European Offshore Wind Deployment Centre

Environmental Statement

Appendix 3.1: Underwater Noise Modelling

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Subsea Noise Modelling in Support of the European Offshore Wind Deployment Centre Development

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1 UNDERWATER NOISE IMPACT ASSESSMENT

1.1 Introduction

1 Subacoustech Environmental has been contracted by Aberdeen Offshore Wind Farm Ltd to investigate the potential impacts that the noise generated by the construction of the European Offshore Wind Deployment Centre (EOWDC) off the coast of Aberdeen may have on marine fauna, by means of subsea noise propagation modelling. Of particular concern is the noise generated during impact piling operations to install the foundations of the wind turbines and it is this aspect that this report concentrates on.

2 The EOWDC will be located within an area approximately 2 km from the coast that extends eastwards to approximately 4.5 km offshore. The depth of the wind turbine positions range from approximately 19 m to 30 m. The proposed project will combine a small commercially operated wind farm with a test and research centre, allowing manufacturers to test “first of run” wind turbines and innovative foundation solutions along with related operation and maintenance access logistics. The project may also include an Ocean Laboratory which would allow environmental monitoring before, during and after deployments.

3 Aberdeen Bay is an important area for several species of marine mammal, most notably bottlenose dolphin (*Tursiops truncatus*) but also harbour porpoise (*Phocoena phocoena*), grey seals (*Halichoerus grypus*) and harbour seals (*Phoca vitulina*). In summer months white-beaked dolphins (*Lagernorhynchus albirostris*), Minke whales (*Balaenoptera acutorostrata*) and Risso’s dolphins (*Grampus griseus*) have also been sighted.

4 The sections below initially provide some background to the metrics and accepted criteria for the assessment of underwater noise so providing some background to the subject. The report then presents the results of the modelling in which an estimation of the various impact ranges is given including the ranges for lethality, physical injury, auditory damage and behavioural avoidance.

1.2 Measurement of Underwater Noise

1.2.1 Introduction

5 Sound travels much faster in water (approximately 1,500 m/s) than in air (340 m/s). Since water is a relatively incompressible, dense medium, the pressures associated with underwater sound tend to be much higher than in air. As an example, background levels of sea noise of approximately 130 dB re 1 µPa (a definition of these units are covered in section 1.2.2) for UK coastal waters are not uncommon (Nedwell *et al*, 2003 and 2007). This level equates to about 100 dB re 20 µPa in the units that would be used to describe a sound level in air. Such levels in air would be considered to be hazardous. However, marine mammals and fish have evolved to live in this environment and are thus relatively insensitive to sound pressure compared with terrestrial mammals. The most sensitive thresholds are often not below 100 dB re 1 µPa and typically not below 70 dB re 1 µPa (44 dB re 20 µPa using the reference unit that would be used in air).

6 For this reason it is generally of little use and potentially misleading to directly compare sound sources underwater to those in air. Table 1.2-1 presents a summary of the typical levels of noise for various sound sources in air (HSE, 2005) and in water (Nedwell *et al*, 2003, Nedwell *et al,* 2007, Urick, 1983 and Parvin *et al,* 2007). From these data it is clearly evident that the typical levels of underwater noise are far higher than those found in air. This should be borne in mind when considering quoted levels of underwater noise.

Table 1.2-1 – Summary of typical levels of noise from various sources in air (all values referenced to 20 µPa) and in water (all values referenced to 1µPa)

Typical noise levels in air		**Typical noise levels in water**	
Sound Source	**Typical noise level (dB re 20 µPa)**	**Sound Source**	**Typical noise level (dB re. 1 µPa)**
Quiet office	~40 dB	Background noise	100 – 130 dB RMS
Conversation	~60 dB	Fishing trawler	168 dB RMS @ 1 m range
Pneumatic road drill	~100 dB	Impact piling	243 – 257 dB peak to peak @1 m
Jet aircraft taking off 25 m away	~140 dB	Underwater explosive blast	285 dB peak pressure @ 1 m

1.2.2 Units of Measurement

7 Measurements of underwater sound are usually expressed using the decibel (dB) scale, which is a logarithmic measure of sound. A logarithmic scale is used because rather than equal increments of sound having an equal increase in effect, typically a constant ratio is required for this to be the case, that is, each doubling of sound level will cause a roughly equal increase in "loudness".

8 Any quantity expressed in this scale is termed a "level". If the unit is sound pressure, as is the case with underwater noise, it will be termed a "Sound Pressure Level" (SPL). A refinement is that the scale such as when used with sound pressure is that the pressure squared is applied rather than the pressure. If this were not the case, if the acoustic power level of a source rose by 10 dB the Sound Pressure Level would rise by 20 dB.

9 As the dB scale represents a ratio (that is, the result of dividing one quantity by another base quantity), it is used with a reference unit which expresses the base from which the ratio is expressed. For underwater sound, typically a unit of one microPascal (µPa) is used as the reference unit; a Pascal is equal to the pressure exerted by one Newton over one square metre. One microPascal equals one millionth of this. It is important to state the reference unit when describing the level of a sound in decibels as the use of a different reference pressure for a given measured sound pressure will result in a different value. For underwater noise, therefore, a noise level would be expressed as "120 dB re 1 µPa", for example.

1.2.3 Quantities of Measurement

10 A sound level may be expressed in many different ways depending upon the particular type of noise that is being measured, and the parameters of the noise that allow it to be evaluated in terms of a biological effect. For example,

measurement of underwater noise following the detonation of explosives indicates a clear peak in positive (high) pressure and only a much smaller peak in negative (low) pressure. As the resulting impact on any surrounding objects is likely to be related to the positive peak, it is usually appropriate to quote the peak (sometimes also referred to as zero-peak) level of the sound.

11 For impact piling, however, where the pressure wave is roughly equal in positive and negative peaks, the resulting impact is likely to be related to both the positive and negative pressure peaks. It is therefore more appropriate to quote the level in terms of “peak to peak” levels which is the maximum variation between the positive and negative pressures in the sound wave. The zero-peak sound levels have also been included in this report for completeness.

12 When noise and vibration is of a continuous nature such as that associated with drilling, boring, continuous wave sonar, or background sea and river noise levels, it is more appropriate to characterise the noise level over a longer period of time. The variation in sound pressure is therefore measured over a specific time period to determine the Root Mean Square (RMS) level of sound that is varying with time. This is the RMS Sound Pressure Level (RMS SPL) which can be considered to be a measure of the average unweighted level of the sound over the measurement period.

13 Where a particular noise source is expressed in terms of RMS SPL it is necessary to quote the time period over which the RMS level is calculated. For instance, in the case of a transient noise source such as a pile strike lasting say a tenth of a second this is critically important as the mean taken over a tenth of a second will be ten times higher than the mean taken over one second.

14 Another way of expressing sound levels used in this study is the Sound Exposure Level (SEL), which sums the acoustic energy over a measurement period, and effectively takes account of both the SPL of the sound source and the duration the sound is present in the acoustic environment. Where the SPL is a measure of the average level of the broadband noise, the SEL sums the cumulative broadband noise energy. Therefore, for continuous sounds of duration less than one second, the SEL will be lower than the SPL. For periods of greater than one second the SEL will be numerically greater than the SPL (i.e. for a sound of ten seconds duration the SEL will be 10dB higher than the SPL, for a sound of 100 seconds duration the SEL will be 20 dB higher than the SPL and so on).

1.2.4 Source Level and Transmission Loss

15 As sound propagates through water it reduces in level as a result of losses relating to energy dissipation (absorption) and also due to the sound energy simply spreading over a wider area (geometric spreading). Typically, a source of underwater noise is quantified in terms of a Source Level, which is the level of sound energy released by the source, usually described as the level of underwater noise at a range of 1 m from the source. In order to characterise the rate at which energy is lost a value for the Transmission Loss is often given. The level at a particular point in the water space is therefore the Source Level minus the Transmission Loss.

16 Over short distances, absorption effects have little influence on the Transmission Loss and can often be ignored. The Source Level itself may be quoted in any physical quantity, for instance, a piling source may be expressed as having a “peak to peak Source Level of 200 dB re 1 μPa @ 1m”.

17 This simple but convenient formulation ignores the practical difficulty of estimating the Source Level. Since the measurements are usually made at some distance from the source and extrapolated back to the source, the true level at 1 m may actually be very different from the Source Level used in these equations.

18 It is often not realised that, since the value of Source Level quoted for a particular source is obtained by extrapolation; the value will depend on the model that is used to perform the extrapolation. Figure 1.2-1 illustrates this point. The diagram illustrates a set of measurements made of the noise from piling. In the simplest case, in order to draw conclusions about the data, it may be fitted to a straight-line model; this is shown in the figure by the green line. Such a model effectively assumes that the noise level attenuates only as a result of geometric spreading. This however will generally over-estimate the level for low and high ranges, since it ignores the effects of absorption of the noise. An improved model, including absorption, is represented by the red line and gives a better fit to the data, and indeed this simple form is usually adequate for modelling sound propagation from a source in deep water of roughly constant depth. However, in the case of shallow coastal waters, where the proposed project is situated, the depth may rapidly fluctuate between shallow water of a few metres and deep water of tens of metres or more. In these circumstances, the Transmission Loss becomes a more complex function of depth that depends heavily on the local bathymetry and hence should ideally be calculated using a more sophisticated model, such as Impulse Noise Sound Propagation and Impact Range Estimator (INSPIRE). Where these effects are included, as illustrated by the blue line, yet another value of Source Level may result; typically lower levels of noise may be predicted near to the noise source.

19 The variation in estimates of Source Level for the same dataset, when analysed in different ways, indicates how Source Level will in general be a function of the model that is used to express the noise levels.

20 Where actual measured underwater noise data from a particular activity is not available, ideally the most sophisticated model for that noise will be used in all cases. These tend to require a very advanced level of knowledge of how a particular sound behaves in the underwater environment and/or a large amount of information on the conditions at the particular site such as temperature, salinity, etc and of the substrate conditions. Where actual measured data from a similar activity is available the introduction of the numerous variables used in sophisticated models is not required, hence reliance of measured data is generally preferable.

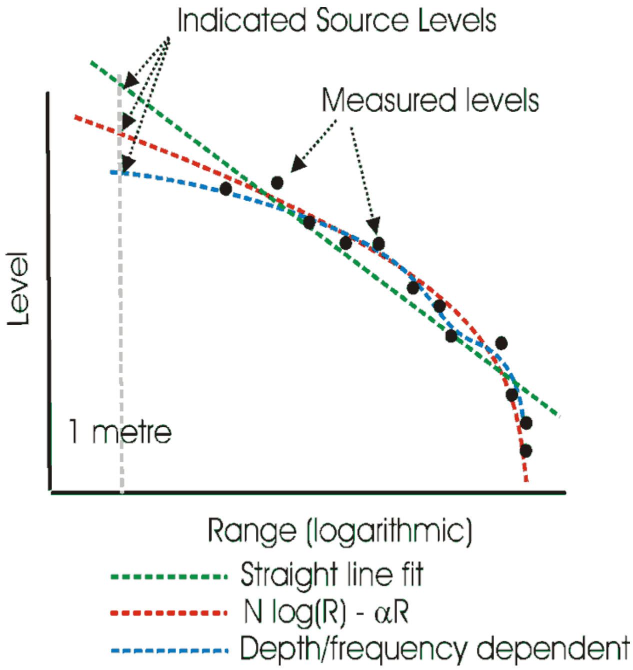

Figure 1.2-1 – Differences in Source Level estimation based on various models

1.3 Key Guidance Documents

21 The following documents have been used to inform this assessment:

- Nedwell J R, Turnpenny A W H, Lovell J, Parvin S J, Workman R, Spinks J A L and Howell D. (2007). *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.
- Southall B L, Bowles A E, Ellison W T, Finneran J J, Gentry R L, Greene C R, Kastak D, Ketten D R, Miller J H, Nachtigall P E, Richardson W J, Thomas J A and Tyack P L. (2007). *Marine Mammal Noise Exposure Criteria Aquatic Mammals*, Vol. 33 (4).
- Joint Nature Conservation Committee (JNCC), National England and Countryside Council for Wales. (2010). *The protection of marine European Protected Species from injury and disturbance;* Guidance for English and Welsh territorial waters and the UK offshore marine area. July 2009.

1.4 Data Information and Sources

22 The INSPIRE acoustic model is tested and validated against Subacoustech Environmental Ltd's extensive digital database of offshore noise measurements.

23 In addition, digital bathymetry supplied by SeaZone Solutions Ltd (License No. 052005.003) is used as an input to the INSPIRE noise propagation model.

1.5 Impact Methodology

1.5.1 Introduction

24 The methodology utilised in this impact assessment is similar to that used for numerous other studies carried out for the offshore wind industry. This approach utilises the proprietary Impulse Noise Sound Propagation and Impact Range Estimator (INSPIRE) model that has been specifically designed over five years to predict the likely level of underwater noise from impact piling operations. INSPIRE is a broadband model, that is, it does not calculate levels frequency by frequency, but in terms of the physics of the absorption of a pulse. INSPIRE uses a combination of loss caused by the spreading of the energy of the sound field (geometric loss) and loss caused by energy in the water column being absorbed in the underlying sea bed (absorption losses). This is used to estimate the likely transmission losses as the sound propagates away from the source; in this case impact piling. The model is therefore capable of estimating the effect of rapidly varying water depths that are commonly found in UK coastal waters. It has been validated against a wide range of actual measurements carried out by Subacoustech Environmental.

1.5.2 Pile Sizes

25 Currently available information suggests that the level of underwater noise from impact piling operations is closely related to both the pile size with sound levels increasing with pile size. The blow force applied to the pile also influences the noise levels produced; however, typically, blow forces also increase with pile size so these two factors are actually interdependent. The INSPIRE model also takes this into account via the inbuilt Source Level function.

26 Figure 1.5-1 shows a summary of Source Levels extrapolated from measured data on a number of impact piling operations using various pile sizes. It can be seen that as the diameter of the pile increases, the source level also increases. The estimated Source Level for an 8.5 m diameter pile is also plotted in Figure 1.5-1.

27 However, it should be noted that since the estimated Source Levels rely on extrapolation of data for other sizes of piles there is a degree of uncertainty associated with the estimate.

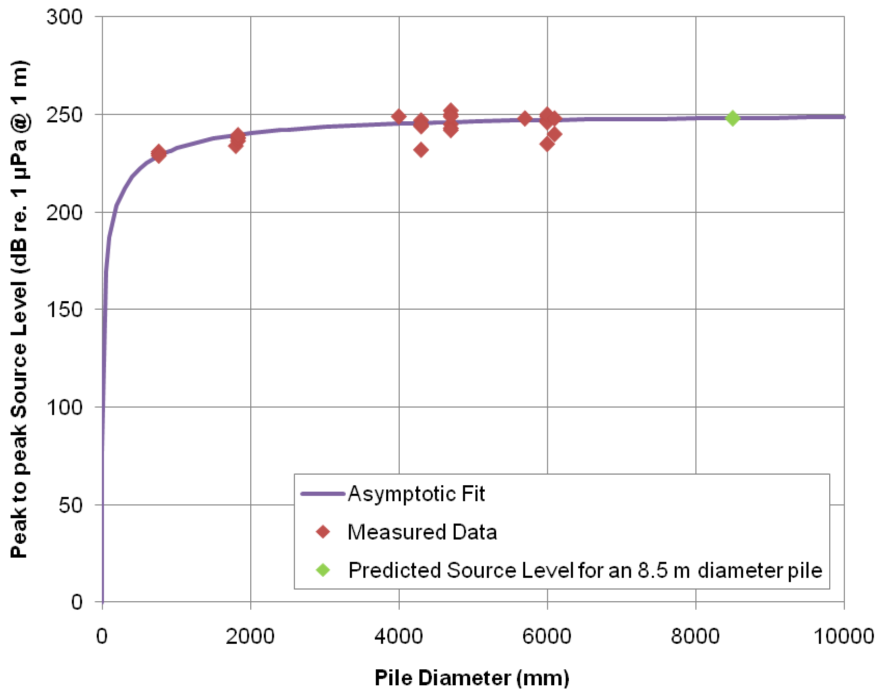

Figure 1.5-1 - Plot showing the asymptotic best fit to source level calculated from measured piling noise data for various pile sizes along with the predicted source level for an 8.5 m pile

1.5.3 Water Depths and Modelling Locations

28 The other main factor that affects the level of underwater noise is the local bathymetry, with sound attenuating at a faster rate over shallow water as opposed to deeper waters. The INSPIRE model uses digital bathymetric data provided by SeaZone Solutions Ltd, to input water depth data into the model.

29 Figure 1.5-2 shows a plan of the proposed EOWDC site along with the four wind turbine positions for which underwater noise modelling has been carried out. These are wind turbine positions 1, 3, 7 and 11. These four positions have been chosen to represent the greatest variation across the site in terms of location and to a lesser extent water depths, ranging from approximately 20 m LAT to the west to just under 30 m to LAT to the east.

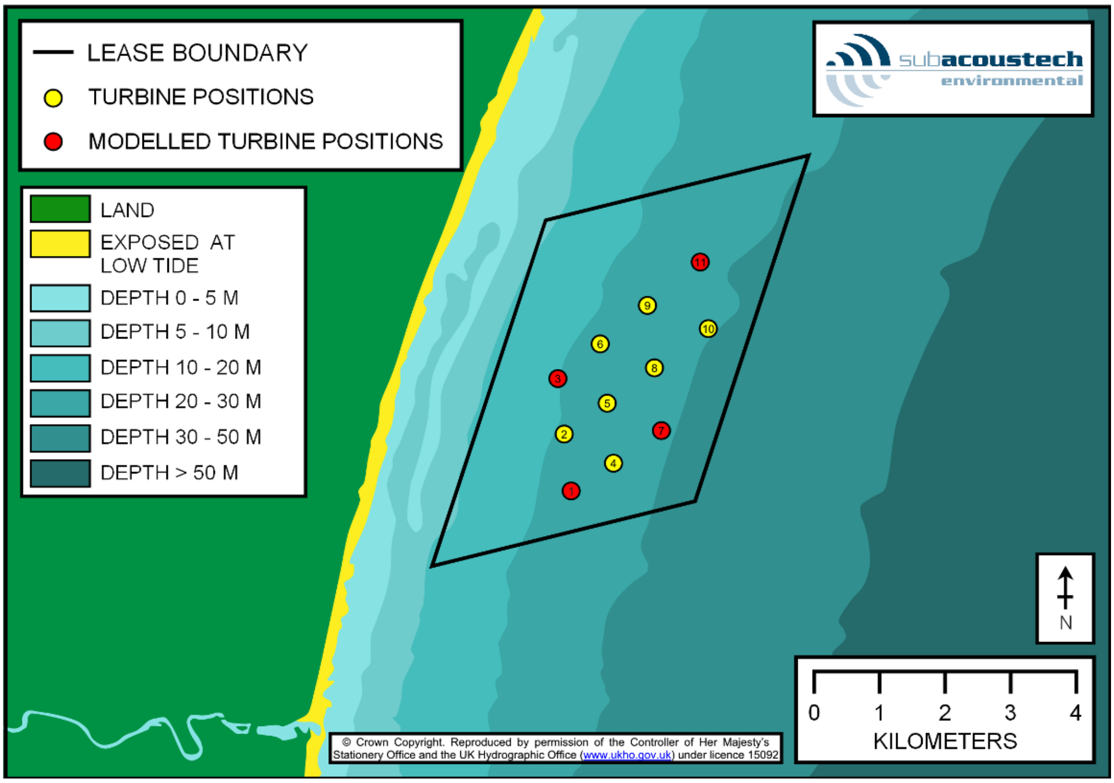

Figure 1.5-2 Map showing the four modelled wind turbine positions (Wind turbines 1, 3, 7 and 11) at the proposed EOWDC site

30 It should be noted that the INSPIRE acoustic model is not exact and does not use a Source Level / Transmission Loss (SL-TL) formulation; however, the testing and validation of the model against actual measured impact piling data confirms that the model accurately predicts the likely noise levels from impact piling operations.

1.6 Impact of Underwater Sound on Marine Species

1.6.1 Introduction

31 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 in a particular species is dependent upon the incident sound level, frequency content, duration and/or repetition rate of the sound wave (see, for example Hastings and Popper, 2005). As a result, scientific interest in the hearing abilities of aquatic animal species has increased.

32 Popper *et al* (2006) suggest the use of unweighted sound exposure metrics such as peak level of underwater noise and the SEL of the noise, to develop an interim guidance for estimating the injury range for fish from pile driving operations. Similarly, a review of underwater noise from offshore wind farms on marine mammals (Madsen *et al*, 2006) discusses the use of frequency weighting of the underwater noise. The authors' comment that the impact of underwater sound on the auditory system is frequency dependent and thus,

ideally, noise levels should (as for humans) be weighted using the defined frequency responses of the auditory system of the animal in question.

33 The approach that has been adopted in this study is to use unweighted sound level metrics to define the potential for gross damage such as fatality, swim bladder rupture or tissue damage, since hearing is not involved in this process. In addition, frequency weighted measures of the sound based on the hearing threshold of the affected species have been applied to assess the perceived loudness of the noise for representative marine species, and hence the range at which an aversive response to the piling may be expected.

34 In addition to this, a further set of criteria proposed by Southall *et al* (2007) and subsequently used as the basis for draft Joint Nature Conservation Committee (JNCC) guidance on protection of marine mammals from injury and disturbance (JNCC, draft 2010) have been used in this assessment to estimate the possibility of auditory injury and behavioural disturbance occurring.

1.6.2 Lethality and Injury Impacts and their Associated Sound Levels

35 At the highest level, typically during underwater blast from explosives, sound has the ability to cause injury and, in extreme cases, the death of exposed animals.

36 Due to the current lack of information on potential lethal and physical injury effects from impact piling, this study has used the data from blast exposures to estimate impact zones. The wave forms from these two noise sources are rather different; the transient pressure wave from an impact piling operation has roughly equal positive and negative pressure amplitude components and a relatively long duration of up to a few hundred milliseconds. By contrast, blast waves have a very high positive pressure peak followed by a much lower amplitude, negative wave due to the momentum imparted to the water surrounding the explosive gas bubble. The pressure of a blast wave is normally quantified therefore in terms of the peak level, due to the dominance of the positive peak of the waveform. There is, therefore, a level of uncertainty as to whether a blast wave criterion can be directly applied to a transient waveform arising from an impact piling operation.

1.6.3 Observations of Lethality and Physical Injury

37 Lethal and direct physical injury from an underwater transient pressure wave are related to the peak pressure level, rise time and duration that the peak pressure acts on the body (usually measured by the impulse of the blast wave). The criteria that have been developed for assessing gross injury of this type are based on data from blast injury, at close range, to explosives. Injury has been related both to the incident peak positive pressure of the wave and to the impulse. To obtain an effective measure of the impulse of the wave, an estimate of the effective duration must be made by integrating over the waveform. A number of different techniques for assessing the duration of an impulsive waveform are described by Hamernik and Hsueh (1991) based on the studies by Coles *et al* (1968), Pfander *et al* (1980) and Smoorenburg (1982). The measure of impulse will, therefore, depend upon which technique is applied.

38 There is currently very limited data relating to fish kill from piling (Hastings *et al*, 2005), although the study by Caltrans (2001) during impact piling operations on the San Francisco to Oakland Bay Bridge indicated fish kill to a range of approximately 50 m. By fitting the results of Abbot *et al* (2002) to a spreading model, it is possible to estimate the peak to peak Source Level (SL) of the piling to be about 242 dB re 1 µPa @ 1 m. This equates to fish being killed when the peak pressure level exceeds about 208 dB re 1 µPa, which corresponds to an interim criterion that has been proposed by Popper, discussed in the following section.

39 Studies carried out on the effects of blast on various species of fish by Yelverton *et al* (1975) (also reproduced in Richardson *et al*, 1995) demonstrated that mortality rates were related to body mass and magnitude of the impulsive wave. The results show that a 50% mortality rate would occur in fish weighing 1 kg when exposed to an impulse of about 340 Pa.s (Pascals per second). According to this model, to cause the same mortality rate in fish weighing 10 kg they would have to be exposed to an impulse of approximately 800 Pa.s. The work indicates that there are levels below which a sound would cease to be lethal to a fish of a certain weight. While this sound level may not cause the swim bladder to rupture or kidney and liver damage that may be seen after lethal doses of sound, there may still be considerable tissue damage to susceptible organs such as the lungs, gastro-intestinal tract or eyes and hence possible long term survival implications.

1.6.4 Observations of Auditory Damage

40 At lower received SPLs, temporary and permanent hearing loss has been demonstrated by constraining marine animals within a high level sound environment for prolonged periods. Temporary hearing loss usually presents as a temporary hearing threshold shift (TTS) which is recoverable over a period of time. However, following prolonged exposure at levels sufficient to cause TTS, a permanent threshold shift (PTS) or deafness, results from the death of the sensory hair cells of the ear. TTS is thus symptomatic of hearing damage. Some information is available concerning hearing damage in fish. Cox *et al* (1986, 1987) suggested that goldfish (*Cassius auratus*) exposed to pure tones at 250Hz at 204dB re 1µPa and 500Hz at 197dB re 1µPa for two hours developed hearing damage, corresponding to levels of 142 – 147 dB_{ht}(*Cassius auratus*). Enger (1981) also noted auditory damage in cod (*Gadus morhua*) exposed at frequencies from 50 – 400Hz at 180dB re 1µPa for one to five hours, corresponding to a level of about 100 dB_{ht}(*Gadus morhua*). The dB_{ht} metric is explained in section 1.11.1.8 in the appendix of this report

41 Hastings *et al* (1996) found damage to the sensory hair cells of the oscar fish (*Astronotus ocellatus*) caused by exposure to a pure 300Hz tone (sound generated at a single frequency) at 180dB re 1µPa for one hour. Comparing these results to the audiogram given by Kenyon *et al* (1998), this corresponds to a level of 74 dB_{ht}(*Astronotus ocellatus*).

42 Smith *et al* (2004) discovered that goldfish had a 5 dB TTS in hearing following a ten minute continuous exposure to noise in the frequency range from 100 Hz – 10 kHz at a level of 170 dB re 1 µPa. Popper *et al* (in Hastings and Popper, 2005) exposed rainbow trout (*Oncorhynchus mykiss*) and channel catfish (*Ictalurus punctatus*) to Low Frequency Active Sonar signals

(a submarine detection system deployed by the US Navy) for three periods of 108 seconds at a received level of 193 dB re 1µPa (RMS) over the frequency band 160 – 325 Hz. A goldfish with a 10dB TTS took 24 – 48 hours to recover. Popper *et al* (2005) exposed broad whitefish (*Coregonus nasus*), a salmonid, to five airgun emissions having a received peak sound level of 205 dB re 1µPa (corresponding to a received mean SEL of 175 dB re 1µPa^2-s). No TTS was observed in the whitefish, whereas northern pike (*Esox lucius*) and Lake Chub (*Couesius plumbeus*) demonstrated a 10 – 15 dB TTS from which the recovery time was around 24 hours.

43 The recent review by Madsen *et al* (2006) highlighted that experiments with marine mammals demonstrated a near inverse relationship between sound exposure level and duration of exposure (i.e. the same equal energy noise dose relationship). This was based on data from Schlundt *et al* (2000) which indicated that this effect translates to marine mammal exposure to underwater sound. In the study, short duration sound exposures (one second continuous wave) at levels of approximately 130 dB above hearing threshold caused a small TTS hearing injury in the bottlenose dolphin. Longer duration exposures at levels of 80 – 90 dB above hearing threshold have been shown to induce TTS after many hours of exposure (Nedwell *et al*, 2007).

44 The data reviewed above highlights typical levels of sound and the exposure durations at which audiological injury in fish and marine mammals have been measured. In the context of exposure of fish and marine mammal species to underwater sound it is very unlikely that fish or marine mammals would experience auditory injury unless constrained in a very high level continuous sound field for a prolonged period. Although it should be noted that physical injury and fatality, which is discussed in more detail below, can occur for very high level, short duration exposures such as those for underwater blast.

1.6.5 Criteria for Assessing Lethality and Physical Injury

45 The following criteria have been applied in this study for levels of noise likely to cause physical effects (Parvin *et al* (2007)), based on data in the studies of Yelverton *et al* (1975), Turnpenny *et al* (1994), Hastings and Popper (2005):

- Lethal effect may occur in marine species where peak to peak levels exceed 240 dB re 1 µPa; and
- Physical injury may occur in marine species where peak to peak levels exceed 220 dB re 1 µPa.

1.6.6 Criteria for Assessing Audiological Injury

46 The concept of auditory injury from exposure to noise is well established for airborne sound exposure of humans. At a high enough level of sound, traumatic hearing injury may occur even where the time of exposure is short. Injury also occurs at lower levels of noise where the period of exposure is long. In this case, the degree of hearing damage depends on both the level of the noise and the time of exposure to it. To estimate the effect of impact piling taking place over a long period of time this concept of cumulative “Noise Dose” relationship has been used.

47 For complex or time varying signals the degree of hearing damage has been related to the Noise Dose of the noise. The Noise Dose combines the continuous noise level containing the same sound energy as the time varying signal (the equivalent level of noise, or L_{eq}), and the duration of exposure. This is usually given in terms of $L_{EP, D}$, which is the daily personal noise exposure. This approach appears to translate to the underwater exposure of marine mammals, since for single exposure sounds Ward (1997) developed a level against exposure duration guide indicating that for sounds from 126 to 144 dB above hearing threshold (i.e. dB_{ht}), hearing injury can occur for exposure periods from 60 seconds to 1 second respectively. The data from Schlundt *et al* (2000) also indicates that this effect translates to marine mammal exposure to underwater sound. In the study, short duration sound exposures (one second continuous wave) at levels of approximately 130 dB above hearing threshold caused a small Temporary Threshold Shift (TTS) hearing injury in the bottlenose dolphin.

48 A review by Madsen *et al* (2006) highlighted that experiments with marine mammals demonstrate a near linear relationship between sound exposure level and duration of exposure (i.e. an equal energy Noise Dose relationship). In other words, each doubling of the noise energy (3 dB increase) results in a halving of the acceptable noise exposure period. The same Noise Dose (and therefore potential for auditory injury) occurs, for instance, following an exposure of 90 dB above threshold for a period of 8 hours, 93 dB above threshold for a period of 4 hours, or 130 dB above threshold for a few seconds as shown in Table 1.6-1 below. Hearing impairment in the form of a TTS in hearing may occur where an animal is exposed to a these levels, and Permanent Threshold Shift (PTS) will occur with repetitive exposure. The higher the Noise Dose above this limit, the more rapid will be the damage.

Table 1.6-1 – Comparison of noise exposure level and duration for the same cumulative 90 $L_{EP, D}$ Noise Dose

Exposure Level dB(A) (dB_{ht})	Exposure Duration
90	8 hours
93	4 hours
99	1 hour
110	Approx. 5 minutes
120	Approx. 30 seconds
130	Approx. 3 seconds

49 In summary, it is likely that hearing impairment will occur where fish or marine mammals are exposed to continuous or repeated high level underwater sound for relatively long periods of time; for impact piling the noise exposure can build up over many pile strikes. The Noise Dose that the animals will accumulate will depend on the received level of the underwater sound, which varies with range, and hence with the behaviour of the animal, and the time period and repetition rate of the pile strikes.

50 Nedwell *et al* (2007) has suggested that the use of a 130 dB_{ht} level, similar to that used for human exposure in air, provides a suitable criterion for predicting the onset of traumatic hearing damage (that is, where immediate traumatic and irreversible damage occurs), which recognises the varying hearing sensitivity of differing species.

51 Based on the evidence of auditory damage from numerous studies, Southall *et al* (2007) propose a set of auditory injury criteria based on peak pressure levels and M-weighted Sound Exposure Levels (dB re. 1 µPa^2-s (M)) for various groups of marine mammals. These criteria are presented in Table 1.6-2 and the results of this study have also been presented in terms of this metric. A detailed description of the M-weighting metric and the groups of marine mammals considered is presented in the Appendix to this report.

Table 1.6-2 – Proposed injury criteria for various marine mammal groups (Southall et al., 2007)

	Sound type	
Marine mammal group	**Single pulses**	**Multiple Pulses**
Low Frequency Cetaceans		
Sound Pressure Level	230 dB re 1 µPa (peak)	230 dB re 1 µPa (peak)
Sound Exposure Level	198 dB re 1 µPa^2/s (M_{lf})	198 dB re 1 µPa^2/s (M_{lf})
Mid Frequency Cetaceans		
Sound Pressure Level	230 dB re 1 µPa (peak)	230 dB re 1 µPa (peak)
Sound Exposure Level	198 dB re 1 µPa^2/s (M_{mf})	198 dB re 1 µPa^2/s (M_{mf})
High Frequency Cetaceans		
Sound Pressure Level	230 dB re 1 µPa (peak)	230 dB re 1 µPa (peak)
Sound Exposure Level	198 dB re 1 µPa^2/s (M_{hf})	198 dB re 1 µPa^2/s (M_{hf})
Pinnipeds (in water)		
Sound Pressure Level	218 dB re 1 µPa (peak)	218 dB re 1 µPa (peak)
Sound Exposure Level	186 dB re 1 µPa^2/s (M_{pw})	186 dB re 1 µPa^2/s (M_{pw})

52 The Southall study criteria can be used for both single pulse noise sources and multiple pulse sources. This report presents estimated impact ranges for both of these in terms of pile driving to provide impact ranges for exposure to a single pile strike and also the accumulated exposure to multiple pulses over a typical installation. The accumulated exposure is taken into account using the dB_{ht} metric by the noise dose modelling outlined above: This has also been carried out for the M-weighting metric. This modelling is carried out using a similar method to the noise dose modelling by assuming a swim speed and starting range for the animals and, hence calculating the accumulated exposure as the animal moves away from the noise source. The M-weighted Sound Exposure Level at each range is calculated based on analysis of previously measured data from numerous impact piling operations.

53 Predictive underwater noise modelling can be used to estimate the range at which a marine mammal can receive sound levels that could cause audiological impairment. By using the impact ranges and factoring a degree of precaution these can be used to help inform standoff ranges (exclusion zones) for use in the mitigation during piling activities. That is, the range at which the animal can be at the onset of piling to ensure it can flee the area before receiving an exposure level that is likely to damage hearing.

54 Once again, similarly to the dB_{ht} noise dose modelling, the M-weighted SEL modelling does not take into account the mitigating effects of a soft start procedure. The accumulated exposure is calculated assuming a high blow force at the onset of piling. Where a soft start procedure is used the effect is likely to be mitigated as the initial exposure is reduced.

1.6.7 Criteria for Assessing Behavioural Response

55 Measurements of underwater noise are frequently presented in terms of the overall linear level of that sound, such as its spectral level or peak pressure. This, however, does not provide an indication of the impact that the sound will have upon a particular fish or marine mammal species. This is of fundamental importance when considering the behavioural response of species to activities generating underwater noise, as avoidance is associated with the perceived level of loudness and vibration of the sound by the species. Therefore, the same underwater noise may have a different impact on different species with different hearing sensitivities.

56 The dB_{ht}(*Species*) metric (Nedwell *et al*, 2007) has been developed as a means for quantifying the potential for a behavioural impact on a species in the underwater environment. As any given sound will be perceived differently by different species (since they have differing hearing abilities) the species name must be appended when specifying a level. For instance, the same construction event for salmon (*Salmo salar*) might have a level of 70 dB_{ht}(*Salmo salar*) and for bottlenose dolphin a level of 110 dB_{ht}(*Tursiops truncatus*). Table 1.6-3 below summarises the assessment criteria for the dB_{ht}.

Table 1.6-3 – Assessment criteria proposed by Nedwell *et al* (2007) used in this study to assess the potential behavioural impact of underwater noise on marine species

Level in dB_{ht}(Species)	Effect
90 and above	Strong avoidance reaction by virtually all individuals.
Above 110	Tolerance limit of sound; unbearably loud.
Above 130	Possibility of traumatic hearing damage from single event.

57 In addition, a lower level of 75 dB_{ht} has been used for analysis as a level of "significant avoidance." At this level, about 85% of individuals will react to the noise, although the effect will probably be limited by habituation.

58 In Southall *et al* (2007), a further set of criteria are also suggested, again based on the M-weighted Sound Exposure Levels to assess the likelihood of behavioural disturbance. These criteria are presented in Table 1.6-4 below and, as with the criteria for auditory injury proposed by Southall, it has also been used in this study.

59 Southall suggests the onset of temporary Threshold Shift (TTS) as a criterion for a behavioural effect of single impulsive noises. No evidence is offered to substantiate this criterion. This approach is considered highly speculative; for instance, humans can tolerate substantial levels of noise, well above an aversive level, of up to 130 dB(A) re 20 μPa, for short periods of time without exhibiting a TTS. The authors are not aware of any equivalent criterion for human exposure, where aversion is generally specified in terms of the level of the noise in dB(A).

Table 1.6-4 – Proposed Behavioural response criteria in terms of single pulses for various marine mammal groups (Southall *et al.*, 2007)

	Sound type
Marine mammal group	**Single pulses**
Low Frequency Cetaceans	
Sound Pressure Level	224 dB re 1 µPa (peak)
Sound Exposure Level	183 dB re 1 µPa^2/s (M_{lf})
Mid Frequency Cetaceans	
Sound Pressure Level	224 dB re 1 µPa (peak)
Sound Exposure Level	183 dB re 1 µPa^2/s (M_{mf})
High Frequency Cetaceans	
Sound Pressure Level	224 dB re 1 µPa (peak)
Sound Exposure Level	183 dB re 1 µPa^2/s (M_{hf})
Pinnipeds (in water)	
Sound Pressure Level	212 dB re 1 µPa (peak)
Sound Exposure Level	171 dB re 1 µPa^2/s (M_{pw})

1.7 Selection of Species

60 The species upon which the dB_{ht} analysis has been conducted in this study have been based upon regional significance and also crucially upon the availability of a good peer-reviewed audiogram data shown in Figures 1.7-1 to 1.7-3.

61 The species of marine mammal considered in this study are:

- **Bottlenose Dolphin** – (Johnson, 1967) A marine mammal (toothed whale) with good high frequency hearing sensitivity. It is also used in this report an indicative surrogate audiogram for **Risso's Dolphin**. Although some audiogram data are available for the Risso's dolphin, the authors consider that the quality of the data is not confirmed. Hence the bottlenose dolphin has been used to provide a conservative over-estimate of potential impacts.
- **Harbour Porpoise** – A marine mammal (toothed whale) that, based on current peer reviewed audiogram data (Kastelein, 2002), is the most sensitive marine mammal to high frequency underwater sound.
- **White-Beaked Dolphin** – a marine mammal (toothed whale) with similar high frequency hearing to the bottlenose dolphin, but lower sensitivity to lower frequency noise (using the Striped Dolphin (*Stenella coeruleoalba*) audiogram (Kastelein, 2003) as a surrogate as the White-Beaked Dolphin audiogram (Nachtigall *et al*, 2007) does not cover the entire audiometric range.
- **Harbour (Common) Seal** – a pinniped that based on current peer reviewed audiogram data (Mohl, 1968, Kastak and Schusterman, 1978) the most sensitive seal species to underwater sound. It is also used as a surrogate audiogram for **Grey Seal**.

62 As there is no single published dataset for seal species that covers the full audiometric range, the analysis undertaken in this report is based on a weighting filter for the harbour seal that is the locus of the minimum threshold (most sensitive) data from several audiogram sources for the harbour seal. The data of Kastak and Schusterman (1998) is used for the frequency range from 100 Hz to 6.4 kHz, and the data from Mohl (1968) over the higher frequency range from 8 to 128 kHz.

63 The species of fish considered in this study are:

- **Herring** (*Clupea Harengus*) – A fish hearing specialist that, based on current peer reviewed audiogram data (Enger, 1967) is the most sensitive marine fish to underwater sound.
- **Salmon** – A fish with relatively poor hearing sensitivity and therefore they may be classed as hearing generalists. For this study the audiogram produced by Hawkins and Johnstone (1978) has been used.
- **Dab** (*Limanda limanda*) – A flatfish species with generalist hearing capability but that based on current peer reviewed audiogram data (Chapman and Sand,1974) is the most sensitive flatfish to underwater sound. It is also sometimes used as a surrogate for sole (*Solea solea*).

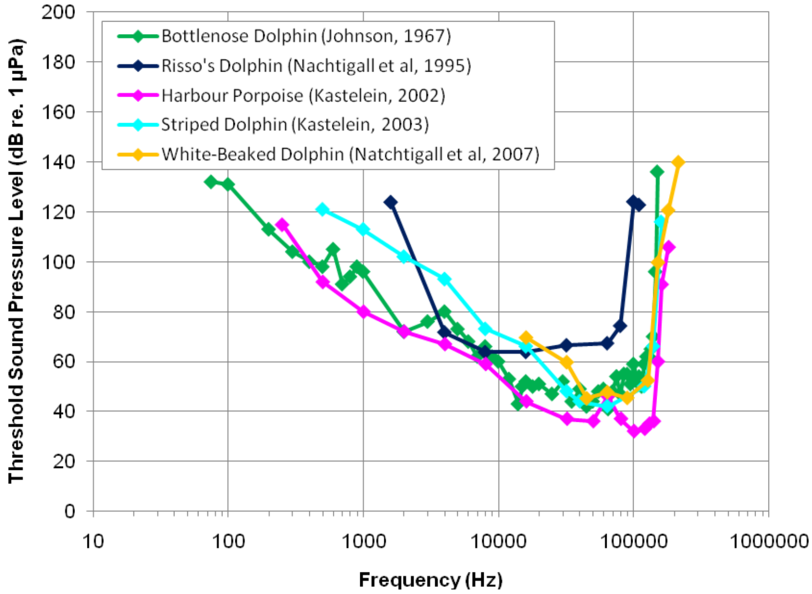

Figure 1.7-1 – Audiograms for the various species of cetacea interest in this study

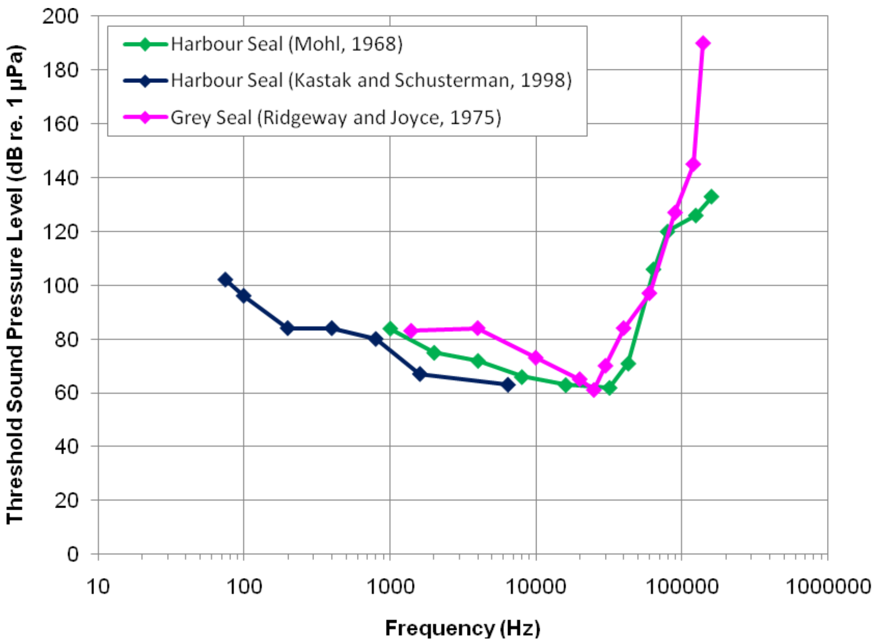

Figure 1.7-2 – Audiograms for the harbour seal and the grey seal

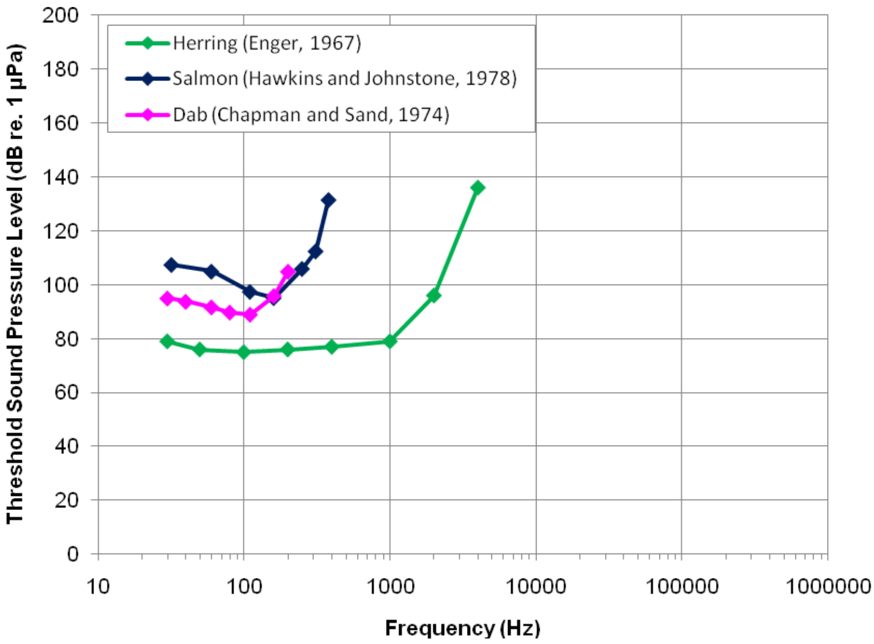

Figure 1.7-3 – Audiograms for the three fish species of interest in this study

1.8 Anticipated Worst Case Scenario for the Impacts of Underwater Noise during the EOWDC Construction

64 The two primary variables that are likely to affect the levels of underwater noise during impact piling operations are water depths and the diameter of the pile. To account for the worst case scenario in terms of water depths, an adjustment to the Lowest Astronomical Tide (LAT) depths provided by

Seazone to give high water conditions at the site (4.064 m above the lowest astronomical tide, taken from an Oceanographic survey undertaken for the AOWFL) has been made (EMU Ltd., 2008).

65 In order to inform discussions with the design engineers so that a realistic worst case scenario in terms of pile diameter could be determined preliminary modelling was carried out during the early stages of the project for various sizes of piles. From the consultations with the engineers using this modelling as a guide it was decided by the client that the modelling should be carried out assuming piles of 8.5 m in diameter at each location. This preliminary modelling report is included as an appendix to this report in section 1.11.2.

66 The simplest evaluation of the behavioural effects of noise considers the area of sea excluded to an animal by the noise. Where this is large or includes important areas, such as spawning grounds, the risk of an environmental effect of the noise may be significant. An alternative approach, which includes the significance of the period of exposure, is to consider the time for which the area is excluded, for instance by considering the impact in terms of kilometres squared of area and days of seabed excluded. On this basis, the influence of persistent lower level sources may dominate over intermittent high level sources, like piling. Thus, on this basis, it may be important to consider the changes in both duration and level of an activity when assessing the relative impact of two different methods of construction.

1.9 Impact Assessment: Impact Piling of 8.5 m Diameter Monopiles

1.9.1 Introduction

67 Presented in the following pages are the results of the modelling undertaken by Subacoustech Environmental Ltd using the underwater noise modelling software, INSPIRE (currently version 2.0), for the proposed piling operations for the installation of 8.5 m diameter piles at the EOWDC.

68 Figure 1.9-1 shows four representative example transects extending from wind turbine position 11 illustrating the varying bathymetry in the areas around the proposed EOWDC site. Comparison of the water depths at a bearing of 20° from WTG 11 which extends towards the shore with the transect at a bearing of 60° which extends directly out into the deeper water clearly shows a very large variation on water depths. For relatively shallow coastal waters, sound typically propagates with fewer losses in deeper water than for shallow water. It would therefore be expected that maximum impact ranges will be predicted for the deeper water transects.

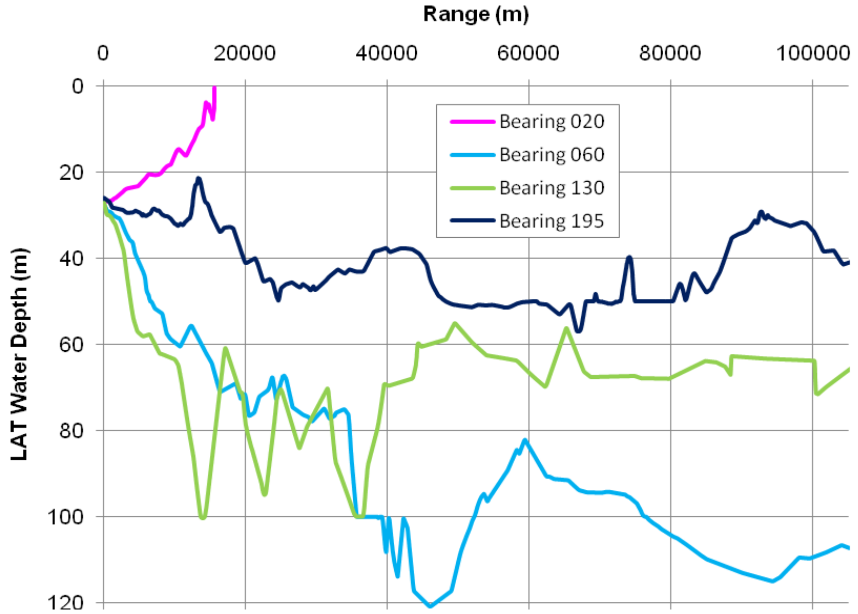

Figure 1.9-1 – Comparison of four representative depth profiles along transects from Wind turbine position 11, indicating the varying bathymetry around the proposed EOWDC site used for the INSPIRE modelling

69 Figure 1.9-2 shows the attenuation of unweighted peak to peak noise level against range for the four representative transects shown in Figure 3-1 for piling an 8.5 m diameter pile at wind turbine position 11. It can be seen that the shallower the water, such as for transects at bearings 020 and 195, the more rapidly the piling noise is likely to attenuate.

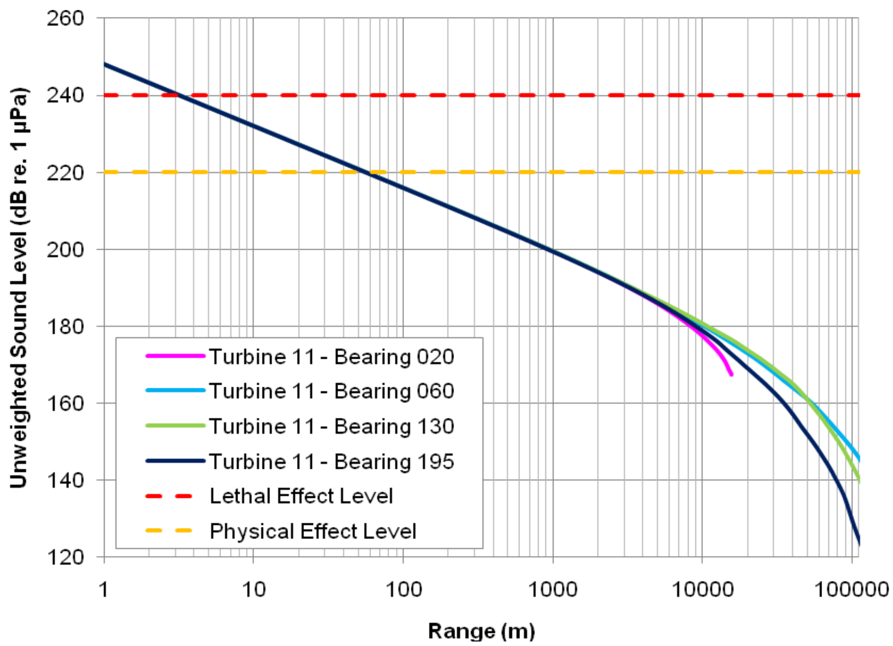

Figure 1.9-2 – Graph showing the unweighted peak to peak noise level with range for the four transects extending from wind turbine 11 shown in Figure 1.9-1

1.9.2 Unweighted Sound Levels; Potential for Lethality and Physical Injury to Marine Species

70 Table 1.9-1 shows the estimated ranges out to which lethal and physical injury may occur in marine species based on unweighted peak to peak sound levels and the criteria presented in section 1.6.5. The data indicate that marine species may suffer a lethal effect out to a range of approximately 3 m from the piling operation and that physical injury is likely to occur out to a range of 60 m. It should be noted that these impact ranges are based on the extrapolation of data from measurements taken at considerably greater ranges since it is generally not possible to carry out measurements this close to impact piling operations. “Near field” acoustic effects are likely to occur at close range to the piling operations so the levels of underwater noise maybe lower than those estimated by the INSPIRE model. It is therefore thought that lethality is therefore unlikely to occur in this case.

71 These impact ranges have been calculated using an estimated optimum blow force for installing an 8.5 m diameter pile. This is calculated using the piling logs from previous measurements undertaken by Subacoustech Environmental Ltd and extrapolating these figures to calculate an optimum blow force for a particular sized pile. In the case of an 8.5 m diameter pile it is estimated that a blow force of 1400 kJ (kilojoules) will be necessary to install the pile. However, this is dependent on the piling hammer used and ground type at the size.

72 Any residual risk of lethality and physical injury may be further mitigated by the use of a soft start procedure, or the use of acoustic mitigations devices such as seal scrammers or fish exclusion systems.

Table 1.9-1 – Summary of ranges out to which lethal effect and physical injury is expected to occur in marine species using the criteria proposed in Parvin *et al* (2007)

Peak to Peak Levels	Wind turbine 1	Wind turbine 3	Wind turbine 7	Wind turbine 11
Lethal Effect Range to 240 dB re. 1 µPa	3 m	3 m	3 m	3 m
Physical Injury Range to 220 dB re. 1 µPa	60 m	60 m	60 m	60 m

73 Figure 1.9-3 presents a contour plot of the estimated unweighted peak to peak levels of underwater noise from the four wind turbine positions, with each contour representing regions of the same unweighted sound level in 10 dB increments. It can be seen that the noise attenuates more rapidly in the slightly shallower waters directly to the east of the site, whereas the contours extend further to the north east where the water is deepest.

74 The figures indicate that there is likely to be relatively little variation in noise propagation for different wind turbine sites as the contours are all broadly similar in extent. This is likely due to the fact that the variation in water depths across the site is relatively small compared to the differences in water depths in the surrounding waters.

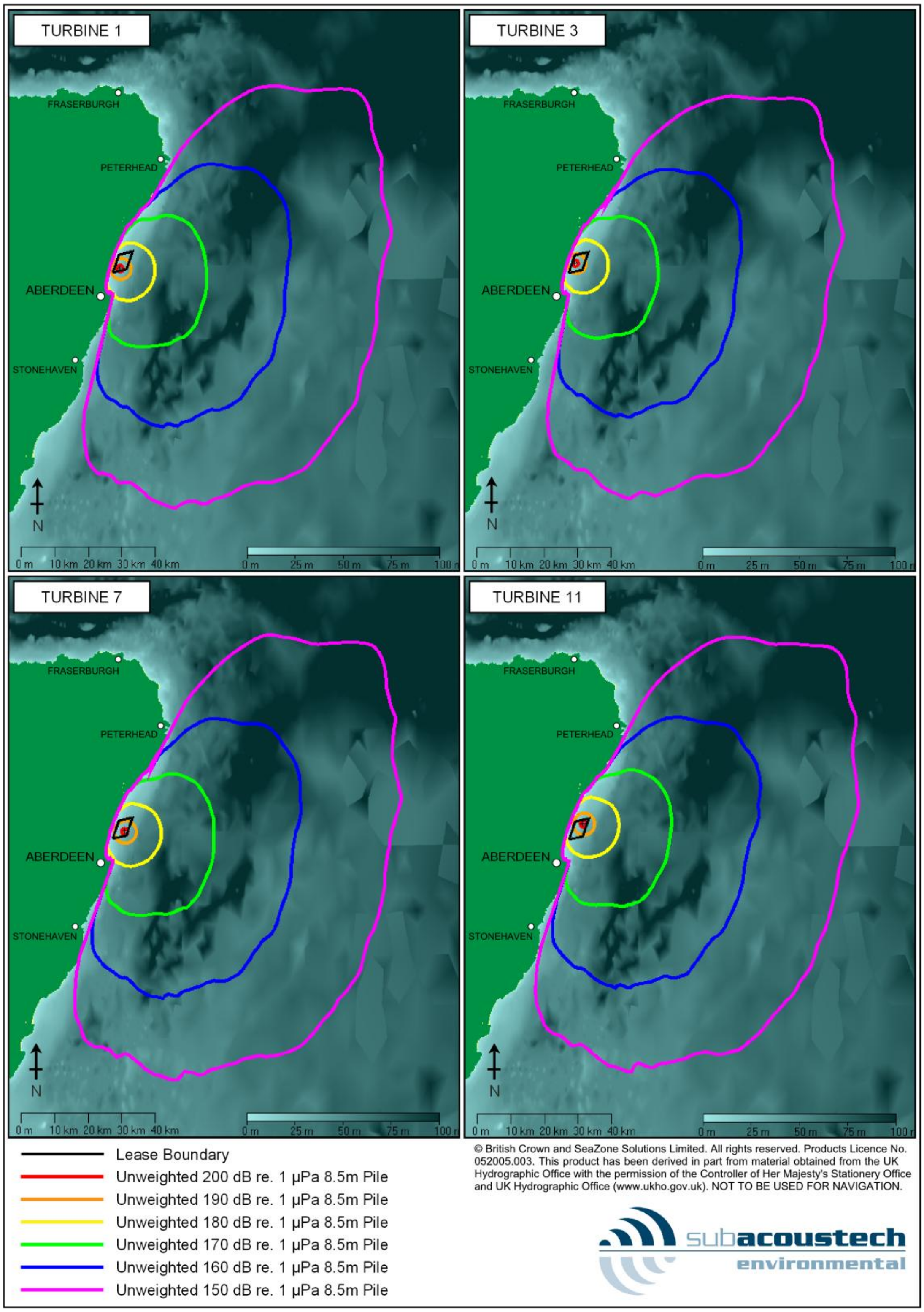

Figure 1.9-3 – Contour plots showing the estimated unweighted peak to peak noise levels from installing an 8.5 m diameter pile at the EOWDC site

75 Tables 1.9-2 to 1.9-4 summarise the estimated extent of underwater noise propagation in terms of three unweighted metrics, peak to peak level, peak level and sound exposure level calculated from single pile strikes analysed over a 0.5 second interval. It should be noted that the peak underwater noise levels, summarised in Table 1.9-3, have been calculated by reducing the

peak to peak noise levels predicted by the INSPIRE model by 6 dB. As the waveform of a pile strike is typically symmetrical about the ambient pressure level (equal high and low pressure excursions) it can be reasonably assumed that the peak pressure level is half of the peak to peak pressure level (a reduction of 6 dB). Also shown in Table 1.9-3 are the injury and behavioural avoidance impact ranges using the single pulse peak level criteria for species of cetacean and pinniped proposed by Southall *et al* (2007), outlined in tables 1.6-2 and 1.6-4.

76 Overall, the data indicate that the underwater noise is likely to propagate marginally further for wind turbine positions 7 and 11. This indicates the effect of wind turbines located to the east of the site, in close proximity to the deep water of the North Sea, as propagation losses are typically lower in deeper water.

Table 1.9-2 – Summary of the estimated mean ranges to various unweighted peak to peak noise levels during installation of 8.5 m diameter piles

Peak to Peak Levels	Wind turbine 1	Wind turbine 3	Wind turbine 7	Wind turbine 11
Range to 200 dB re. 1 µPa	920 m	890 m	960 m	940 m
Range to 190 dB re. 1 µPa	3.1 km	2.8 km	3.3 km	3.2 km
Range to 180 dB re. 1 µPa	7.2 km	6.5 km	8.1 km	7.8 km
Range to 170 dB re. 1 µPa	14 km	13 km	16 km	15 km
Range to 160 dB re. 1 µPa	25 km	24 km	27 km	27 km
Range to 150 dB re. 1 µPa	38 km	36 km	41 km	40 km

Table 1.9-3 – Summary of the estimated mean ranges to various unweighted peak noise levels during installation of 8.5 m diameter piles, including the PTS and TTS criteria shown in Tables 1.6-2 and 1.6-4

Peak Levels	Wind turbine 1	Wind turbine 3	Wind turbine 7	Wind turbine 11
Range to 230 dB re. 1 µPa (Cetacean Injury criteria, Southall *et al* 2007)	5 m	5 m	5 m	5 m
Range to 224 dB re. 1 µPa (Cetacean Behavioural avoidance criteria, Southall *et al* 2007)	15 m	15 m	15 m	15 m
Range to 218 dB re. 1 µPa (Pinniped Injury criteria, Southall *et al* 2007)	30 m	30 m	30 m	30 m
Range to 214 dB re. 1 µPa (Pinniped Behavioural avoidance criteria, Southall *et al* 2007)	60 m	60 m	60 m	60 m
Range to 200 dB re. 1 µPa	410 m	400 m	420 m	420 m
Range to 190 dB re. 1 µPa	1.5 km	1.5 km	1.6 km	1.6 km
Range to 180 dB re. 1 µPa	4.5 km	4.0 km	5.0 km	4.8 km
Range to 170 dB re. 1 µPa	9.6 km	11 km	11 km	10 km
Range to 160 dB re. 1 µPa	18 km	20 km	20 km	20 km
Range to 150 dB re. 1 µPa	30 km	33 km	33 km	32 km

Table 1.9-4 – Summary of the estimated mean ranges to various unweighted sound exposure levels (SELs) during installation of 8.5 m diameter piles

Sound Exposure Levels	Wind turbine 1	Wind turbine 3	Wind turbine 7	Wind turbine 11
Range to 200 dB re. 1 $\mu Pa^2/s$	20 m	20 m	20 m	20 m
Range to 190 dB re. 1 $\mu Pa^2/s$	100 m	100 m	100 m	100 m
Range to 180 dB re. 1 $\mu Pa^2/s$	510 m	500 m	520 m	520 m
Range to 170 dB re. 1 $\mu Pa^2/s$	2.2 km	2.1 km	2.4 km	2.3 km
Range to 160 dB re. 1 $\mu Pa^2/s$	6.8 km	6.1 km	7.6 km	7.3 km
Range to 150 dB re. 1 $\mu Pa^2/s$	16 km	14 km	17 km	17 km

1.9.3 *Estimates of Ranges at which Traumatic Hearing Damage may occur for Single Pulses*

1.9.3.1 The dB_{ht} metric

77 Table 1.9-5 shows the estimated impact ranges for traumatic hearing injury, using the dB_{ht} metric, for the marine species of interest, based on the 130 dB_{ht} criterion from Nedwell *et al* (2007). The results are given for each of the four locations modelled at the proposed EOWDC site. The 130dB_{ht} perceived level is used to indicate traumatic hearing damage over a very short exposure time of only a few pile strikes at most.

78 The largest estimated ranges out to which hearing damage may occur are for harbour porpoise with an estimated impact range of 570 m for impact piling an 8.5 m pile at both wind turbine positions 7 and 11. Of the marine mammals, the data indicate that the seal species are likely to suffer these effects out to the smallest ranges. The data indicate that salmon and dab are only likely to suffer traumatic hearing damage out to 20 – 30 m, however, it is estimated that herring are likely to suffer this effect out to considerably larger ranges of up to approximately 480 m.

79 It should be noted that, as with the lethality and physical injury criteria, and with all predicted behavioural avoidance criteria, the risk of hearing damage may be mitigated by the use of soft start for the piling operation, or the use of suitable acoustic mitigation devices such as seal scrammers or fish exclusion systems.

Table 1.9-5 – Summary of ranges out to which traumatic hearing injury is predicted to occur in various marine species using the 130 dB_{ht}(*Species*) criteria (Nedwell *et al, 2007)* while piling a 8.5 m diameter pile

Species	130 dB_{ht} Ranges			
	Wind turbine 1	Wind turbine 3	Wind turbine 7	Wind turbine 11
Bottlenose Dolphin Risso's Dolphin	290 m	290 m	290 m	290 m
Harbour Porpoise	560 m	550 m	570 m	570 m
White-Beaked Dolphin	240 m	240 m	250 m	240 m
Harbour Seal Grey Seal	120 m	120 m	120 m	120 m
Herring	470 m	460 m	480 m	480 m
Salmon	20 m	20 m	20 m	20 m
Dab	30 m	30 m	30 m	30 m

1.9.3.2 M-Weighted Sound Exposure Levels

80 Auditory injury criteria for marine mammals have been proposed by Southall *et al*. (2007) based on M-weighted SELs; SELs calculated from single pile strikes over a 0.5 second interval and then filtered using the M-weighting

criteria for low, mid and high cetacean groups as well as pinnipeds. This study has recently been used as the basis for draft guidance from the Joint Nature Conservation Committee (JNCC) on assessing the likelihood of a particular activity causing a disturbance to marine mammals. Modelling has therefore been carried out in order to provide the estimated mean impact ranges for the four groups of marine mammals specified in the Southall paper, in terms of these metrics. The results of this modelling assuming a single pulse (i.e. a single pile strike at the receiver) are summarised in Tables 1.9-6 to 1.9-9.

81 Tables 1.9-6 to 1.9-9 summarise the estimated impact ranges out to which auditory injury may occur, based on the single pulse Southall *et al* (2007) criteria. The largest estimated ranges are for the pinnipeds marine mammal group, with a mean range to likely auditory injury of between 120 and 130 m. For the three cetacean groups the largest impact ranges are predicted for the low frequency cetaceans followed by the mid frequency cetaceans with the smallest ranges predicted for the high frequency cetaceans. This is due to piling noise containing mainly low frequency components.

Table 1.9-6 – Summary of ranges out to which audiological injury to cetaceans in the low frequency cetaceans group may occur using the Southall *et al* (2007) criteria

Low Frequency Cetaceans	Auditory Injury Range 198 dB re. 1 µPa^2/s (M_{lf})
Wind turbine 1	20 m
Wind turbine 3	20 m
Wind turbine 7	20 m
Wind turbine 11	20 m

Table 1.9-7 – Summary of ranges out to which audiological injury to cetaceans in the mid frequency cetaceans group may occur using the Southall *et al* (2007) criteria

Mid Frequency Cetaceans	Auditory Injury Range 198 dB re. 1 µPa^2/s (M_{mf})
Wind turbine 1	10 m
Wind turbine 3	10 m
Wind turbine 7	10 m
Wind turbine 11	10 m

Table 1.9-8 – Summary of ranges out to which audiological injury to cetaceans in the high frequency cetaceans group may occur using the Southall *et al* (2007) criteria

High Frequency Cetaceans	Auditory Injury Range 198 dB re. 1 µPa^2/s (M_{hf})
Wind turbine 1	7 m
Wind turbine 3	7 m
Wind turbine 7	7 m
Wind turbine 11	7 m

Table 1.9-9 – Summary of ranges out to which audiological injury to pinnipeds (in water) may occur using the Southall *et al* (2007) criteria

Pinnipeds (in water)	Auditory Injury Range 186 dB re. 1 µPa^2/s (M_{pw})
Wind turbine 1	120 m
Wind turbine 3	120 m
Wind turbine 7	130 m
Wind turbine 11	130 m

1.9.3.3 dB_{ht}/M-weighting results comparison

82 It may be noted that these ranges disagree with those predicted using the dB_{ht} model, these M-weighted results are summarised for wind turbine position 1 alongside the equivalent dB_{ht} (*Species*) results for auditory injury in Table 1.9-10 shown below. The data indicate substantially lower ranges of effect for the species of cetacean when using the single pulse Southall *et al* (2007) criteria.

83 The recommendations of Southall are founded on re-interpretation of existing public-domain information, which the authors themselves note are "variable in quantity and quality." Further, the recorded observations of the behavioural effects on marine animals caused by noise have been re-evaluated by Southall using SPL as a measure of level, and applying simple assumptions regarding transmission loss to estimate the received level of noise as an SEL. It should be noted however that the SEL of a noise source will very probably vary with range in a different way to that which has been assumed for its SPL; and this may account in part for the anomalous results.

Table 1.9-10 Summary of impact ranges comparing the single pulse auditory injury ranges predicted using the dB_{ht} criteria (Nedwell *et al*, 2007) and the M-weighted SEL (Southall *et al*, 2007) criteria

dB_{ht} (Nedwell *et al*, 2007)		M-weighted SELs (Southall *et al*, 2007)	
Species	**Single pulse auditory injury range (130 dB_{ht})**	**Equivalent M-weighting group**	**Single pulse auditory injury range**
Bottlenose Dolphin	290 m	Mid Frequency Cetacean	10 m
Harbour Porpoise	560 m	High Frequency Cetacean	7 m
Harbour Seal	120 m	Pinnipeds (in water)	130 m

1.9.4 *Estimated Ranges at Which Traumatic Hearing Damage may Occur for Multiple Pulses*

1.9.4.1 dB_{ht} Cumulative Noise Dose for Fleeing Animal Scenario

84 An estimate of the minimum safe standoff distances from the piling operation based on the INSPIRE fleeing animal noise dose algorithm have also been made. Each standoff range indicates that if a particular species is closer than that range at the onset of piling, then they are unlikely to be able to flee the area before suffering hearing damage. This is based on a conservative swim speed of 1 metre per second (m/s) and takes into account the accumulated noise dose over a typical piling operation.

85 Figure 1.9-4 shows a detailed plot of the results of this modelling that has been carried out for each of the key species, in this case the figure is shown for species of seal. It can be seen that the 90 dB_{ht} $L_{EP,\,D}$ criteria (illustrated by the dashed line) is met between the 100 and 200 m starting range datasets. This means that if the seal were to be closer to the piling operations than these ranges at the onset of piling it is unlikely to escape the area without receiving a damaging noise dose.

86 Table 1.9-11 below presents the results of this modelling for the other key species of fish and marine mammal. It can be seen from these data that herring and harbour porpoise will need to be at the greatest distance from the piling operation at its onset to avoid suffering hearing damage. If the fleeing animal is beyond the ranges presented in Table 1.9-11 that they are likely to be able to reach a safe distance before receiving an unacceptable noise dose.

Table 1.9-11 Summary of the maximum starting ranges for various marine species using the fleeing animal noise dose model

Marine Species	Maximum Starting Range for Fleeing Animal
Bottlenose Dolphin / Risso's Dolphin	**120 m**
Harbour Porpoise	**1350 m**
White-Beaked Dolphin	**460 m**
Harbour Seal / Grey Seal	**190 m**
Herring	**1750 m**
Salmon	**1 m**
Dab	**20 m**

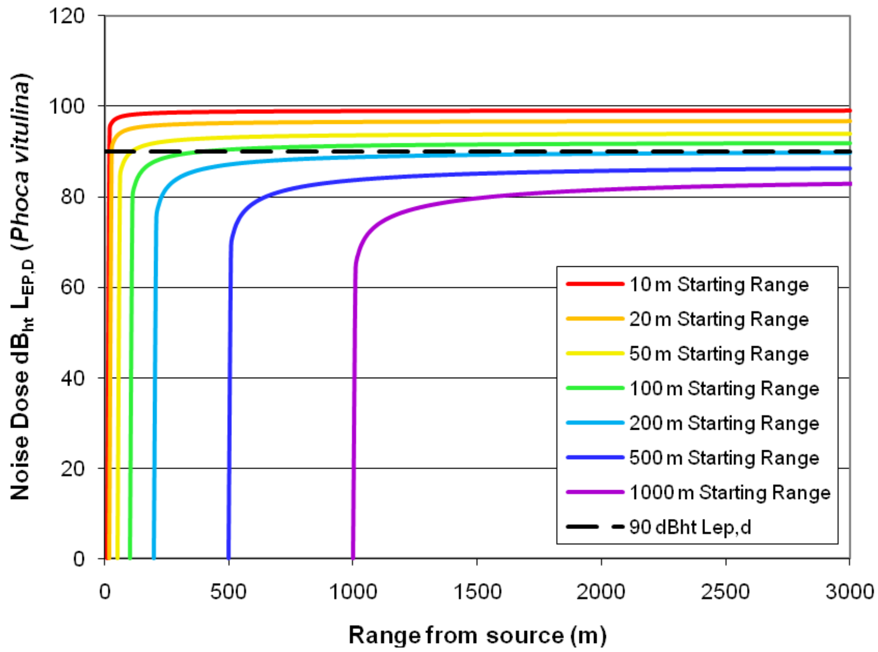

Figure 1.9-4 – Estimated noise dose for a fleeing Harbour Seal or Grey Seal for impact piling of an 8.5 m diameter pile

1.9.4.2 dB$_{ht}$ Cumulative Noise Dose for Stationary Animal Scenario

87 Noise dose modelling has also been carried out for a stationary animal during piling operations. It should be noted that this is considered an unlikely scenario as it implies that the animal makes no attempt to flee the high sound field area. This assessment has been carried out for the harbour seal, and the results can be seen in Figure 1.9-5.

88 It can be seen that the results for the stationary animal modelling give much higher starting ranges than for the fleeing animal modelling, with the starting range for the harbour seal rising from 190 m for a fleeing animal up to almost 1 km for a stationary animal.

89 Further modelling to estimate similar impact ranges for other species has not been carried out for the stationary animal scenario as it is not felt to represent a realistic case. The data presented for the seal is provided to indicate the potential differences in the two scenarios.

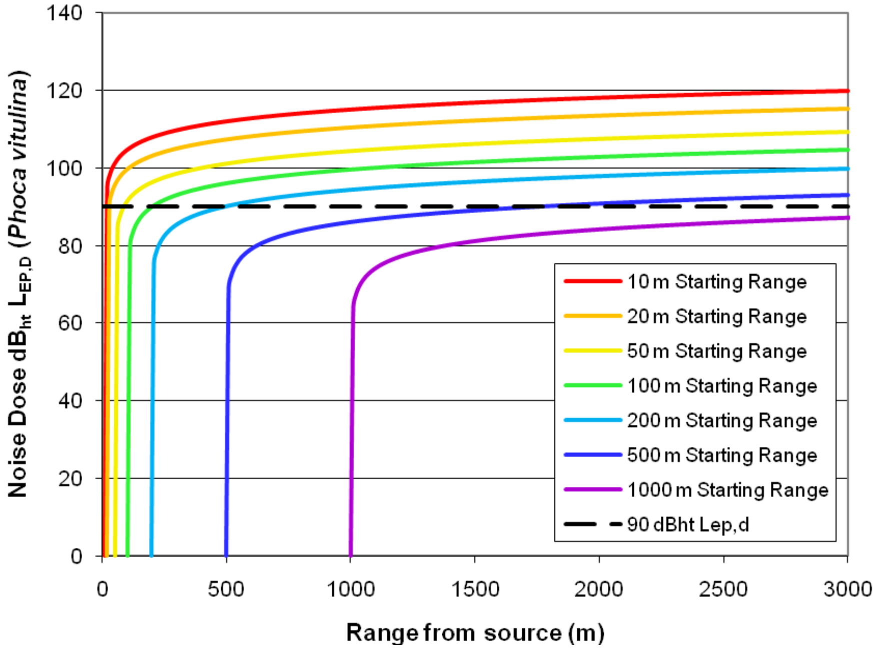

Figure 1.9-5 Estimated noise dose for a stationary Harbour Seal or Grey Seal for impact piling of an 8.5 m diameter pile

1.9.4.3 M-Weighting SEL Multiple Pulses

90 The accumulated exposure to sound for marine mammals has been assessed using the auditory injury criteria proposed by Southall *et al* (2007). This has been done by calculating a standoff range for each marine mammal group, whereby it would safely be able to escape the affected area without receiving a damaging exposure to the sound. Table 1.9-12 shows a summary of these standoff ranges for fleeing animals, assuming a swim speed of 1 m/s. The largest standoff ranges are calculated for the pinnipeds, which, based on the M-weighting criteria are likely to need to be at a range of at least 3.6 km at the onset of piling to avoid a damaging exposure to the sound. Lower standoff ranges are predicted for the three cetacean groups with low frequency cetaceans being the most sensitive to the sound and high frequency cetaceans being the least.

91 Once again, it should be noted that these results do not take into account the mitigating effects of a soft start procedure; these results assume a high blow force at the onset of piling. As long as a soft start procedure is used the effect is likely to be reduced.

92 Figure 1.9-6 shows the calculated multiple pulse M-weighted sound exposure levels for a fleeing high frequency cetacean at various starting ranges, from this it can be seen that if the animal was situated at a range of less than approximately 500 m from the piling operations at the onset of piling it is unlikely to escape the area without receiving a damaging exposure to noise according to the Southall *et al* (2007) criteria. Figure 1.9-7 shows similar data for the high frequency cetacean group; however, this is for a stationary animal during the piling operations. It can be seen that the animal would have to be between 1 and 1.5 km at the onset of piling to avoid a damaging sound exposure level, assuming that it stayed in the same position throughout the entire piling operation. It should be noted that this scenario is considered highly unlikely as marine species are likely to attempt to escape areas where injury is likely to be caused.

Table 1.9-12 Summary of the maximum starting ranges for marine mammal groups before receiving an exposure level that could cause auditory injury, using the multiple pulse criteria from Southall *et al* (2007).

Marine Mammal Group	Maximum Starting Range
Low Frequency Cetaceans	1350 m
Mid Frequency Cetaceans	820 m
High Frequency Cetaceans	650 m
Pinnipeds (in water)	3600 m

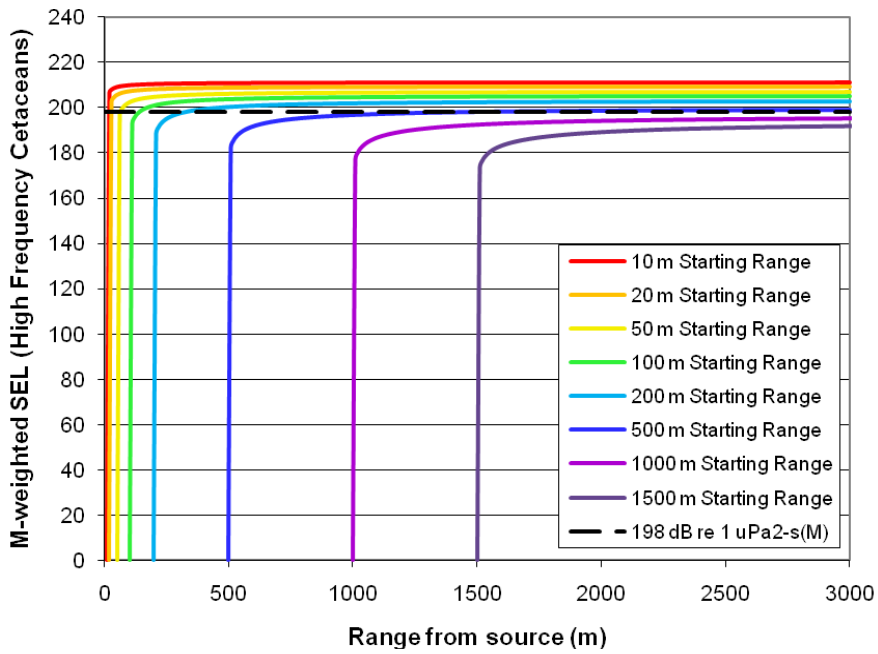

Figure 1.9-6 – Estimated M-weighted Sound Exposure levels from various starting ranges for High Frequency Cetaceans using the multiple pulse criteria from Southall *et al* (2007) for a fleeing animal

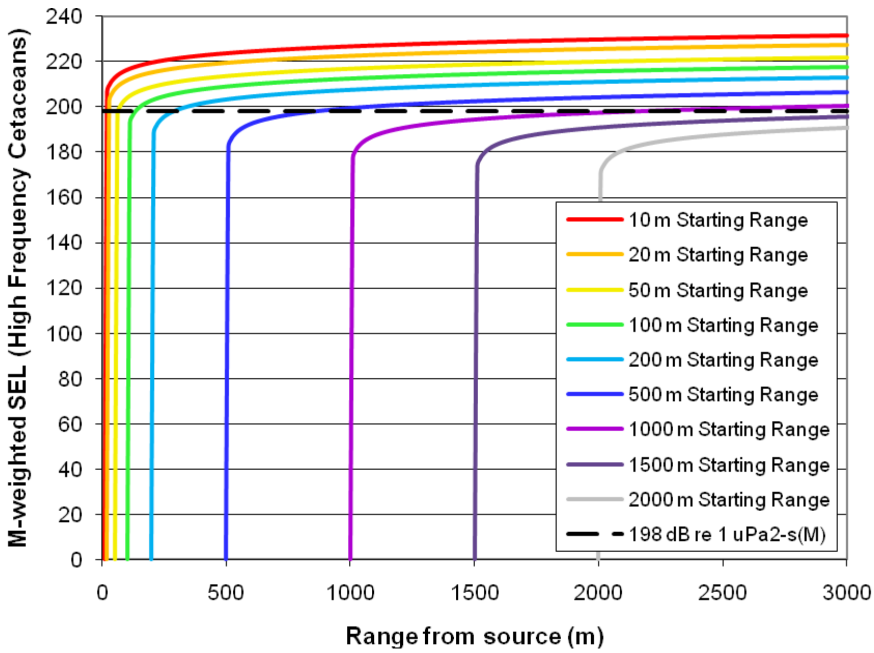

Figure 1.9-7 – Estimated M-weighted Sound Exposure levels from various starting ranges for High Frequency Cetaceans using the multiple pulse criteria from Southall *et al* (2007) for a stationary animal

93 Table 1.9-13 shows a comparison between multiple pulse auditory injury impact ranges for three marine mammals species calculated using the dB_{ht} criteria and the three equivalent M-weighted SEL marine mammal groups.

94 The data indicate that, unlike the single pulse exposure modelling, in some cases the dB_{ht} metric provides the largest estimated range of impact and in some cases the M-weighted SEL metric provides the largest impact range. This discrepancy is result of the different approaches adopted for the two metrics, however, the potential issues with the M-weighting metric have been discussed earlier in this report.

Table 1.9-13 Summary of impact ranges comparing the multiple pulse auditory injury ranges, using the fleeing animal model, predicted using the dB_{ht} criteria (Nedwell *et al*, 2007) and the M-weighted SEL (Southall *et al*, 2007) criteria

dB_{ht} (Nedwell *et al*, 2007)		M-weighted SELs (Southall *et al*, 2007)	
Species	**Multiple pulse auditory injury range (fleeing animal)**	**Equivalent M-weighting group**	**Multiple pulse auditory injury range (fleeing animal)**
Bottlenose Dolphin	120 m	Mid Frequency Cetacean	820 m
Harbour Porpoise	1350 m	High Frequency Cetacean	650 m
Harbour Seal	190 m	Pinnipeds	3600 m

1.9.5 Estimates of Behavioural Impact on Marine Species

1.9.5.1 Peak to Peak dB_{ht}

95 Figures 1.9-4 and 1.9-5 show the results for modelling 8.5 m diameter piles in terms of peak to peak dB_{ht} (*Species*) perceived sound levels for the marine species of interest for a deep water transect and a shallower water transect respectively. The depth profiles for these transects are shown in Figure 1.9-1.

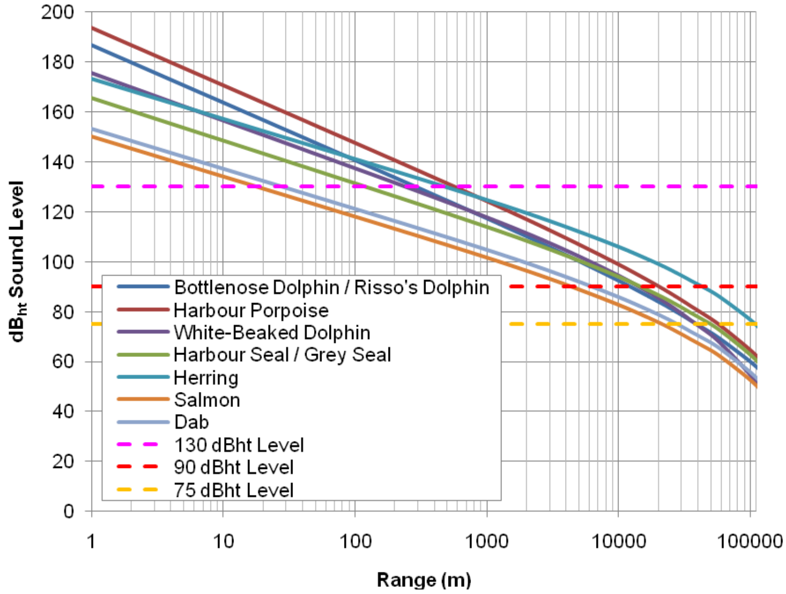

Figure 1.9-8 – Estimated peak to peak dB_{ht} level with range plot of various marine species along a deep water transect (Wind turbine 11, Bearing 060) during the installation of an 8.5 m diameter pile

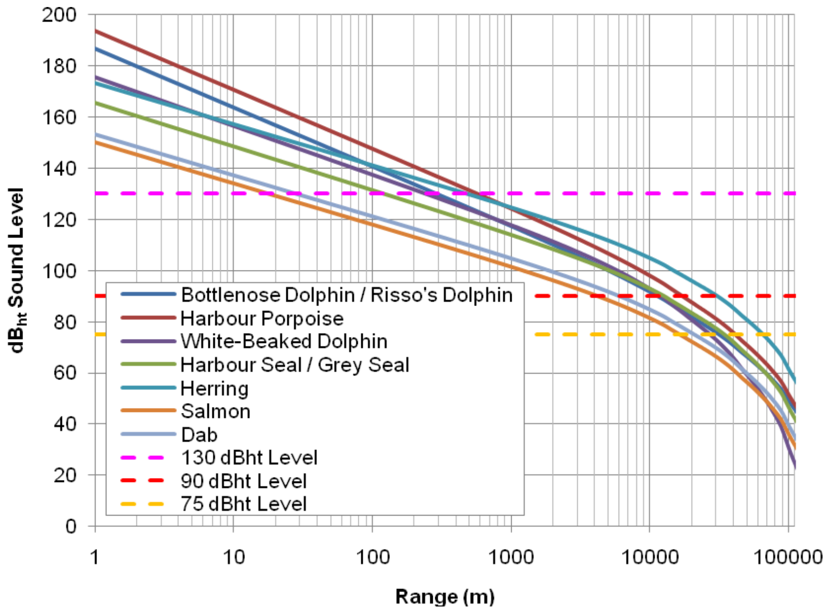

Figure 1.9-9 – Estimated peak to peak dB_{ht} level with range plot of various marine species along a shallow water transect (Wind turbine 11, Bearing 195) during the installation of an 8.5 m diameter pile

96 Table 1.9-14 to 1.9-17 present a comparison of estimated 90 dB_{ht} impact ranges for behavioural response for the species of interest at MHWS. Mean ranges along with the overall range of values are presented for all four wind turbine positions.

97 It can be seen that the largest impact ranges predicted are for herring, where maximum 90 dB_{ht} impact ranges of between 44 and 47 km are predicted. The other key fish species assessed in this study, salmon and dab, have much smaller impact ranges, from between 4.2 and 4.7 km for salmon and between 6.2 and 6.8 km for dab.

98 For species of marine mammal, the largest impact ranges are predicted for the harbour porpoise, which is likely to receive an underwater noise level of $90dB_{ht}$ out to maximum of 22 km from piling operations. The smallest 90 dB_{ht} impact ranges predicted for species of marine mammal is for bottlenose dolphin and Risso's dolphin, which are predicted maximum 90 dB_{ht} impact ranges of between 12 and 13 km.

99 The INSPIRE model calculates impact ranges along transect paths from a selected point, in this case the wind turbine positions, along 180 equally spaced transects (one every 2º). The maximum, minimum and mean ranges from all of these transects are collected in the tables below. It should be noted that the minimum ranges are for transects heading into shallow water, and in most cases, are reaching the coastline before the sound has attenuated to below 90 dB_{ht}. Hence why, for example, all the minimum ranges from Wind turbine 1 are calculated to be 3 km, as this is the minimum distance between the wind turbine position and the coastline. All the predicted received noise for all the key species is still above 90 dB_{ht} at this particular piece of coastline.

100 As the mean values quoted in the tables take into account all of the transects, these apparently shorter impact ranges are also used on the averaging. It is, therefore, suggested that the maximum values quoted and the contour plots presented later are also considered along with these results.

Table 1.9-14 – Summary of the estimated impact ranges for piling an 8.5 m diameter pile at wind turbine position 1 on various marine species

Species	90 dB_{ht} Range	
	Mean	Range of values
Bottlenose Dolphin Risso's Dolphin	8.5 km	3.0 – 13 km
Harbour Porpoise	12 km	3.0 – 21 km
White-Beaked Dolphin	9.3 km	3.0 – 15 km
Harbour Seal Grey Seal	9.6 km	3.0 – 16 km
Herring	22 km	3.0 – 45 km
Salmon	3.9 km	3.0 – 4.4 km
Dab	5.2 km	3.0 – 6.5 km

Table 1.9-15 – Summary of the estimated impact ranges for piling an 8.5 m diameter pile at wind turbine position 3 on various marine species

Species	90 dB_{ht} Range	
	Mean	Range of values
Bottlenose Dolphin Risso's Dolphin	7.9 km	2.3 – 12 km
Harbour Porpoise	11 km	2.3 – 20 km
White-Beaked Dolphin	8.4 km	2.3 – 14 km
Harbour Seal Grey Seal	8.7 km	2.3 – 15 km
Herring	20 km	2.3 – 44 km
Salmon	3.5 km	2.3 – 4.2 km
Dab	4.6 km	2.3 – 6.2 km

Table 1.9-16 – Summary of the estimated impact ranges for piling an 8.5 m diameter pile at wind turbine position 7 on various marine species

Species	90 dB_{ht} Range	
	Mean	Range of values
Bottlenose Dolphin Risso's Dolphin	9.5 km	4.1 – 13 km
Harbour Porpoise	13 km	4.1 – 22 km
White-Beaked Dolphin	10 km	4.1 – 16 km
Harbour Seal Grey Seal	11 km	4.1 – 16 km
Herring	24 km	4.1 – 47 km
Salmon	4.2 km	3.6 – 4.7 km
Dab	5.8 km	4.1 – 6.8 km

Table 1.9-17 – Summary of the estimated impact ranges for piling an 8.5 m diameter pile at wind turbine position 11 on various marine species

Species	90 dB_{ht} Range	
	Mean	Range of values
Bottlenose Dolphin Risso's Dolphin	9.2 km	3.8 – 13 km
Harbour Porpoise	13 km	3.8 – 21 km
White-Beaked Dolphin	10 km	3.8 – 16 km
Harbour Seal Grey Seal	10 km	3.8 – 16 km
Herring	23 km	3.8 – 47 km
Salmon	4.1 km	3.4 – 4.6 km
Dab	5.6 km	3.8 – 6.6 km

101 These results are also presented graphically as contour plots in Figures 1.9-10 to 1.9-16, with each group of images showing the 90 and 75 dB_{ht} impact ranges for each marine species of interest. The 75 dB_{ht} level is a lower behavioural avoidance level which has been used for analysis to show a level of "significant avoidance". At this level, about 85% of individuals will react to noise, although the effect will probably be limited in duration by habituation. In general, the 90dB_{ht} criteria level is thought to represent the most useful measure of behavioural disturbance in this case. It should be noted that the figures for dab and salmon are shown in a larger scale that the contours for the other species, this is so the extents of these smaller impact ranges can be seen in detail.

102 It can be seen from these figures that the maximum impact ranges stretch out to the east and north east of the proposed EOWDC into the deeper water of the North Sea, where, in some places, water depths are in excess of 100 m LAT. The data indicate that, in nearly all cases, the minimum 90 dB_{ht} contours are the same for each pile; this is due to sound levels being above 90 dB_{ht} for these species at the Scottish coastline. Salmon is the exception to this where, on two occasions, Turbine 7 and Turbine 11, noise levels during the

installation of 8.5m diameter piles have dropped below 90 dB_{ht}(*Salmo salar*) before reaching the Scottish coastline to the west.

103 As with the unweighted results it can be seen from these contour plots that the difference between the impact ranges at the four wind turbine sites are similar. The largest impact ranges are estimated for wind turbines 7 and 11; this is due to being situated on the east boundary of the proposed EOWDC, which is closer to the deep water of the North Sea.

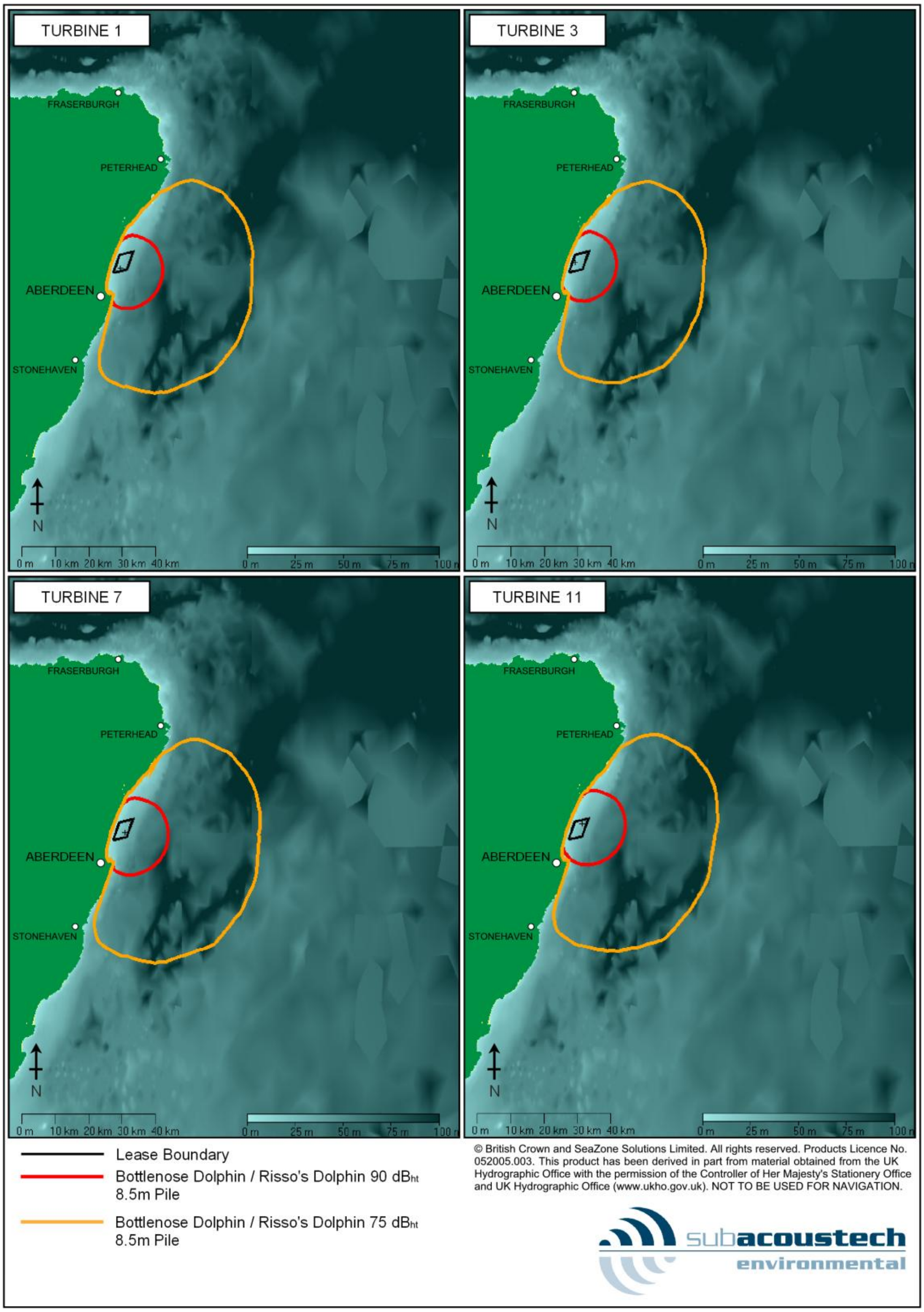

Figure 1.9-10 – Contour plots showing the estimated 90 and 75 dB$_{ht}$ peak impact ranges for Bottlenose Dolphin and Risso's Dolphin during installation of an 8.5 m diameter pile

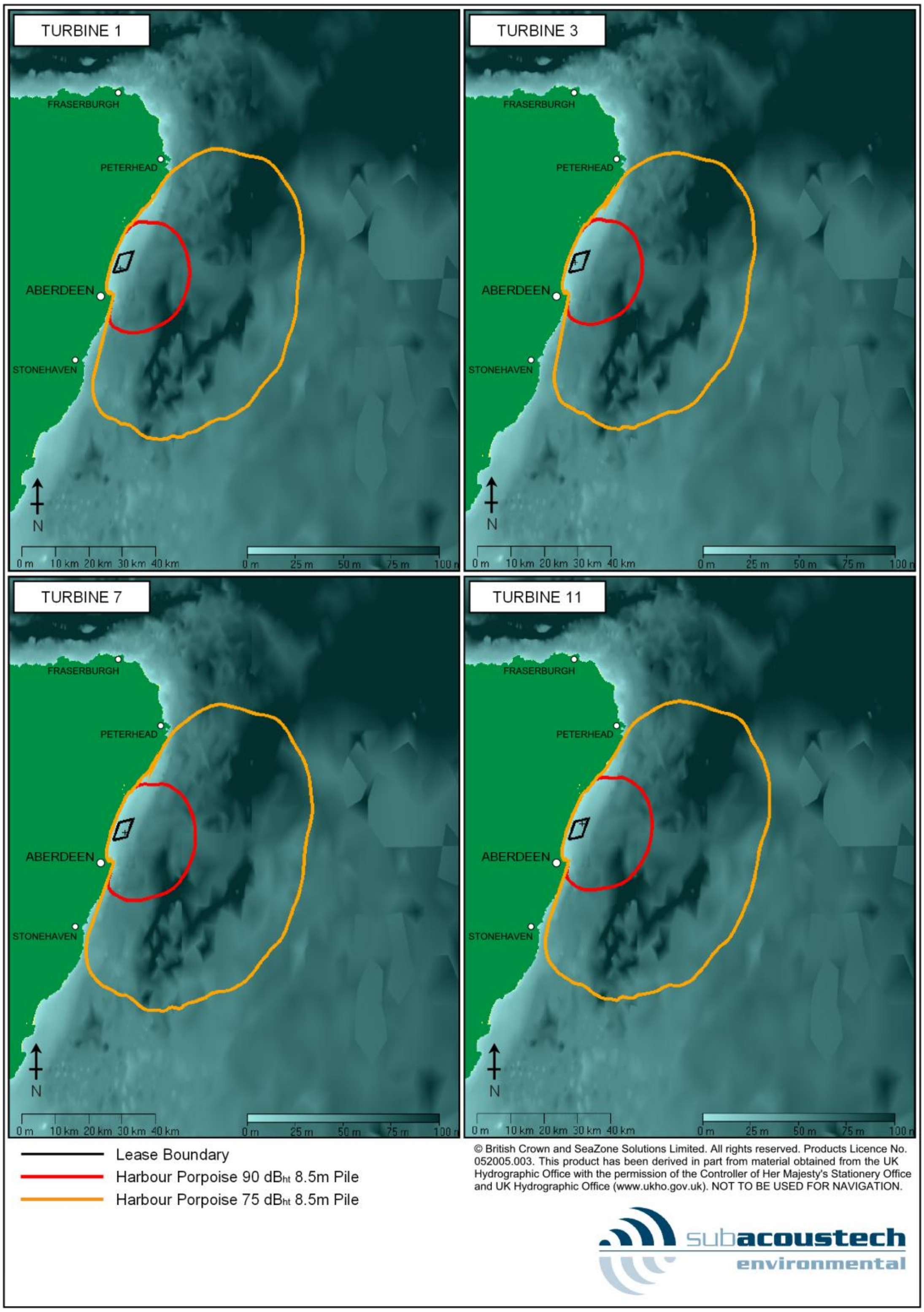

Figure 1.9-11 – Contour plots showing the estimated 90 and 75 dB_{ht} peak impact ranges for Harbour Porpoise during installation of an 8.5 m diameter pile

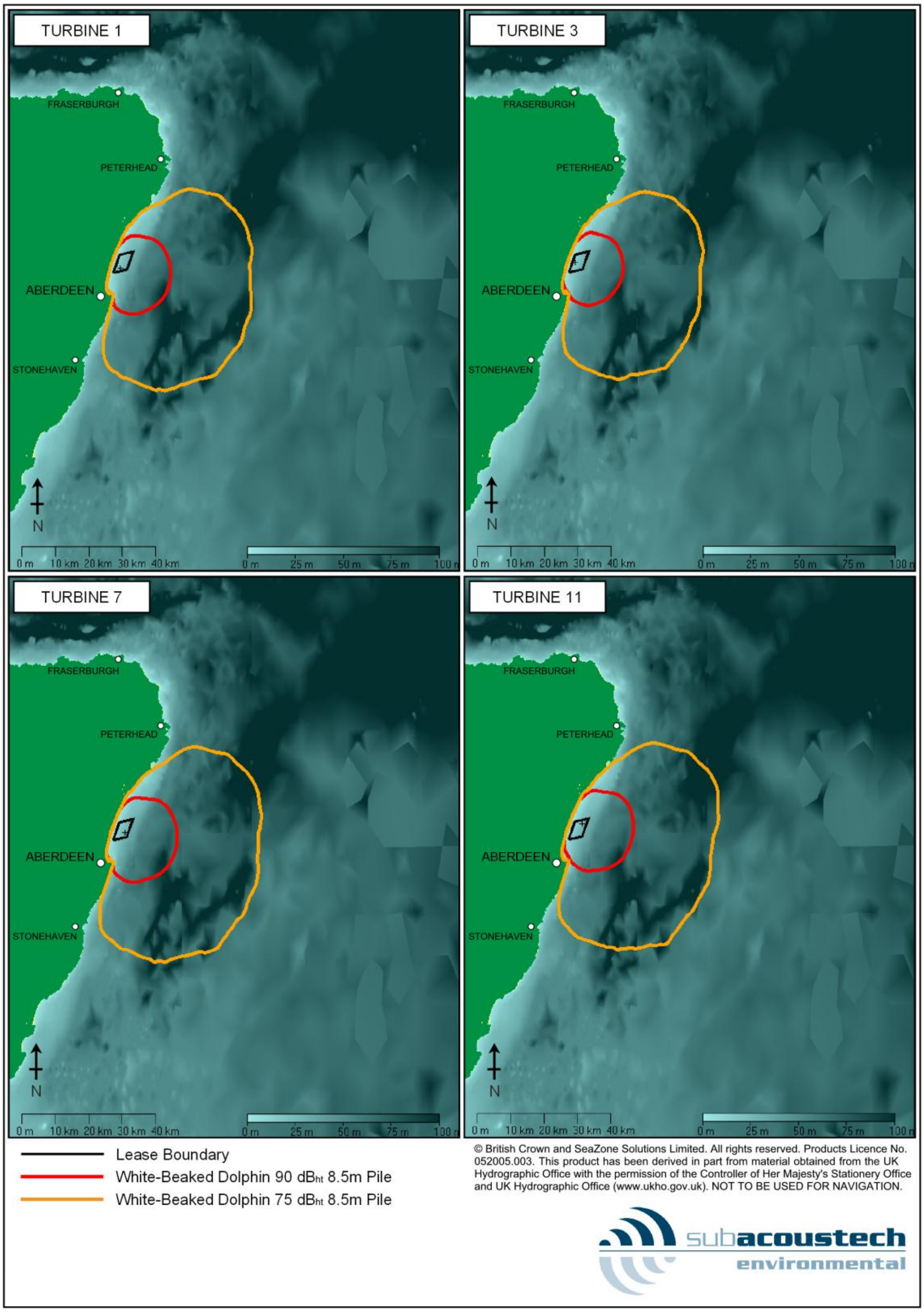

Figure 1.9-12 – Contour plots showing the estimated 90 and 75 dB_{ht} peak impact ranges for White-Beaked Dolphin during installation of an 8.5 m diameter pile

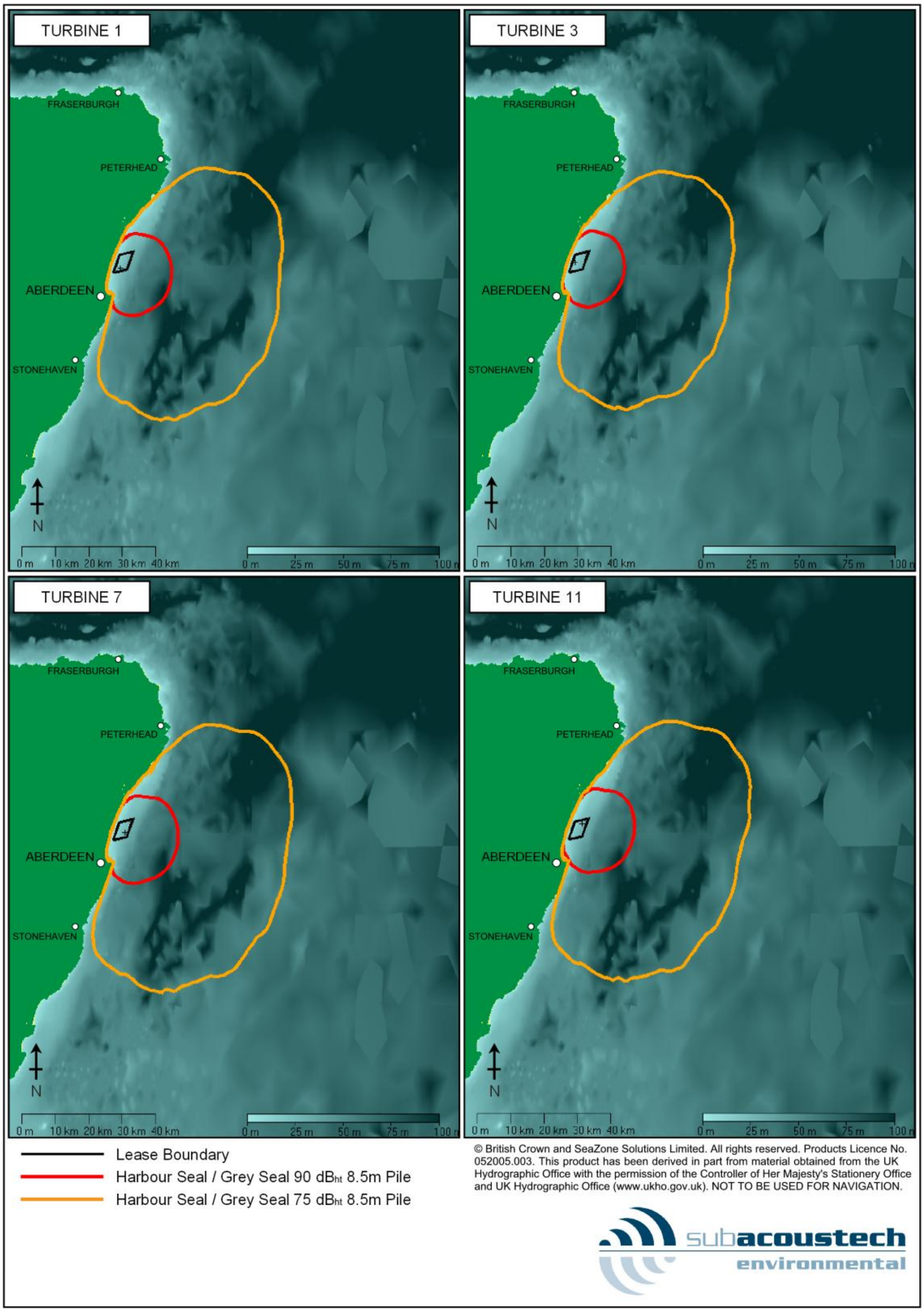

Figure 1.9-13 – Contour plots showing the estimated 90 and 75 dB$_{ht}$ peak impact ranges for Harbour Seal and Grey Seal during installation of an 8.5 m diameter pile

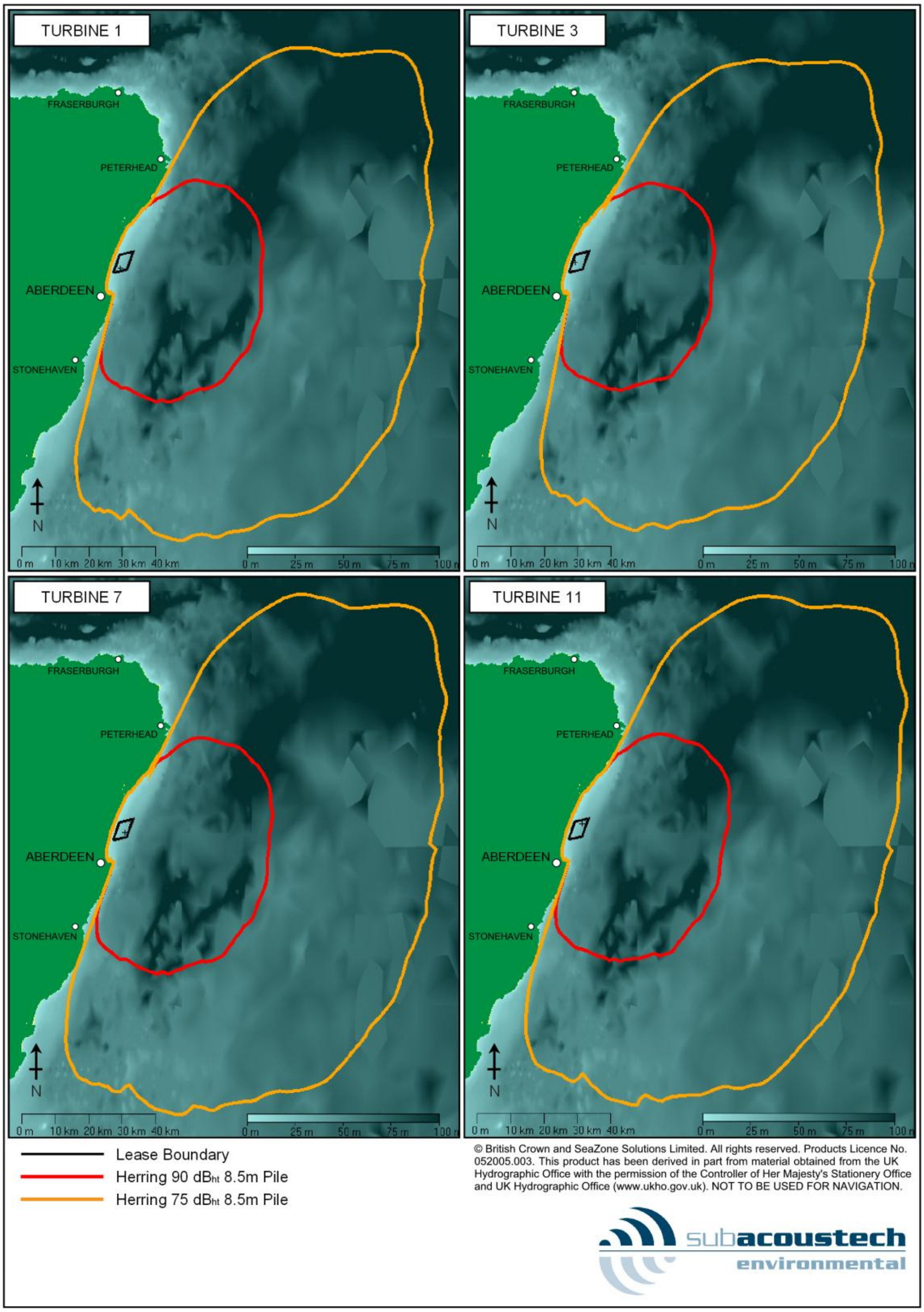

Figure 1.9-14 – Contour plots showing the estimated 90 and 75 dB_{ht} peak impact ranges for Herring during installation of an 8.5 m diameter pile

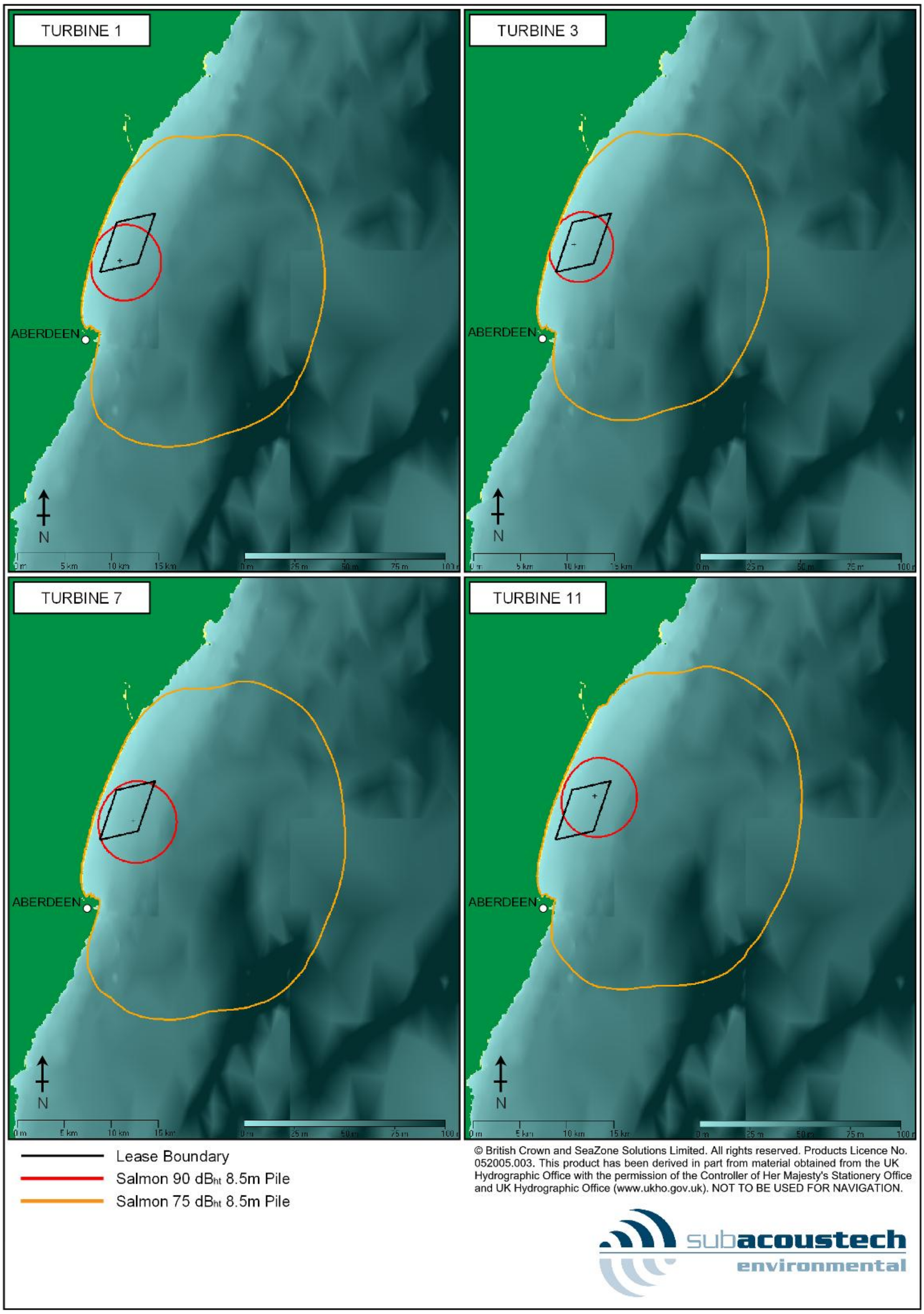

Figure 1.9-15 – Contour plots showing the estimated 90 and 75 dB$_{ht}$ peak impact ranges for Salmon during installation of an 8.5 m diameter pile, please note the larger scale on these figures

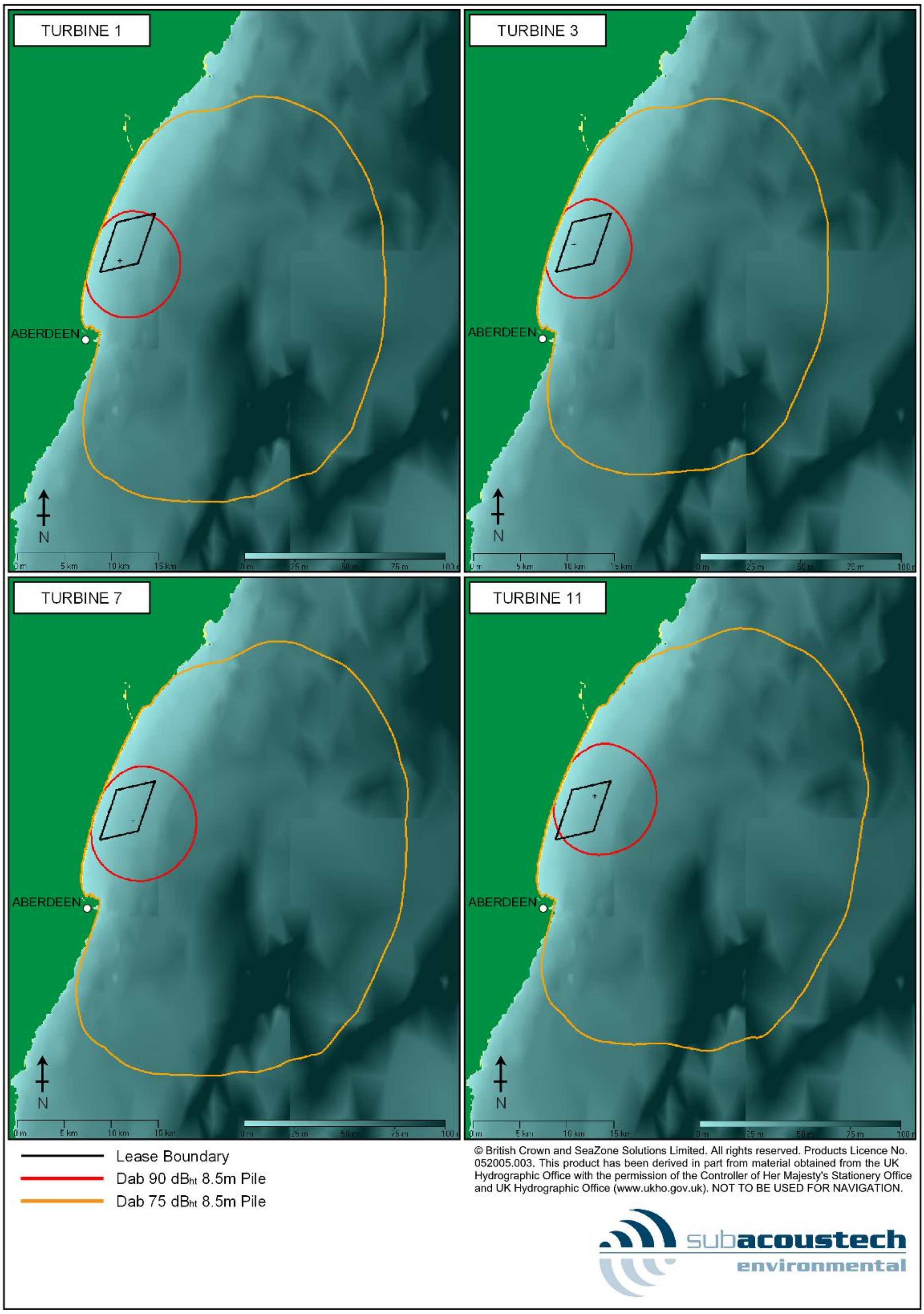

Figure 1.9-16 – Contour plots showing the estimated 90 and 75 dB$_{ht}$ peak impact ranges for Dab during installation of an 8.5 m diameter pile, please note the larger scale on these figures.

1.9.6 Estimates of Behavioural Impact on Marine Species; M-weighted SELs

104 Tables 1.9-18 to 1.9-21 show summaries of the single pulse behavioural impact ranges predicted using the Southall *et al* (2007) criteria. It can be seen that the largest impact ranges are predicted for the Pinnipeds group with behavioural avoidance predicted out to a range of 1.6 km during the installation of an 8.5 m diameter pile. The three cetacean groups predict lower single pulse behavioural impact ranges, ranging from 280 m, for low frequency cetaceans, to 100 m, for high frequency cetaceans.

105 Due to these SEL levels predicting relatively low impact ranges, no maximum and minimum ranges have been included as, at these close ranges, changes in bathymetry do not affect the attenuation of sound significantly, resulting in relatively uniform results.

Table 1.9-18 – Summary of ranges out to which a behavioural avoidance reaction in cetaceans in the low frequency cetaceans group may occur using the Southall *et al* (2007) criteria

Low Frequency Cetaceans	Behavioural Avoidance Range 183 dB re. 1 μPa^2/s (M_{lf})
Wind turbine 1	270 m
Wind turbine 3	260 m
Wind turbine 7	280 m
Wind turbine 11	280 m

Table 1.9-19 – Summary of ranges out to which a behavioural avoidance reaction in cetaceans in the mid frequency cetaceans group may occur using the Southall *et al* (2007) criteria

Mid Frequency Cetaceans	Behavioural Avoidance Range 183 dB re. 1 μPa^2/s (M_{mf})
Wind turbine 1	120 m
Wind turbine 3	110 m
Wind turbine 7	120 m
Wind turbine 11	120 m

Table 1.9-20 – Summary of ranges out to which a behavioural avoidance reaction in cetaceans in the high frequency cetaceans group may occur using the Southall *et al* (2007) criteria

High Frequency Cetaceans	Behavioural Avoidance Range 183 dB re. 1 μPa^2/s (M_{hf})
Wind turbine 1	100 m
Wind turbine 3	100 m
Wind turbine 7	100 m
Wind turbine 11	100 m

Table 1.9-21 – Summary of ranges out to which a behavioural avoidance reaction in pinnipeds (in water) may occur using the Southall *et al* (2007) criteria

Pinnipeds (in water)	Behavioural Avoidance Range 171 dB re. 1 μPa^2/s (M_{pw})
Wind turbine 1	1.6 km
Wind turbine 3	1.5 km
Wind turbine 7	1.6 km
Wind turbine 11	1.6 km

106 Table 1.9-22 presents a comparison between the mean predicted dB_{ht} behavioural avoidance impact ranges and the mean M-weighted SEL behavioural avoidance impact ranges for the equivalent marine mammal groups for modelling undertaken for wind turbine position 1.

107 Once again it can be seen that the impact ranges for dB_{ht} differ substantially from those predicted using the M-weighted SEL criteria. The ranges using the M-weighted SEL criteria are thought to be highly optimistic, and are in conflict with the limited amount of published information currently available. For instance, harbour porpoise have been found to avoid an area around similar pile driving operations out to a distance of 15 km (Tougaard *et al*, 2006).

Table 1.9-22 – Summary of impact ranges comparing the single pulse behavioural avoidance ranges, at wind turbine position 1, predicted using the dB_{ht} criteria (Nedwell *et al*, 2007) and the M-weighted SEL (Southall *et al*, 2007) criteria

dB_{ht} (Nedwell *et al*, 2007)		M-weighted SELs (Southall *et al*, 2007)	
Species	**Mean behavioural avoidance range (90 dB_{ht})**	**Equivalent M-weighting group**	**Mean behavioural avoidance range**
Bottlenose Dolphin	8.5 km	Mid Frequency Cetacean	120 m
Harbour Porpoise	12 km	High Frequency Cetacean	100 m
Harbour Seal	9.6 km	Pinnipeds (in water)	1.6 km

1.10 Summary

108 Subsea noise modelling has been carried out by Subacoustech Environmental Ltd to estimate the potential impact on various species of marine mammal and fish during the installation of 8.5 m diameter piles at the proposed EOWDC. Four modelling locations were chosen to provide a representative overview of potential impact ranges from the impact piling; showing the greatest variation across the site in terms of locations. The modelling has been carried out using the latest version of the INSPIRE acoustic model (version 2.0).

- Data analysed in terms of unweighted levels of underwater noise have indicated that, for impact piling operations of 8.5 m diameter piles, the levels of underwater noise produced are predicted to be of a sufficient level to cause lethality out to a range of 3 m (using the 240 dB re. 1 μPa criteria) and physical injury out to a range of 60 m (using the 220 dB re.1 μPa criteria). Beyond these ranges severe physical effects are not expected to occur based on the assessment criteria used.
- The ranges at which traumatic hearing injury is likely to occur in the selected marine species have been estimated based on the 130 dB_{ht} (*Species*) perceived noise level. The modelled data have indicated that hearing damage may occur out to a maximum of 570 m for the harbour porpoise (the most sensitive marine mammal species to underwater noise) and 480 m for the herring (the most sensitive fish species in terms of sensitivity to underwater noise).
- Modelling to determine the potential ranges of behavioural impact for selected marine species has been carried out in terms of the dB_{ht} (*Species*) specific metric for key species of marine mammal and fish. The data have indicated that herring are likely to perceive levels of underwater noise above 90 dB_{ht} out to the greatest ranges. The maximum ranges out to which the noise is expected to remain above 90 dB_{ht} for this species is between 20 and 24 km during piling of an 8.5 m diameter pile.
- Of the marine mammals considered the perceived levels of underwater noise for harbour porpoise is estimated to remain above the behavioural impact criteria out to the greatest ranges. The maximum strong behavioural avoidance impact ranges for this species are estimated to be between 11 and 13 km for the 8.5 m diameter pile.
- The maximum ranges for all the key species are predicted to be out to the east of the site into the North Sea where the water depths are in excess of 100 m. There is not predicted to be great variation in impact ranges for the four modelling locations.
- Analysis of the modelled data has also been carried out so that an assessment can be made in terms of the M-weighted SEL criteria presented by Southall *et al* (2007). These data have indicated that, for an 8.5 m diameter pile, auditory injury from a single pulse is likely to occur out to a maximum range of 130 m for pinnipeds and 20 m for the most sensitive cetacean species.
- Using the same analytical approach for single pulses a behavioural avoidance response may be expected out to a maximum range of 1.6 km for pinnipeds and 280 m for the most sensitive cetacean species for the proposed piling operations. However, these M-weighted SEL ranges are

thought to be highly optimistic, and are in conflict with published information.

- Analysis for multiple pulses has also been carried out using the dB_{ht} Noise Dose metric and the M-Weighted SEL metric presented by Southall *et al* (2007). The dB_{ht} data indicate that the most sensitive marine mammal species, harbour porpoise, and the most sensitive fish species, herring, would have to be less than 1350 m and 1750 m away respectively from the piling operation respectively at the onset of piling to exceed the 90 dB_{ht} $L_{EP, D}$ criterion. Provided these animals were beyond these ranges at the onset of piling they would not be expected to suffer auditory damage as a result of cumulative noise dose.
- For the multiple pulse criteria for auditory injury proposed by Southall *et al* (2007). The data indicate that the pinnipeds group would have to start at a range of at least 3.6 km from the piling to avoid a damaging sound exposure from the piling noise. The cetacean group most sensitive to piling noise, the low frequency cetaceans, which includes Humpback whales (*Megaptera novaeangliae*) and Minke whale, are predicted to have to start at a range of at least 1350 m from the piling operations to escape the area without receiving a damaging exposure to the noise.
- It should be noted that these ranges for multiple pulses were calculated using the assumption that a high blow force is used at the onset of piling, this is an unlikely scenario and a soft start procedure is likely to result in a reduction to these standoff ranges.

1.11 Appendices

1.11.1 Underwater Sound Measurements

1.11.1.1 *Units of Measure*

109 The fundamental unit of sound pressure is the Newton per square metre, or Pascal. However, in quantifying underwater acoustic phenomena it is convenient to express the sound pressure (either peak, or Root Mean Square (RMS)) as a Sound Pressure Level (SPL) through the use of a logarithmic scale.

110 There are three reasons for this:

- there is a very wide range of sound pressures measured underwater, from around 0.0000001 Pascal in quiet sea to say 10000000 Pascal for an explosive blast. The use of a logarithmic scale compresses the range so that it can be easily described (in this example, from 0 dB to 260 dB re. 1 µPa (referenced to a sound level of 1 µPa)).
- many of the mechanisms affecting sound underwater cause loss of sound at a constant rate when it is expressed on the dB scale.
- the effects of noise tend to increase in proportion to the SPL rather than the linear level. For instance, a given increase in effect will occur each time the sound is doubled, rather than each time it increases by a given unit of pressure.

111 The Sound Pressure Level, or SPL, is defined as

$$SPL = 20\log\left(\frac{P}{P_{ref}}\right)$$

eqn. 1.11-1.

where P is the sound pressure to be expressed on the scale and P_{ref} is the reference pressure, which for underwater applications is 1 µPa.

1.11.1.2 *Peak Level*

112 The peak level of the noise is the maximum variation in the acoustic pressure from the ambient level within the measurement period. Peak pressures are often quoted for underwater blast measurements where there is a clear positive peak following detonation.

1.11.1.3 *Peak-to-Peak Level*

113 The peak-to-peak level is calculated using the maximum variation of the pressure from positive to negative within the wave. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak level will be twice the peak level, and hence 6 dB higher.

1.11.1.4 Root-Mean-Square (RMS) Level

114 For both continuous sound, or sound that varies in level, the RMS is used as an “average” value when calculating the level. The time period over which the averaging is conducted has to be quoted as this will influence the average level. For instance, in the case of a pile strike lasting say a tenth of a second, the mean taken over a tenth of a second will be ten times higher than the mean taken over one second.

1.11.1.5 Source Level

115 Where there is a single, well-defined source of noise, underwater sound pressure measurements may be expressed as dB re 1 µPa @ 1m, which represents the apparent level at a distance of one metre from the source. In fact, since the measurements are usually made at some distance from the source, and extrapolated back to the source, the true level at one metre may be very different from the Source Level. The Source Level may itself be quoted in any of the measures above, for instance, a piling source may be expressed as having a “peak-to-peak Source Level of 200 dB re 1 µPa @ 1 m”.

1.11.1.6 Sound Exposure Level

116 The degree by which a noise source affects marine animals may depend on the duration the sound is present above background levels. Sound Exposure Level (SEL) takes into account both the SPL of the sound source and the duration the sound is present in the acoustic environment. Sound Exposure (SE) is defined by the equation:

$$SE = \int_0^T p^2(t)\,dt$$

eqn. 1.11-2.

where p is the acoustic pressure in pascals, T is the duration of the sound in seconds and t is time.

117 Equation A-2 gives units of pascal squared seconds (Pa^2-s).

118 The SE can be expressed as a deciBel level by using a reference pressure (P_{ref}) and a reference time (T_{ref}) on a logarithmic scale giving Sound Exposure Level (SEL):

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

eqn. 1.11-3.

119 P_{ref} and T_{ref} are typically 1 µPa and 1 second respectively for underwater noise.

120 Equation 3 can also be expressed by:

$$SEL = SPL + 10\log_{10}(T)$$ **eqn. 1.11-4**

where T is the duration of the noise in seconds.

121 Using the reference pressures above Equation 1.11-4 shows that for a sound of 1 second duration the Sound Exposure Level is equal to the Sound Pressure Level as $10\log_{10}(1) = 0$. For a sound of 10 seconds duration the SEL will be 10 dB higher than the SPL, for a sound of 100 seconds duration the SEL will be 20 dB higher than the SPL and so on.

1.11.1.7 *Frequency Content*

122 To interpret an underwater sound signal for the manner in which it will be heard by an underwater animal, the sound signal in a time history format must be converted into its frequency components. This is because the response of marine species to underwater sound is frequency dependent (see the audiograms in Figures 1.7-1 to 1.7-3). This transformation of the sound is achieved by performing a Power Spectral Density (PSD) analysis of the signal. 'The PSD's (frequency spectra) presented in this report may therefore be regarded as dividing up the total power of the sound into its frequency components, and are presented in decibels (dB) referenced to 1 µPa.

1.11.1.8 *The dB_{ht} (Species)*

123 Measurement of sound using electronic recording equipment provides an overall linear level of that sound. The level that is obtained depends upon the recording bandwidth and sensitivity of the equipment used. This, however, does not provide an indication of the impact that the sound will have upon a particular fish or marine mammal species. This is of fundamental importance when considering the behavioural impact of underwater sound, as this is associated with the perceived loudness of the sound by the species. Therefore, the same underwater sound will affect marine species in a different manner depending upon the hearing sensitivity of that species.

124 The measurements of noise in this study have therefore also been presented in the form of a dB_{ht} level for the species. This scale incorporates the concept of "loudness" for a species. The metric incorporates hearing ability by referencing the sound to the species' hearing threshold, and hence evaluates the level of sound a species can perceive. In Figure 1.11-1, the same noise spectrum is perceived at a different loudness level depending upon the particular fish or marine mammal receptor. The aspect of the noise that can be heard is represented by the 'hatched' region in each case. The receptors also hear different parts (components) of the noise spectrum. In the case shown, Fish 1 has the poorest hearing (highest threshold) and only hears the noise over a limited low frequency range. Fish 2 has very much better hearing and hears the main dominant components of the noise. Although having the lowest threshold to the sound, the marine mammal only hears the very high components of the noise and so it may be perceived as relatively quiet.

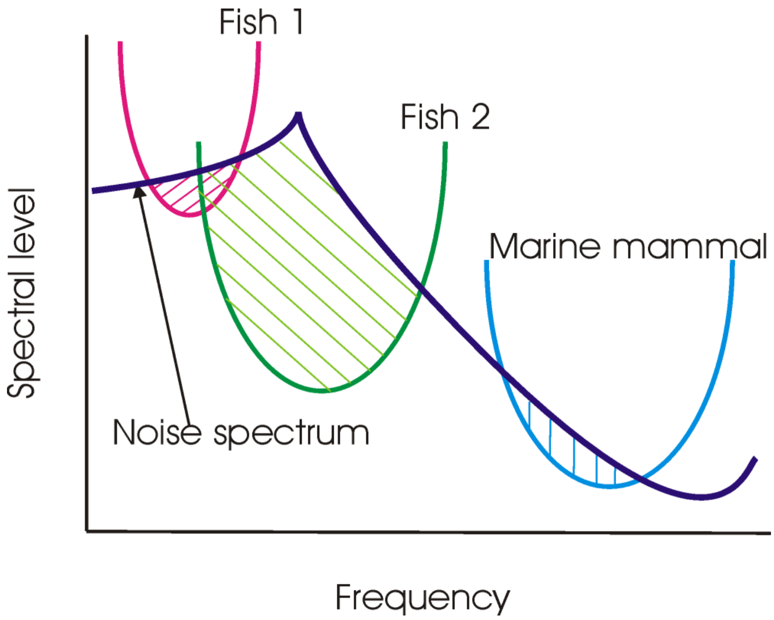

Figure 1.11-1. Illustration of perceived sound level (dBht) for representative fish and marine mammal species.

125 Since any given sound will be perceived differently by different species (since they have differing hearing abilities) the species name must be appended when specifying a level. For instance, the same sound might have a level of 70 dB_{ht} for a cod (*Gaddus morhua*) and 40 dB_{ht} for a salmon (*Salmo salar*).

126 The perceived noise levels of sources measured in dB_{ht} (*Species*) are usually much lower than the un-weighted (linear) levels, both because the sound will contain frequency components that the species cannot detect, and also because most aquatic and marine species have high thresholds of perception to (are relatively insensitive to) sound.

1.11.1.9 M-weighted Sound Exposure Levels

127 Southall *et al*., (2007) proposes the use of generalised frequency weighting functions to filter underwater sound exposure levels to better represent the levels of underwater noise various marine species are likely to be able to hear. The authors group marine mammals into 5 groups, 4 of which are relevant to underwater noise (the fifth is for pinnipeds in air). For each group an approximate frequency range of hearing is proposed based on known audiogram data, where available, or inferred from other information such as auditory morphology. These are summarised in Table 1.11-1 below.

Table 1.11-1 Functional marine mammal groups, their assumed auditory bandwidth of hearing and genera presented in each group (reproduced from Southall *et al* (2007))

Function hearing group	Estimated auditory bandwidth	Genera represented	Example species
Low frequency cetaceans	7 Hz to 22 kHz	*Balaena, Caperea, Eschrichtius, Megaptera, Balaenoptera* (13 species/subspecies)	Grey whale, Right whale, Humpback whale, Minke whale
Mid frequency cetaceans	150 Hz to 160 kHz	*Steno, Sousa, Sotalia, Tursiops, Stenella, Delphinus, Lagenodelphis, Lagenorhynchus, Lissodelphis, Grampus, Peponocephala, Feresa, Pseudorca, Orcinus, Globicephala, Orcaella, Physeter, Delphinapterus, Monodon, Ziphius, Berardius, Tasmacetus, Hyperoodon, Mesoplodon* (57 species/subspecies)	Bottlenose dolphin, striped dolphin, Killer whale, Sperm whale
High frequency cetaceans	200 Hz – 180 kHz	*Phocoena, Neophocaena, Phocoenoides, Platanista, Inia, Kogia, Lipotes, Pontoporia, Cephalorhynchus* (20 species/subspecies)	Harbour porpoise, River dolphins, Hector's dolphin
Pinnipeds (in water)	75 Hz to 75 kHz	*Arctocephalus, Callorhinus, Zalophus, Eumetopias, Neophoca, Phocarctos, Otaria, Erignathus, Phoca, Pusa, Halichoerus, Histriophoca, Pagophilus, Cystophora, Monachus, Mirounga, Leptonychotes, Ommatophoca, Lobodon, Hydrurga,* and *Odobenus* (41 species/subspecies)	Fur seal, Harbour (common) seal, Grey Seal

1.11.1.10 Background Levels

128 Of critical importance in assessing the impact of noise and vibration from an activity is a measure of the ambient noise environment. The pre-existing noise and vibration levels in fast flowing rivers, busy estuaries and coastal waters will be high compared to the levels that are associated with airborne perception by terrestrial animals. As an example, ambient underwater noise in coastal waters measured as a broadband level from 1 Hz to 100 kHz, typically varies from 100 to 130 dB re. 1 µPa.

1.11.1.11 Attenuation of Sound

129 To normalise underwater sound and vibration measurements to a common reference point, levels are normally quoted as Source Levels. As the sound propagates out from the source the level will reduce both as a result of geometric spreading and absorption in the propagation medium. These effects when combined provide a model for the Transmission Loss (TL) of the noise and vibration with range. This means that the received level at range is substantially lower than the Source Level in the immediate vicinity of the activity.

130 The sound level at range from an activity can be described by the expression;

$L(r) = SL – TL$ **eqn. 1.11-5.**

where L(r) is the Sound Pressure Level at distance r from a source (m), SL is the (notional) source level at 1 m from the source, and TL is the transmission loss.

131 The Transmission Loss is frequently described by the equation

$TL = N \log(r) + \alpha r$ **eqn. 1.11-6.**

where r is the distance from the source (m), N is a factor for attenuation due to geometric spreading, and α is a factor for the absorption of sound in water and boundaries (dB.m-1).

132 Using this form of sound transmission loss, the sound level with range L(r) can be described by the expression

$L(r) = SL – N \log(r) - \alpha r$ **eqn. 1.11-7.**

1.11.2 Preliminary subsea noise modelling at the proposed European Offshore Wind Deployment Centre

1.11.2.1 Introduction

133 Preliminary underwater noise modelling has been undertaken by Subacoustech Environmental to provide an indication of the likely differences in impact ranges between impact piling different size piles at the proposed EOWDC site.

134 Underwater noise levels have been estimated along one transect using the INSPIRE model (currently version 2.0), a proprietary acoustic propagation modelling program developed by Subacoustech Environmental. INSPIRE has been tested and validated against a large database of measured underwater noise data from previous impact piling operations and calculates absorption and depth-dependent transmission losses. These are used in conjunction with bathymetric data to calculate estimated impact ranges for the underwater noise produced during the proposed impact piling operations.

135 The two options being considered at proposed EOWDC are monopile foundations, using 8.5m diameter piles, and jacket foundations, using four 2.5 m diameter piles. To make this assessment a representative transect has been chosen from turbine position 11, which is in the deepest water (approximately
30 m deep at mean high water springs (MHWS)), at a bearing of 60º, which extends into water that is over 100 m in depth. This particular transect has been chosen to give a “worst case” estimate of the impact ranges for the proposed piling operations at the proposed EOWDC.

136 It should be noted that the INSPIRE model has been developed using the best available underwater noise data, however, the largest pile diameter for which reliable measured data is available is 6.1 m in diameter. Impact range estimates for pile sizes greater than this have been calculated by extrapolation and it is not yet possible to validate the results experimentally.

137 The results of the modelling have been presented here as linear (unweighted) peak to peak sound levels and weighted peak to peak dB_{ht}(*Species*) levels for four species of marine mammal that are of interest in the areas surrounding the proposed EOWDC site; bottlenose dolphin, harbour porpoise, harbour seal and white-beaked dolphin (using the striped dolphin as a surrogate, as currently available information suggests that both species have a similar sensitivity to sound).

1.11.2.2 Unweighted Results

138 Figure 1.11-2 illustrates the predicted unweighted peak to peak underwater noise levels, using the INSPIRE model, shown as level against range plots. The results were calculated along one deep water transect of bearing 60º from turbine position 11 estimating the impact of installing an 8.5 m diameter and a 2.5 m diameter pile, these impact ranges are also summarised in Table 1.11-2. It can be seen from these results that the sound is likely to remain at

high levels out to considerably larger distances for the 8.5 m pile when compared to the 2.5 m pile.

139 Table 1.11-3 summarises the unweighted impact ranges using predicted peak underwater noise levels. As the waveform of a pile strike is typically symmetrical about the ambient pressure level (equal high and low pressure excursions) it can be reasonably assumed that the peak pressure level is half of the peak to peak pressure level (a reduction of 6dB). The impact ranges in Table 2 have been calculated by reducing the peak to peak noise levels predicted by the INSPIRE model by 6dB.

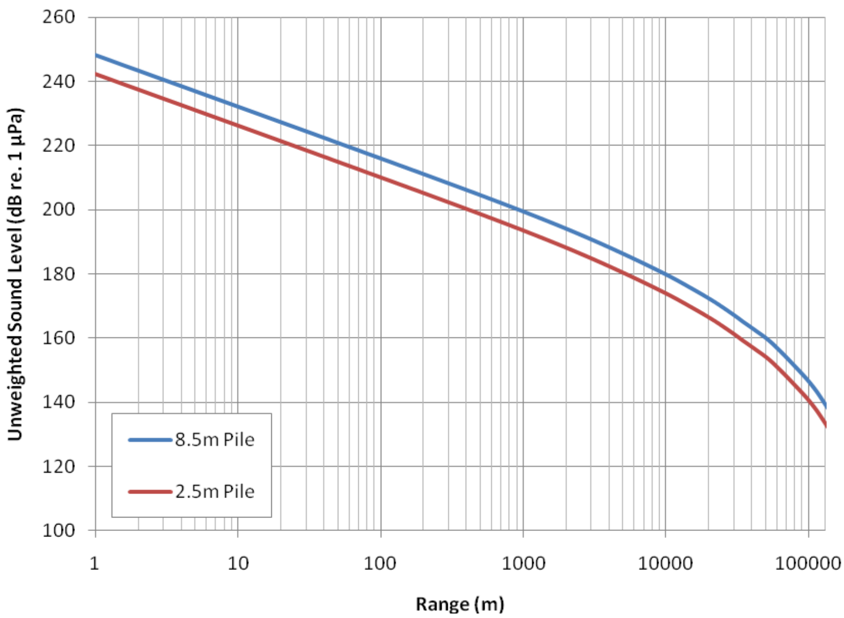

Figure 1.11-2 – Level with range plot for the estimated unweighted peak to peak underwater noise levels at Position 11 for 8.5m and 2.5m diameter piles.

Table 1.11-2 – Summary of the estimated ranges to various unweighted peak to peak underwater noise levels at Position 11 for 8.5 m and 2.5 m diameter piles.

Peak to peak	8.5 m Diameter Pile	2.5 m Diameter Pile
Range to 200 dB re. 1 µPa	960 m	420 m
Range to 190 dB re. 1 µPa	3.3 km	1.6 km
Range to 180 dB re. 1 µPa	9.9 km	5.3 km
Range to 170 dB re. 1 µPa	24 km	15 km
Range to 160 dB re. 1 µPa	51 km	33 km
Range to 150 dB re. 1 µPa	86 km	64 km

Table 1.11-3 – Summary of the estimated ranges to various unweighted peak underwater noise levels at Position 11 for 8.5 m and 2.5 m diameter piles.

Peak	8.5 m Diameter Pile	2.5 m Diameter Pile
Range to 200 dB re. 1 µPa	390 m	180 m
Range to 190 dB re. 1 µPa	1.6 km	720 m
Range to 180 dB re. 1 µPa	5.3 km	2.6 km
Range to 170 dB re. 1 µPa	15 km	8.2 km
Range to 160 dB re. 1 µPa	33 km	21 km
Range to 150 dB re. 1 µPa	64 km	44 km

1.11.2.3 dB_{ht}(Species) Results

140 The dB_{ht}(*Species*) metric (Nedwell *et al.*, 2007) has been developed as a means for quantifying the potential for a behavioural impact on a species in the underwater environment. Since any given sound will be perceived differently by different species (since they have differing hearing abilities) the species name must be appended when specifying a level. For instance, the same sound might have a level of 70 dB_{ht}(*Phocoena phocoena*) for harbour porpoise and 40 dB_{ht}(*Phoca vitulina*) for harbour seal.

141 Currently, on the basis of a large body of measurements of fish avoidance of noise (Maes *et al,* 2004), and from re-analysis of marine mammal behavioural response to underwater sound, the following assessment criteria was published by the Department of Business, Enterprise and Regulatory Reform (BERR) (Nedwell *et al,* 2007) to assess the potential impact of the underwater noise on marine species:

Table 1.11-4 – Assessment criteria used in this study to assess the potential impact of underwater noise on marine species.

Level in dB_{ht}(*Species*)	Effect
90 and above	Strong avoidance reaction by virtually all individuals.
Above 110	Tolerance limit of sound; unbearably loud.
Above 130	Possibility of traumatic hearing damage from single event.

142 In addition, a lower level of 75 dB_{ht} has been used for analysis as a level of “significant avoidance”. At this level, about 85% of individuals will react to the noise, although the effect will probably be limited in duration by habituation.

143 Figures 11.1-3 and 11.1-4 show the results for modelling 8.5 m diameter piles and 2.5 m diameter piles respectively in terms of peak to peak dB_{ht}(*Species*) perceived sound levels for the four marine mammals as level with range plots. The levels where traumatic hearing injury (130 dB_{ht}), strong behavioural avoidance (90 dB_{ht}) and significant behavioural avoidance (75 dB_{ht}) may occur in species are also indicated in these figures. The modelling was carried out along the same transect as before at a bearing of 60º from turbine position 11. A summary of these impact ranges is presented in Tables 11.1-5 and 11.1-6.

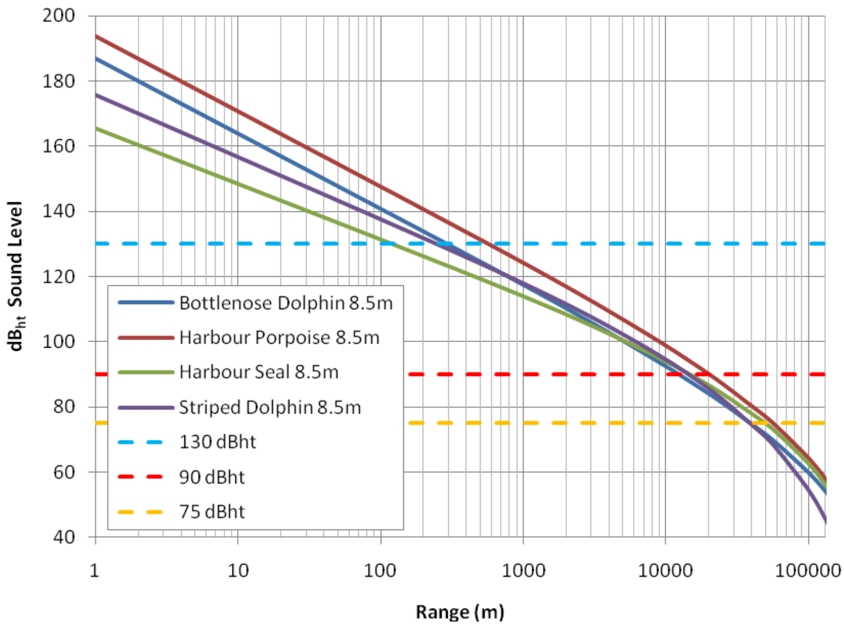

Figure 1.11-3 – Estimated peak to peak dB_{ht} level with range plot for four species of marine mammal during the installation of an 8.5 m diameter pile.

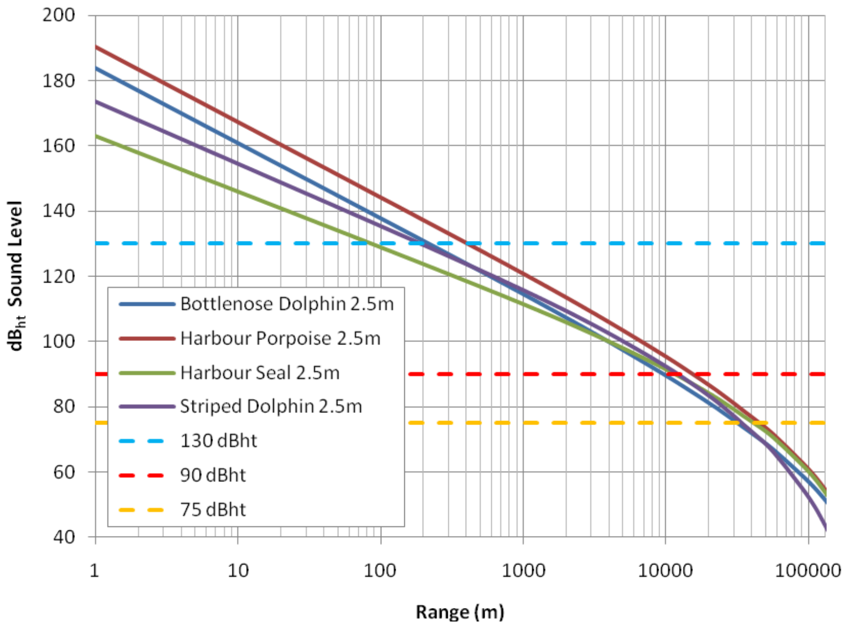

Figure 1.11-4 – Estimated peak to peak dB_{ht} level with range plto for four species of marine ammal during the installation of a 2.5m diameter pile.

Table 11.1-5 – Summary of the estimated impact ranges for piling an 8.5 m diameter pile on various species of marine mammals.

8.5 m Diameter Pile	**Range to 130 dB_{ht}**	**Range to 90 dB_{ht}**	**Range to 75 dB_{ht}**
Bottlenose Dolphin (dB_{ht}(*Tursiops truncatus*))	300 m	12 km	39 km
Harbour Porpoise (dB_{ht}(*Phocoena phocoena*))	570 m	20 km	57 km
Harbour Seal (dB_{ht}(*Phoca vitulina*))	150 m	15 km	50 km
Striped Dolphin (dB_{ht}(*Stenella coeruleoalba*))	270 m	14 km	39 km

Table 11.1-6 – Summary of the estimated impact ranges for piling a 2.5 m diameter pile on various species of marine mammals.

2.5 m Diameter Pile	**Range to 130 dB_{ht}**	**Range to 90 dB_{ht}**	**Range to 75 dB_{ht}**
Bottlenose Dolphin (dB_{ht}(*Tursiops truncatus*))	240 m	10 km	32 km
Harbour Porpoise (dB_{ht}(*Phocoena phocoena*))	420 m	16 km	46 km
Harbour Seal (dB_{ht}(*Phoca vitulina*))	90 m	12 km	42 km
Striped Dolphin (dB_{ht}(*Stenella coeruleoalba*))	210 m	12 km	35 km

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