mainstream Renewable Power) and Firth of Forth (FoF) Phase 1 (Seagreen Wind Energy Limited) wind farms. For consistency, the six positions

shown in Figure 11.7 below have been used in the underwater noise assessments provided to each member of FTOWDG to inform their Environmental Impact Assessment. The modelling was undertaken at sites with a focus on marine species that could be most affected by the wind farm construction at those sites. Cumulative modelling was undertaken using most likely blow energies and piling durations as it was considered to be less unrealistic and this approach was agreed with regulators. Detail on the modelling outputs and how these noise ranges are interpreted in terms of predicted impact upon receptors can be found in *Chapter 13* and *Chapter 14*.

Figure 11.7: Map Showing Locations for FTOWDG INSPIRE Noise Modelling



57 Using all six of the locations and data provided by all three FTOWDG developers, a situation in which multiple piling events may occur simultaneously or within the same 24-hour period was modelled.

58 Table 11.22 and Table 11.23 provide the blow energy profile provided by the NnG and FoF developers as being indicative for the driving of the noted diameter piles into the seabed of the relevant site. Each Developer undertook and reviewed of the relevant site geophysical and geotechnical data available to them and undertook pile drivability assessments to produce these indicative blow energy profiles.

59 The scenarios modelled include both one and two vessels operating on all three sites, and are detailed below in Table 11.24 and Table 11.25 below.

Table 11.22: Most Likely Predicted Blow Energy Profile Required to Drive a 2500 mm Diameter Pin Pile at the Neart na Gaoithe Site

Energy (kJ)	Number of strikes	Duration (s)
240	600	1200
996	5400	10800

Table 11.23: Most Likely Predicted Blow Energy Profile Required to Drive a 2000 mm Diameter Pin Pile at the Firth of Forth Site

Energy (kJ)	Number of strikes	Duration (s)
180	223	298
420	527	702
660	478	637
900	217	289

11.7.2 Modelling of Sound Propagation

60 The following tables (Tables 11.24 and 11.25) give an overview of the modelling and the results presented for the various cumulative scenarios. All the outputs of the scenarios modelled for each of the receptors can be found within *Appendix 11A*.

Table 11.24: Summary of Conditions Modelled for Piles Driven at a Single Location at Inch Cape Development Area (IC), Firth of Forth (FoF) and Neart na Gaoithe (NnG)

Pile Diameter (mm)	Number of piles/location	Maximum blow energy (kJ)	Species/Filter	Results shown
2438 (IC) 2500 (NnG) 2000 (FoF)	Position F3 Position F5 Position F1A	1080 (IC) 996 (NnG) 900 (FoF) (most likely)	Dab (as a surrogate for Plaice), Herring, Salmon, Sand Lance (as a surrogate for Sandeel), Trout, Bottlenose Dolphin, Humpback Whale (as a surrogate for Minke Whale).	90 and 75 dB_{ht} contours
2438 (IC) 2500 (NnG) 2000 (FoF)	Position F4 Position F5 Position F1A	1080 (IC) 996 (NnG) 900 (FoF) (most likely)	Harbour Seal.	90 and 75 dB_{ht} contours

Pile Diameter (mm)	Number of piles/location	Maximum blow energy (kJ)	Species/Filter	Results shown
2438 (IC) 2500 (NnG) 2000 (FoF)	Position F3 Position F5 Position F2	1080 (IC) 996 (NnG) 900 (FoF) (most likely)	Harbour Porpoise.	90 and 75 dB_{ht} contours
2438 (IC) 2500 (NnG) 2000 (FoF)	Position F4 Position F5 Position F2	1080 (IC) 996 (NnG) 900 (FoF) (most likely)	Bottlenose dolphin (as a surrogate for White-beaked Dolphin).	90 and 75 dB_{ht} contours
2438 (IC) 2500 (NnG) 2000 (FoF)	2 piles sequentially at Position F3, 1 pile at Position F5 and 1 pile at Position F1A	1080 (IC) 996 (NnG) 900 (FoF) (most likely)	Low Frequency Cetacean. Mid Frequency Cetacean.	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M) for an animal fleeing at 1.5 m/s
2438 (IC) 2500 (NnG) 2000 (FoF)	2 piles sequentially at Position F4, 1 pile at Position F5 and 1 pile at Position F1A	1080 (IC) 996 (NnG) 900 (FoF) (most likely)	Pinnipeds (in Water).	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M) for an animal fleeing at 1.5 m/s
2438 (IC) 2500 (NnG) 2000 (FoF)	2 piles sequentially at Position F3, 1 pile at Position F5 and 1 pile at Position F1A	1080 (IC) 996 (NnG) 900 (FoF) (most likely)	High Frequency Cetacean.	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M) for an animal fleeing at 1.5 m/s
2438 (IC) 2500 (NnG) 2000 (FoF)	2 piles sequentially at Position F4, 1 pile at Position F5 and 1 pile at Position F1A	1080 (IC) 996 (NnG) 900 (FoF) (most likely)	Mid Frequency Cetacean.	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M) for an animal fleeing at 1.5 m/s

Table 11.25: Summary of Conditions Modelled for Piles Driven at Two Locations at Inch Cape, Firth of Forth and Neart na Gaoithe

Pile Diameter (mm)	Number of piles/location	Maximum blow energy (kJ)	Species/Filter	Results shown
2438 (IC) 2500 (NnG) 2000 (FoF)	Position F3, F4 Position F5, F6 Position F1A, F2	1080 (IC) 996 (NnG) 900 (FoF) (most likely)	Dab (as a surrogate for Plaice), Herring, Salmon, Sand Lance (as a surrogate for Sandeel), Trout, Bottlenose Dolphin, Harbour Porpoise, Harbour Seal, Humpback Whale (as a surrogate for Minke Whale), Bottlenose dolphin (as a surrogate for White-beaked dolphin)	90 and 75 dB_{ht} contours
2438 (IC) 2500 (NnG) 2000 (FoF)	2 piles sequentially at Positions F3 and F4. 1 pile at each F5, F6, F1A and F2.	1080 (IC) 996 (NnG) 900 (FoF) (most likely)	Low Frequency Cetacean, Mid Frequency Cetacean, High Frequency Cetacean, Pinnipeds (in water).	198, 193, 188 and 186 dB re 1 $\mu Pa^2 s$ (M) for an animal fleeing at 1.5 m/s

11.8 Conclusions

61 The propagation of noise from activities likely to occur within the Development Area and associated with the Offshore Export Cable Corridor have been modelled. Both a worst case and most likely scenario for piling have been considered for foundation installation at the wind farm, and cumulative scenarios, where simultaneous foundation installation may occur at multiple proposed offshore wind farms within the Firth of Forth and Tay, have also been modelled.

62 The different effects have been modelled in terms of unweighted decibels with respect to lethal and physical injury effects, 'M-weighted' sound exposure levels to calculate potential auditory damage to marine mammals and dB_{ht}(*Species*) primarily for behavioural effects of marine mammals and fish. The information presented in this chapter has been used to inform the assessment of impacts of underwater noise on fish and shellfish, and marine mammals (see *Chapter 13* and *Chapter 14)*.

References

Bailey, H. (2006). *Distribution and habitat use of bottlenose dolphins (Tursiops truncates) at varying temporal and spatial scales*. PhD thesis.

Chapman, C.J. and Hawkins, A.D. (1973). *A field study of hearing in the cod, Gadus morhua L.* Journal of comparative physiology, 85: pp147 – 167, Reported in Hawkins A D and Myberg (1983) A A, Hearing and sound communication underwater, In: Bioacoustics: a comparative approach, Lewis, B., (ed) pp 347 – 405, Academic press, New York.

Chapman, C.J. and Sand, O. (1974). *Field studies of hearing in two species of flatfish Pleuronectes platessa (L.) and Limanda limanda (L.) (Family Pleuronectidae).* Comp.Biochem. Physiol. 47A, 371-385.

Enger, P.S. (1967). *Hearing in herring*. Comp. Biochem. Physiol., Vol 22: pp527-538.

Erbe, C. (2002). *Underwater noise of whale-watching boats and potential effects on killer whales (Orcinus orca), based on an acoustic impact model*. Mar. Mammal Sci. 18:394-418.

Hastings, M.C. and Popper, A.N. (2005). *Effects of sound on fish. Report to the California Department of Transport*, under contract No. 43A01392005, January 2005.

Hawkins and Johnstone (1976). (full details of ref. not available in photocopy of Hawkins and Myrberg seen).

Johnson, C.S. (1967). *Sound detection thresholds in marine mammal*s. In W N Tavolga (ed), Marine bioacoustics, Vol 2, Pergamon, Oxford, UK.

Joint Nature Conservation Committee (2010). *Statutory nature conservation agency protocol for minimising the risk of injury to marine mammals from piling noise*. August 2010. Available at: http://jncc.defra.gov.uk/pdf/JNCC_Guidelines_Piling%20protocol_August%202010.pdf

Kastak, D. and Schusterman, R.J. (1998). *Low frequency amphibious hearing in pinnipeds: Methods, measurements, noise and ecology*. Journal of the Acoustical Society of America, 103(4), 2216-2228.

Kastak, D. Schusterman, R.J. Southall, B.L. and Reichmuth, C.J. (1999). *Underwater temporary threshold shift induced by octave-band noise in three species of pinnipeds*. Journal of the Acoustical Society of America 106(2): 1142-1148.

Kastelein, R.A., Hagedoorn, M., Au, W.W.L. and Haan, D. (2002). *Audiogram of a striped dolphin (Stenella coeruleoalba)*. J.Acoust.Soc.Am., Vol 113 (2), pp1130-1137.

Kastelein, R.A., Hagedoorn, M., Au, W.W.L. and Haan, D. (2003). *Audiogram of a harbour porpoise (Phocoena phocoena) measured with narrow-band frequency-modulated signals*. J Acoust Soc Am, 112, 334-344.

Lenhardt, M.L. and Sismour, E. (1995). *Hearing in the sea lamprey (Petromyzon marinus) and the long nose gar (Lepisosteus spatula)*. Journal of the Association for Research in Otolaryngology.

Mohl, B. (1968). *Auditory sensitivity of the common seal in air and water*. Journal of Auditory Research, 8, 27-38.

Nachtigall, P.E., Au, W.W.L., Pawloski, J. and Moore, P.W.B. (1995). *Risso's dolphin (Grampus griseus) hearing thresholds in Kaneohe Bay, Hawaii.* In Sensory Systems of Aquatic Mammals (ed. R. A. Kastelein, J. A. Thomas and P. E. Nachtigall), pp. 49-53. Woerden, The Netherlands: DeSpil.

Nedwell, J.R. and Howell, D. (2004). *A review of offshore wind farm related underwater noise sources* Subacoustech Report ref. 544R0308.

Nedwell, J.R., Turnpenny, A.W.H., Lovell, J.M., and Edwards, B. (2006). *An investigation into the effects of underwater piling noise on salmonids*. J. Acoust. Soc. Am. Volume 120, Issue 5, pp 2550-2554.

Nedwell, J.R., Parvin, S.J., Edwards, B., Workman, R., Brooker, A.G. and Kynoch, J.E. (2007a). *Measurement and interpretation of underwater noise during construction and operation of offshore windfarms in UK waters*. Subacoustech Report No. 544R0738 to COWRIE ISBN: 978-09554279-5-4.

Nedwell, J.R., Turnpenny, A.W.H., Lovell, J., Parvin S.J., Workman R., Spinks. J.A.L., Howell, D. (2007b). *A validation of the dB_{ht} as a measure of the behavioural and auditory effects of underwater noise.* Subacoustech Report Reference: 534R1231, Published by Department for Business, Enterprise and Regulatory Reform.

Nedwell, J.R., Barham R., Brooker, A. (2011). *The INSPIRE piling noise model and its test against actual data*. Subacoustech report ref no. E287R0619.

Popper, A.N. (2005). *A review of hearing by sturgeon and lamprey*. Submitted to the U.S Army Corps of Engineers, Portland District.

Southall, Brandon L.; Bowles, Ann E.; Ellison, William T.; Finneran, James J.; Gentry, Roger L.; Greene, Charles R.; Kastak, David; Ketten, Darlene R.; Miller, James H.; Nachtigall, Paul E.; Richardson, W. John; Thomas, Jeanette A.; Tyack, Peter L, (2007). *Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations*. Aquatic Mammals, Vol 33 (4).

Suga, T., Akamatsu, T., Sawada, K., Hashimoto, H., Kawabe, R., Hiraishi, T., and Yamamoto, K. (2005). *Audiogram measurement based on the auditory brainstem response for juvenile Japanese Sand Lance (Ammodytes personatus)*. Fisheries Science, Volume 71, Number 2 (2005) pp 287-292.

Szymanski, M.D., Bain D.E., Kiehl, K., Henry K.R., Pennington, S. and Wong, S. (1999). *Killer whale (Orcinus orca) hearing: auditory brainstem response and behavioral audiograms*. J. Acoust. Soc. Amer. 106:1134-1141.

Thompson, P. and Hastie, G. (2011). *Proposed revision of noise exposure criteria for auditory injury in pinnipeds*. Awaiting publication.

Thomsen, F., Lüdemann, K., Kafemann, R. and Piper, W. (2006). *Effects of offshore wind farm noise on marine mammals and fish*, on behalf of COWRIE Ltd.

Tougaard, J., Carstensen, J., Henriksen, O.D., Skov, H., and Teilmann, J. (2003a). *Short-term effects of the construction of wind turbines on harbour porpoises at Horns reef*. Technical report to TechWise A/S. HME/362-02662. Hedeselskabet, Roskilde, Denmark.

Tougaard, J. Castensen, J., Henriksen, O.D., Teilmann, J. and Hansen, J.R. (2003b). *Harbour Porpoises on Horns Reef - Effects of the Horns Reef Wind Farm*. Annual Status Report 2003 to Elsam Engineering A/S. NERI Technical Report, Roskilde, Denmark.