Underwater acoustic field and impact prediction of monopile construction for the Humber Gateway offshore wind farm development.

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1 INTRODUCTION

This report summarises a study assessing the potential impact to marine life of underwater noise fields generated by the construction phase of the Humber Gateway Offshore Wind Farm. This has involved making estimates of the acoustic field around the array site due to the marine piling which will be undertaken during the construction phase.

This work requires several distinct steps. Firstly, an estimate is made of the likely Source Level of the noise sources. This has been done by reference to measurements made at other windfarm sites in UK waters. Secondly, modelling has been undertaken of acoustic propagation losses around the proposed site to estimate likely received acoustic levels at various ranges. Finally, an estimate is made of likely impact, both in terms of physical injury and behavioural changes, due to the received levels with regards to the current knowledge of species-specific physiological hearing responses for the primary species of interest in the area.

A measurement of the ambient noise in the area has also been made. This has been reported elsewhere in NPL report DQL-AC (RES)017.

To enable comparison with other studies undertaken for UK windfarm developments, and at the request of the customer, the methodology for the prediction has been aligned as far as possible with that used in a previous study [Parvin *et al* (2006)]. Additional methodologies and criteria drawn from current best scientific knowledge are also included as appropriate.

The report is organised as follows. Section 2 describes the windfarm site and provides a background to the work. Section 3 covers some basic considerations for assessment of underwater noise including types of propagation model and broad classes of impact. The metrics used for impact assessment and the effect of species hearing sensitivity is discussed in Section 4. Section 5 reviews the results of previous measurements of piling noise and estimates the likely Source Level for the Humber Gateway installation. Section 6 discusses the prediction of the acoustic field in the vicinity of the windfarm. Sections 7 and 8 provide assessments of the impact, both physical and behavioural, of the radiated noise. Section 9 provides analysis of various uncertainties associated with provided analysis. A summary is provided in Section 10.

2 HUMBER GATEWAY WINDFARM SITE

2.1 INTRODUCTION

Humber Gateway is a “Round 2” windfarm development located in the northern part of the Greater Wash Strategic Environmental Assessment Area (SEA). The site is located approximately 8 km east of the Yorkshire coast, near the Humber Estuary off the north east coast of England.

The site (at its closest approach to the coast) lies just to the east of Spurn Head (the long sand peninsula that shelters the entrance of the estuary). At its northernmost point, the site is 8.2 km from Easington on the Holderness coast. At the site’s southernmost point, it is approximately 18 km from Grimsby and 10 km from the nearest point on the Lincolnshire coast, Donna Nook. It’s southern edge borders the natural deepwater channel New Sand Hole. To the east and south of the project are the deep water channels for vessels entering the River Humber.

The windfarm will have a maximum of 300 MW of installed capacity and covers an area of 35 km^2. The farm will consist of between 42 and 83 turbines depending on the size of the wind turbines chosen.

Figure 2.1 shows the footprint of the site.

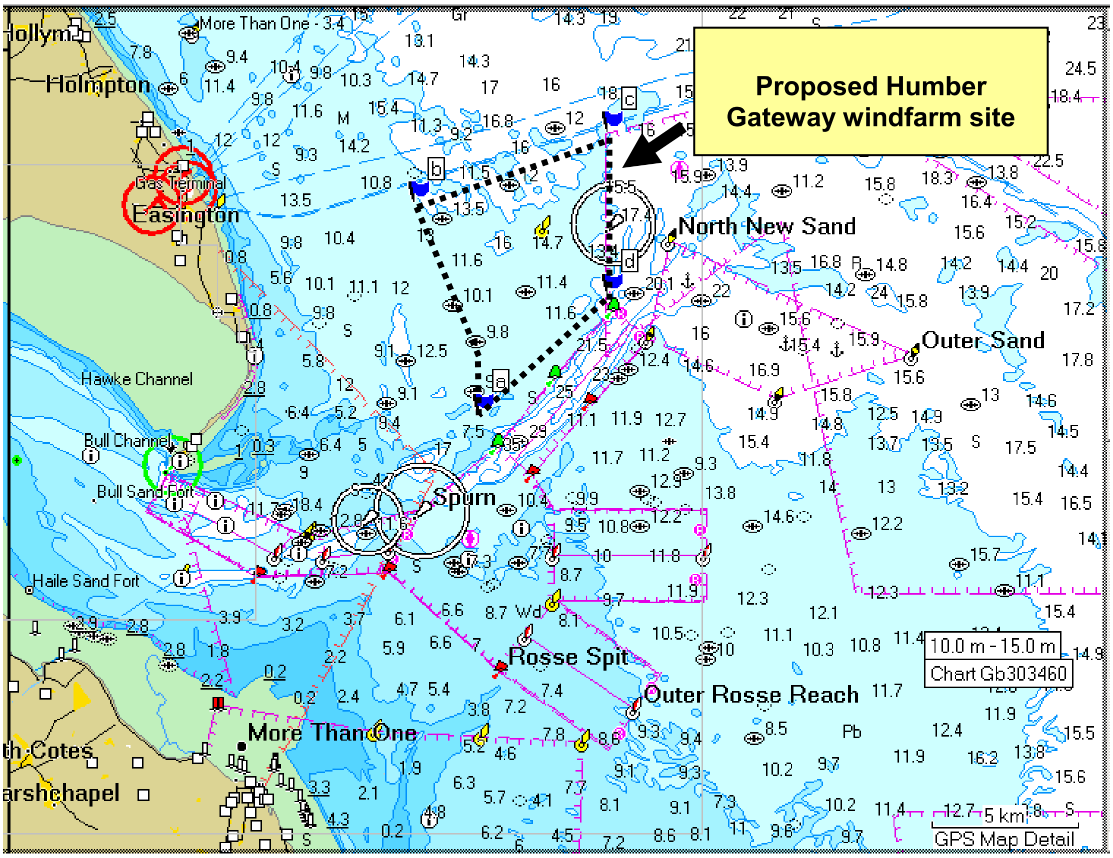

Figure 2.1 Site footprint for Humber Gateway windfarm.

2.2 INTRODUCTION TO THE ACOUSTIC FIELD PREDICTION

This study has been conducted to allow prediction of the potential acoustic field associated with the full construction of the Humber Gateway wind farm array. Two methodologies are outlined to estimate Source Level for a 6 m piling operation on the Humber Gateway site, estimates of likely transmission losses and finally likely received and perceived receive levels. Comparison were made with received level prediction methodologies used in previous studies summarised in Parvin *et al* (2006) forming the basis acoustic fields and impacts from other UK windfarm sites.

Various impact criteria for injury and behavioural disturbances are discussed and examples of several zones of impact predictions for areas both in range and depth for received levels of above various threshold are then made. Comparison was again made with impact assessment from various methodologies. These methodologies are derived from previous studies of acoustic impact of construction of a number of UK windfarms and current best available scientific knowledge of physiological and behavioural responses.

The acoustic field estimates are based on a 6 m diameter driven monopile used for a 3.6 MW turbine. Turbine positions are designated in proposed site layout 1 for a total number of 83 turbines [Section 6 of the Humber Gateway offshore report].

3 CONSIDERATIONS FOR UNDERWATER NOISE ASSESSMENT

This section provides an introduction to some of the concepts used in underwater acoustics, and draws analogies with those used for air acoustics.

3.1 SOME COMPARISONS WITH AIR-BORNE SOUND

For the reader mainly familiar with sound in air, it is perhaps useful to describe some of the differences between the propagation of sound in air and in water. Table 3.1 shows a summary of some of these differences. It can be seen that sound speed is substantially greater in water than in air, and that the absorption is generally less. The low absorption allows sound to travel large distances in the ocean, particularly low frequency sound. The acoustic impedance is also much greater for water than air. This means that for sources with the same noise power (i.e. the same rate of energy input into the medium), the acoustic pressure in water will be greater by a factor of about 60 than that generated in air (assuming the sources have the same directivity and the range and transmission loss between source and receiver is the same).

Parameter	Air	Water
Sound speed (m/s)	344 (20 ºC and 50 % humidity)	1,521 (20 ºC, depth 10 m, salinity 35 parts per thousand)
Acoustic impedance (Pa·s/m)	~ 400	~ 1,500,000
Absorption at 1 kHz (dB/km)	~ 5 (30 % humidity)	~ 0.06 (seawater)
Reference level (μPa)	20	1
Frequency range	20 Hz to 20 kHz (mainly audible range)	<1 Hz to > 1MHz

Table 3.1 – Examples of parameters related to sound propagation in air and water [Kaye and Laby, Kinsler et al, 1982].

The frequency range of the applications of underwater acoustics is very large, with seismic measurements involving frequencies of less than 1 Hz, and with Acoustic Doppler Current Profilers operating at frequencies of several megahertz. For sound in air, although infrasound and ultrasound are of some interest, the vast majority of the interest is in the audible frequency range of 20 Hz to 20 kHz since this is the range perceived by humans.

One particular point worth noting is that the reference level used in water borne acoustics is 1 μPa, and not the 20 μPa familiar from air-borne sound. This means that when expressing sound pressure level in decibels, *for the same acoustic pressure in pascals,* the numeric value of the level in water is higher by 26 dB compared to the numeric value of the level in air.

Whilst the acoustic pressure, measured by a hydrophone, is the most usual parameter by which comparisons are made, other measures of the sound field are also useful. For some applications, the acoustic Sound Exposure Level provides a measure which may be used as a basis for estimating the total noise dose. This also depends on the acoustic impedances given above. In air, the minimum intensity deemed audible by a human at around 1 kHz is 1 pW/m². This has led to the use of the 20 μPa reference level, to set the ultimate airborne audible threshold at 0 dB re. 20 μPa. The equivalent pressure underwater would be about 1,225 μPa, which when expressed using the 1 μPa standard underwater reference level is a sound pressure level of almost 62 dB. It is clear that there is considerable scope for confusion, and that comparison of decibel levels needs to be made with great care.

However, the basic approach to noise adopted in air-borne acoustics is also valid in the underwater environment. The noise exposure process may be divided into several parts:

(i) noise emission from sources (requiring the characterisation of those sources in terms of parameters specific to the source);

(ii) the sound transmission process (which will depend on boundary conditions and environmental conditions);

(iii) the ambient noise level;

(iv) the sensitivity of the subject or receiver at the location where the sound is detected.

One concept used frequently in underwater acoustics is that of Source Level, a term not commonly seen in air acoustics where the acoustic power is more commonly used. As with acoustic power, the Source Level is a characteristic of the source itself. The decibel levels are dB re 1 μPa at 1 m (sometimes expressed as dB re 1 μPa·m). However, it is a very idealised acoustic far-field parameter. It may be considered as the sound pressure level that would exist at a range of 1 m from an equivalent simple source which radiates the same acoustic power into the medium as the source in question, with the pressure inversely dependent on range. However, it should be noted that for real sources in realistic conditions, the value of the Source Level is highly unlikely to represent the actual sound pressure level at this range. Indeed, for a large distributed sources, a position so close to the source may be in the acoustic near-field (or even inside the source). Similarly, the propagation of sound in the ocean rarely corresponds to simple spreading laws.

3.2 SOUND PROPAGATION IN THE OCEAN

3.2.1 Environmental dependence

Perhaps even more than for air-borne sound, noise levels in the ocean produced by human activities are determined not only by the acoustic power output of the source, but equally importantly by the local sound transmission conditions [Urick, (1983)]. A moderate level source transmitting over an efficient propagation path may produce the same received sound pressure level as a higher level source transmitting through a propagation path with losses. In deep water, variations in water properties strongly affect the sound propagation. In shallow water, the surface and bottom have strong effects. Variation in bathymetry (depth) can have significant effects on the transmission of the sound, and for piling noise significant proportions of the sound may be transmitted through the sea-bed itself.

The sound speed in the ocean is an important oceanographic variable and is dependent on three main physical factors: temperature, depth (hydrostatic pressure) and salinity. Other factors which may influence the sound speed are the presence of air bubbles and biological organisms. The sound speed increases with temperature, depth and salinity. However, in general, the temperature decreases with depth, and the strongest dependence is on temperature. This leads to a complex variation of sound speed with depth.

The sound speed profile may be divided into several layers. Just below the surface is what is sometimes called the surface layer where the speed is susceptible to daily changes due to heating, cooling and wind action. This is followed by a seasonal thermocline, a region characterised by a negative sound speed gradient due to the decrease in temperature with depth. Below the main thermocline and extending into the deep ocean is the deep isothermal layer, which is nearly constant in temperature at about 4 ºC. In this layer, the sound speed increases with depth due to the increasing hydrostatic pressure. Between the thermocline and the isothermal layer is a sound speed minimum, toward which sound tends to be bent by the action of refraction. Some of the sound from a source placed in this channel can be trapped within the channel and travel great distances without appreciable losses due to surface or bottom reflections. Whilst spreading losses will still occur, they are reduced from spherical spreading to approximate to cylindrical spreading. The variation with salinity is less of an influence in deep water, but can have a strong influence where water layers of different salinity are mixing, for example at the estuaries of fresh-water rivers.

The sound speed is such an important oceanographic parameter that it is routinely measured as a function of depth. This may be done using an instrument such as a velocimeter, which measures the time for a high frequency pulse to travel over a known path. Alternatively, a measurement is made of the conductivity (to derive salinity), temperature and depth using a CTD meter with the sound speed calculated form empirically-derived relationships.

As a result of the above, the region of influence of a sound source can vary dramatically depending upon the operating site and depth, and on the seasonal changes in water properties. Therefore, model predictions are required to evaluate the potential region of influence of the noise source, with the environmental conditions being important inputs to the modelling.

3.2.2 Types of model

The wave equation describing the propagation of an acoustic field is often difficult to solve in real-world situations. A model describing the propagation of sound in the ocean should take into account:

(i) the interaction with the sea-surface;

(ii) the interaction with (and transmission through) the sea-bed;

(iii) the refraction of the sound due to the sound speed gradient;

(iv) absorption of the sound by the sea-water and the sea-bed;

(v) the geometrical spreading of the sound away from the source.

One common approach is to use a method of normal modes, often applied in cases where the sound speed is stratified (changes vertically with depth but not horizontally with range). The normal mode method is useful to calculate the field in shallow water where the water column acts as a waveguide for a limited number of propagating modes. The theory can be expanded to account for different types of sea-bed (assuming the properties are known), and variations in sound speed gradients. The problem of solving the wave equation for range dependent conditions such as sloping or irregular bottoms and range-varying sound speed profiles has been overcome by an approximation called the parabolic equation. Here, small incremental changes in range and depth are used to accommodate changes in propagation parameters without the occurrence of large errors. However, in deep water with large numbers of modes propagating, the method is computationally cumbersome [Lurton 2003, Richardson et al 1995]. The above methods are essentially frequency domain models. An alternative approach which can prove useful for broadband impulsive sounds is to use a time-domain approach such as a finite-difference method. This method has been used extensively in the geophysical surveying industry.

In water deep enough for propagation of ten or more modes, ray theory may be used. This requires that the sound speed changes slowly, with little change over a distance of one acoustic wavelength, making it best suited to the higher frequencies (and thus smaller wavelengths). The sound field is calculated by tracing ray paths, starting from the source, at uniformly spaced angular intervals. For each increment in range, the ray direction is determined from the ray equations and the local gradient of sound speed versus depth. This method is useful in deep water, where a small number of rays transmit most of the acoustic energy from source to receiver, where there is a direct path from source to receiver, and where only a limited number of surface and bottom reflections contribute. For shallow water, the large number of reflected paths makes the method somewhat impractical [Lurton (2003), Richardson *et al* (1995)].

In some simple cases, acceptable accuracy may be obtained by use of relatively simple geometrical spreading models. Commonly used models include spherical spreading (in decibel notation, this corresponds to a reduction in received level with range, r, of "20.log(r)", or cylindrical spreading, (corresponding to a reduction in received level with range of "10.log(r)". In practice, the spreading may lie somewhere between these two geometries and be described by "N.log(r)" where N typically has a value between 10 and 20. Such a simple models do not include the effect of absorption in the medium. This may be included in a simplified manner by introducing a term which describes the reduction due to absorption with range (leading to a term of the type "α.r" where α is the absorption in dB per metre). A composite model of this kind would then be be used to calculate the received level (RL) from the Source Level (SL) by: RL = SL – N.log(r) – α.r [Parvin *et al* (2006)].

3.2.3 Comparisons of models

Simple "lumped parameter" spreading models which incorporate simplified absorption, and conform to the general type "RL=S–N.log(r)– α.r", have been used in previous UK studies which attempt to estimate the likely noise levels generated by windfarm construction [Parvin *et al* (2006)]. These models have the advantage that they do not require a large amount of input data (only values of N and α), are simple to compute and may be set up to replicate the apparent transmission loss of the sound measured during piling operations at other windfarm sites. However, the limitations of these models should be considered carefully. Such a model does not account for transmission loss effects due to changes in bathymetry, and so cannot (for example) predict the extra reductions in level caused by sand banks and shallow coastal areas (for example due to the effect of mode stripping). In addition, such models do not include reverberation or consider the sound transmitted through the sediment. They are also frequency independent, depending only on range from the source. In practice, the transmission of sound in shallow water will show a strong dependence on frequency due to the modal nature of the propagation and the frequency dependent absorption in the water and in the sediment. These phenomena will cause the time waveform to distort during propagation away from the source, typically causing a dilation of the acoustic pulse.

For the shallow water environments encountered in the area of the Humber estuary, the normal mode approach outlined above has the potential to provide good accuracy. This method can be made to incorporate the effects of variable bathymetry, sound speed profiles and frequency dependent absorption. However, such models have disadvantages in that they require a large amount of input data to describe the bathymetry, sound speed profiles, and sediment properties in the local area. Such information may not be available, and any model is only as accurate as its input data. In addition, to describe the propagation of short broadband pulses, typically a model would be run at a number of discrete frequencies in order to predict the transmission loss at all the frequencies present in the pulse, and this requires greater computational power (and time).

It should also be noted that the accuracy of any model depends on accurate representation of the source. The source in the case of marine piling is very complex, with noise being radiated from the surface of the pile itself, and with noise also being launched directly into the sea-bed by the impact of the pile through the sediment. Currently, a good model does not exist for such a complex distributed source, and representations of the source in terms of simplified idealised sources such as point sources and line sources is likely to limit the accuracy of predictions. This is particularly true for the acoustic field close to the pile (in the near-field), and possibly for greater ranges where sound propagating through the sea-bed re-enters the water column.

3.2.4 Choice of model

For the work described here, a dual approach was taken. The simple lumped parameter geometrical spreading model was adopted at the request of the customer to enable direct comparison with previous studies undertaken [Parvin *et al* 2006]. In addition, a normal mode parabolic equation approach was used to enable a better account to be taken of the bathymetry. Here, two-dimensional Parabolic Equation (PE) models were used for each topography / sediment profile. The PE code algorithm is based on the RAM code [Collins, (1994), and Malme *et al*, (1998)]. This provides a high level of accuracy and computational efficiency for many problems and provides a profile of transmission loss in both range and depth for a range of bearings from the array site. In the case of variable seabed profiles and differing seabed sediment types, this potentially offers more accuracy in the prediction of loss from a source along a specific profile.

3.3 PHYSICAL / BEHAVIOURAL EFFECTS ON MARINE SPECIES

The impact of the noise radiated during marine piling mainly affects species of fish and marine mammals. The impulsive underwater pressure wave that is generated by a piling activity has some similarities with that of airgun arrays used in geophysical surveying, particularly when observed at substantial range. However, it is very different from the long tonal bursts of sound associated with more conventional sonar signals. In general, biological damage is related to total quantity of energy received by a receptor and therefore, a continuous source operating at a given level is more damaging than an intermittent source reaching the sound pressure level. The harmful effects of high-level underwater noise can be summarised as lethal, physical injury, hearing impairment and behavioural disturbance.

3.3.1 Lethality

Very close to the source, the peak pressure levels have the potential to cause death, or severe injury leading to death, to marine mammals and fish. Some of these effects may be considered to be barometric pressure effects due to the shock experienced by the animal, rather than acoustic effects *per se*. There has been considerable research into the levels of incident peak pressure and impulse that cause lethal injury in species of fish and in human divers. The work of Yelverton *et al* (1973, 1975 and 1976), highlighted that for a given pressure wave the severity of the injury and likelihood of a lethal effect is related to the duration of the pressure wave. Although the risk of injury is related to the peak pressure of the blast, the impulse (integral of peak pressure over time) of the shock wave has also been shown to be a predictor of injury to fish. In the Yelverton model, smaller fish are generally more vulnerable than larger ones. Richardson (1995) used a converted Yelverton's expressions for fish mortality into those representative of larger marine mammals.

3.3.2 Injury and hearing impairment

At greater ranges, marine piling noise may cause physical injury to organs such as the lungs, liver, intestines, ears and other soft tissues surrounding gas containing structures of the body. However, there are very few documented examples of injury to marine mammals or fish from transient pressure waves similar to piling.

Where there are repeated high level exposures of sufficient level, from activities such as impact piling, seismic operations, or for continuous wave sound such as sonar, the underwater sound has the potential to cause hearing impairment in marine species. This can take the form of a temporary loss in hearing sensitivity, known as a Temporary Threshold Shift (TTS), or a permanent loss of hearing sensitivity known as a Permanent Threshold Shift (PTS). For transient noise such as piling this may occur where marine mammals are exposed to the underwater noise from a number of repeated pile strikes. Here, the potential for injury is related to the level of the underwater sound, and the duration, duty cycle and hearing bandwidth of the animal.

3.3.3 Behavioural

At lower levels, the underwater sound wave may not directly injure animals or cause hearing impairment. However, it may have the potential to cause behavioral disturbance. There have been many conflicting reports of the behavioral effects of sound on marine species, and a general consensus for criteria has not yet emerged. However, there is general agreement that the hearing sensitivity of the animal should be taken into account with a frequency weighting applied to the received levels. This approach has been recommended by a Marine Mammal Criteria Group set up to review the subject in the USA [Gentry *et al* (2007) and Southall *et al* (2007)]. A similar (though not identical) approach has been adopted for some previous studies in the UK [Parvin *et al* (2007)]. Frequency weighting provides a noise level referenced to an animal's hearing ability either for individual species or classes of species, and therefore a measure of the potential of the noise to cause an effect. The measure that is obtained represents the perceived level of the sound for that animal. This is an important consideration because even apparently loud underwater noise may have no effect on an animal if is at frequencies outside the animal's hearing range.

3.3.4 Audibility

The audible range, the range over which marine species can hear the construction activity, will extend to the distance that the construction noise either falls below the ambient perceived sea noise level or the auditory threshold of the animal.

4 CONSIDERATIONS FOR IMPACT ASSESSMENT

4.1 METRICS

Two primary acoustic amplitude parameters for received levels have been used. These parameters were chosen to be analogous to those used by other researchers and to be in conformance with good practice [Madsen *et al* (2006), Madsen (2005), Blackwell *et al* (2004), Rodkin and Reyff (2004), Betke *et al* (2004), Finneran *et al* (2002), David (2006), Parvin *et al* (2006), Nedwell *et al* (2007)].

The amplitude parameters calculated are peak-to-peak pressure ($P_{pk\text{-}pk}$), Sound Exposure Level (SEL). The SEL is related to the Sound Exposure Level (a measure of the pulse energy content) and expressed as a pulse pressure squared integral in Pa^2s) [Madsen, (2005)].

Peak-to-peak acoustic pressure

For a specific pulse, the peak-to-peak pressure, $P_{pk\text{-}pk}$, is calculated from the pressure, *p*, by the expression:

$$P_{pk-pk} \quad = \quad \max(p) - \min(p)$$

where max(*p*) and min(*p*) are the peak positive and peak negative pressures in the waveform respectively. Since the peak negative pressure has a negative value, the peak-to-peak pressure is equivalent to the sum of the magnitudes of the peak positive and peak negative pressures. The value is expressed as the peak-to-peak sound pressure level in dB re 1 μPa. This is calculated from:

$$SPL_{pk-pk} \quad = \quad 20\log\left[\frac{P_{pk-pk}}{P_0}\right]$$

where P_0 is the reference pressure of 1 μPa (peak-to-peak).

For a symmetric waveform, the peak amplitude is half the value of the peak-to-peak amplitude (the level is less by 6 dB). The waveforms encountered in piling noise measurements sometimes exhibit significant asymmetry, and so the peak-to-peak values have been used. This is also in line with the parameters quoted by other researchers [Parvin *et al* (2006), Nedwell *et al* (2007)].

Sound Exposure Level

The SEL is calculated by integrating the square of the pressure waveform over the duration of the pulse. The duration of the pulse is defined as the region of the waveform containing the central 90% of the energy of the pulse. The calculation is given by:

$$SE_{90} \quad = \quad \int_{t_5}^{t_{95}} p^2(t)\,dt$$

The value is then expressed in dB re 1 μPa^2s and is calculated from:

$$SEL = 10\log\left[\frac{SE_{90}}{SE_0}\right]$$

where SE_0 is the reference sound exposure of 1 μPa^2s.

Note that for a plane-wave in a free-field environment (an unbounded medium), the sound exposure in μPa^2s can be converted to units of energy flux density in J/m^2 (joules per square metre) by dividing the cumulative squared acoustic pressure by the specific acoustic impedance, Z, of the medium, the specific acoustic impedance being the product of medium density and sound speed in the medium (ρc). When expressed in decibel notation, this means that 0 dB re 1 J/m^2 is equivalent to 182 dB re 1 μPa^2s.

The SEL for each impulsive noise event can be aggregated by summation to calculate the total cumulative SEL for the entire piling duration. The concept of SEL is entirely analogous to the use in air acoustics to quantify the total noise dose for a subject receiver.

4.2 AUDIOGRAMS

4.2.1 Introduction

For an estimate to be made of whether an animal will be affected by noise, the hearing sensitivity of the animal must be considered. If the sound is composed of frequencies which do not lie within the reception band of the animal, the impact is likely to be negligible. For example, a sound at an ultrasonic frequency of 50 kHz will not even be heard by a human observer [Kinsler *et al* (1982)].

It is therefore advantageous to apply a weighting to the received sound pressure level according to the sensitivity of the animal perceiving the sound. This is most commonly done by making use of audiometric data for the animal of interest. For example, a frequency weighting which incorporates the relative frequency response of the human ear is commonly used to assess the behavioural effects of noise on humans. The most widely used metric in this case is the dB(A) which incorporates the frequency weighting (the so-called “A-weighting”) based upon the 40-phon Fletcher-Munson human hearing curves [Burns (1973)].

4.2.2 Audiogram techniques

Audiograms are representations of the hearing sensitivity of a subject as a function of frequency. These are presented as the sound pressure levels required for the subject to just perceive the sound (hearing thresholds) or more commonly to perceive the sound with a certain loudness (eg for a loudness of 40 phon).

To determine an audiogram for an animal requires a technique which does not rely on cognitive compliance. The animal cannot be asked whether the sound is perceptible. Two principal techniques have been commonly used. The first relies on behavioural response and requires the animal to be trained to perform a task in response to an aural stimulus. This can only be used for animals that can be trained. The second method involves measurement of the evoked auditory potential which is the electrical impulse in the auditory nerves that results from the sound being heard by the animal. In this approach, electrodes are attached to the animal to measure the electrical response to the sound directly [Richardson *et al* (1995)].

4.2.3 Audiogram data

For the work undertaken here, audiogram data has been chosen to match the data used in previous studies which attempt to estimate the impact of windfarm construction noise on marine life. This is to enable direct comparison with previous work and to conform to the requirements of the customer. Specifically, the data cited in the study by Parvin *et al,* (2006) has been used. A number of other audiometric studies have been undertaken, for example those by Finneran. However, these have not been used here. The range of species examined is governed by the species present in the Humber estuary area. However, where no audiometric data exists for a species, another species may be taken as a surrogate. For example, data does not exist for the sole (*solea vulgaris*) and so another flatfish, the dab (*limanda limanda*) may be used instead. Similarly, thought the striped dolphin is not prevalent in the area, good audiometric data is available and it may be considered (at least provisionally) as representative of other odontocetes for which no audiometric data currently exists. However, it should be noted that different species can exhibit significantly different hearing sensitivity, so this is a crude (though necessary) approximation.

Figure 4.1 shows the audiograms for species of marine mammals, Figure 4.2 shows the audiograms for species of seals and Figure 4.3 shows the audiograms for species of fish.

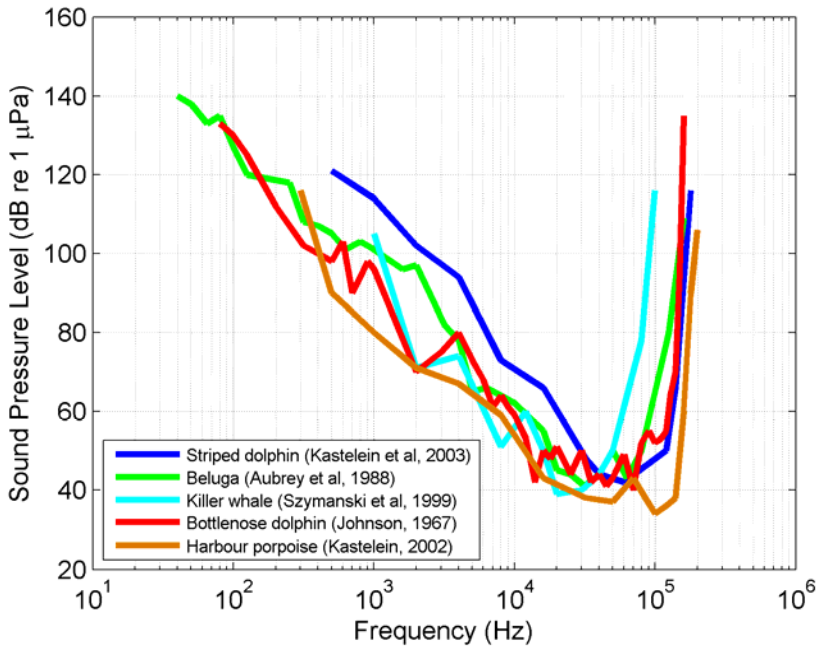

Figure 4.1 Hearing threshold data for a range of marine mammal species.

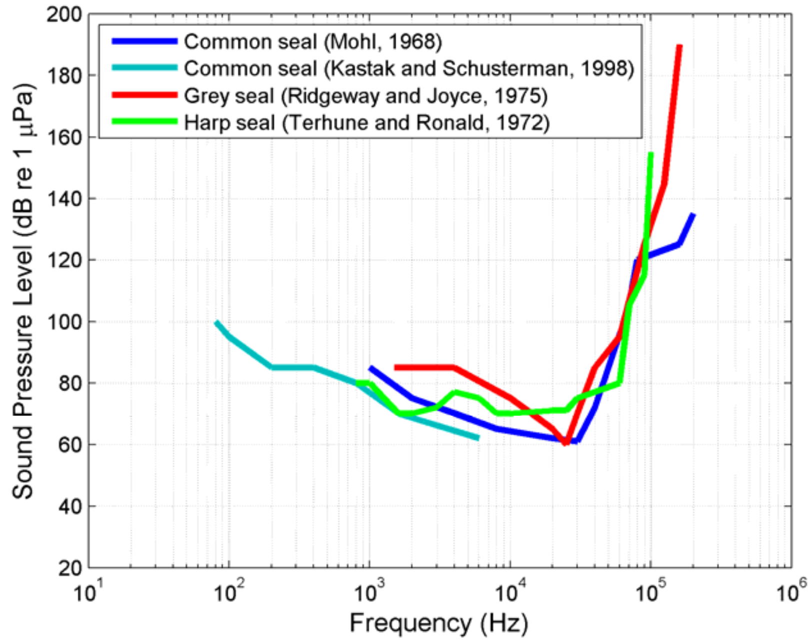

Figure 4.2 Hearing threshold data of a range of pinnipeds species.

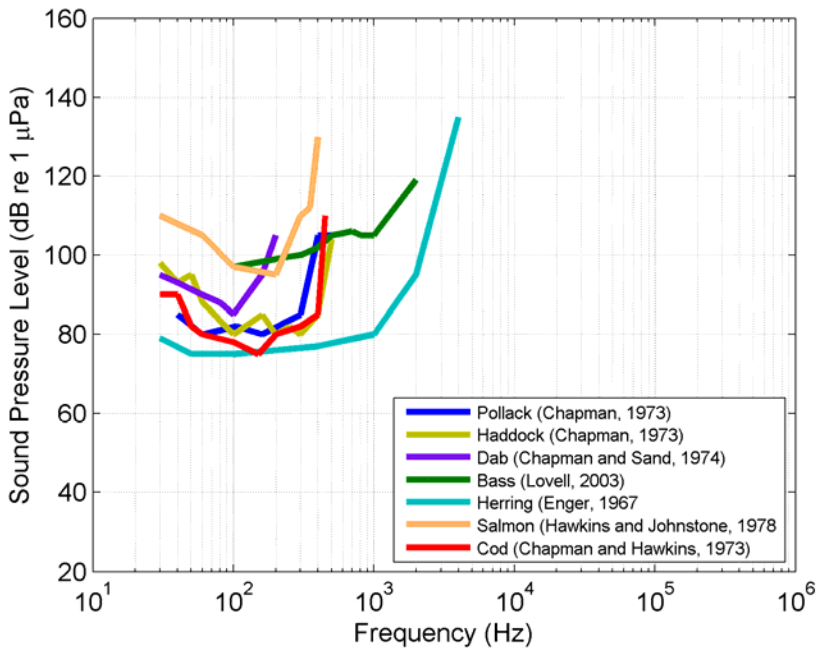

Figure 4.3 Hearing threshold data for a range of fish species.

5 MEASURED PILING NOISE UK WINDFARM DEVELOPMENTS

5.1 INTRODUCTION

Due to concerns of the potential submarine acoustic impact of piling operations for offshore windfarms construction in UK waters, a number of piling noise studies, have been conducted. These have included acoustic characterisation both in time and frequency of noise generated during percussion driving operations on various sites through measurements of received signals at various ranges. These data have then been used in many cases to estimate an equivalent Source Level for a piling operation at that site.

Various measured acoustic characteristics (signal type, frequency content, duty cycle, level etc.) have then used to estimate impact of similar or larger pile types in other wind farm locations under development. Using predicted acoustic fields around an array site, potential impacts on various marine species (marine mammals, fish and crustaceans) have been assessed in a number of studies.

5.2 UK PILING NOISE MEASUREMENTS (SUBACOUSTECH LTD.)

Subacoustech Ltd. have conducted a number of studies on UK windfarm sites assessing piling and other noise sources around array sites. These include North Hoyle, Scroby Sands, Kentish Flats, Barrow and Burbo Bank with pile diameters ranging from 4.0 – 4.7 m. Site water depths varied from a few meters up to 30 m. A summary of these studies can be found in a COWRIE commissioned report (COWRIE NOISE-03-2003), [Nedwell *et al* (2007)]. In each case, peak-to-peak Source Level estimates were made ranging from 243 dB re 1μPa.m in Kentish flats for a 4.3 pile to 257 dB re 1μPa.m for Scroby Sands. Due to variation in water depth, different transmission loss profiles applied to a simple geometric spreading loss model have been applied in each case. Pile diameter, estimated Source Level, and transmission loss model parameters used in each case are summarised in Table 5.1.

Data source	Pile diameter (m)	Peak-to peak Source Level (dB re 1μPa.m)	N	α (dB/m)	Approx. depth at windfarm (m)
North Hoyle	4.0	249	17	0.0011	10-15
Scroby Sands	4.2	257	20	0.0030	3-30
Kentish Flats	4.3	243	20	0.0020	5-8
Barrow	4.7	252	18	0.0003	10-20
Burbo Bank	4.7	249	21	0.0047	15

Table 5.1. Summary of Source Level estimates conducted by Subacoustech Ltd on UK windfarms and geometric scaling factors used for transmission loss estimates.

5.3 PILING NOISE LYNN AND INNER DOWSING

An additional study was conducted by National Physical Laboratory (NPL) and Loughborough University (LU) on a 65 m long 2 m diameter test pile in April 2006 on the Lynn and Inner Dowsing site. On this occasion, the test pile was driven approximately 25 m into a chalk sediment in a water depths 10-15 m. Detailed analysis of the underwater radiated noise was conducted at fixed ranges for the entire piling sequence. This included a ‘soft start’ increase in hammer energy at the beginning of the piling sequence. Post analysis allowed correlation hammer energy and radiated signal characteristics at various ranges.

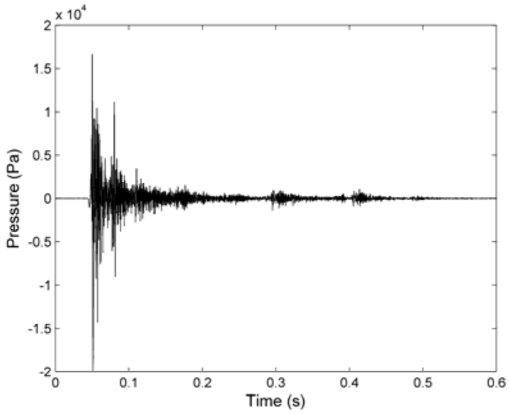

Figure 5.1 Time domain waveform at full power (hammer energy 800 kJ) at a range of 57 m.

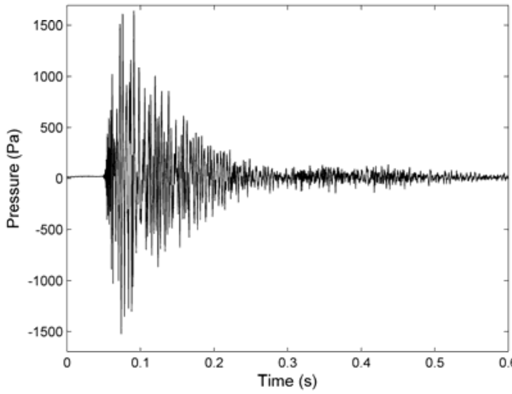

Figure 5.2 Time domain waveform at full power (hammer energy 800 kJ) at a range of 1,850 m.

Figures 5.1 and 5.2 show typical time domain waveforms for received signals at 57 m and 1,850 m respectively for a single piling impact, [Robinson *et al* (2007), Lepper *et al* (2007)]. At the closer range, a large impulse energy is observed lasting around 100 ms. With small signal arrivals extending to over 500 ms. By comparison at the longer range ~ 2 km the peak level is approximately a factor of 10 lower but the pulse duration is extended to 150 ms due to the actions of multi-path arrivals.

At full hammer energy (800 kJ), the mean peak-to-peak pressure levels of 211 dB re 1 μPa (pk-pk) and 191 dB re 1 μPa (pk-pk) were observed at ranges of 57 m and 1,850 m respectively, with equivalent mean Sound Exposure Level levels of 178 dB re 1 $\mu Pa^2 s$ and 164 dB re 1 $\mu Pa^2 s$ observed at the respective ranges, and mean RMS pressure levels of 194 dB re 1 μPa (rms) and 175 dB re 1 μPa (rms).

Figures 5.3 and 5.4 show a time domain and equivalent time-frequency plot for two successive pulses.

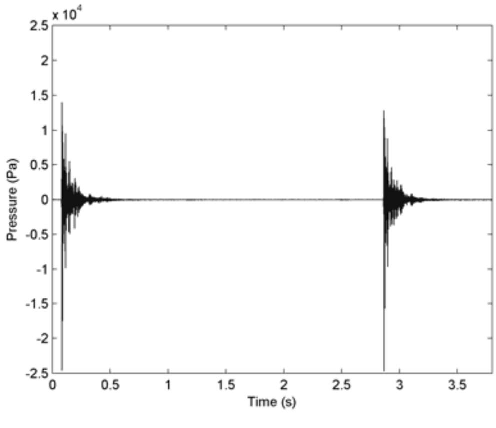

Figure 5.3 Time domain waveforms for two pulses at full power (hammer energy 800 kJ) at the location of the piling vessel (range 57 m).

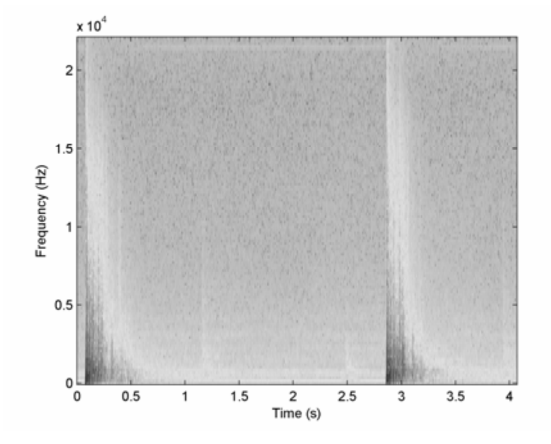

Figure 5.4 Spectrogram of the time waveform shown in Figure 5.3. Note that the frequency axis extends up to 22 kHz.

The spectra of the signal measured at the piling vessel (57 m) showed a peak level between 200 Hz. With a majority of the energy between 200 Hz and 600 Hz. The frequency content of the signals at 1,850 m showed a peak level between 200 Hz and 300 Hz. A significant reduction in level was observed for frequencies below 100 Hz. A significant reduction in levels was observed for frequencies above 5 kHz, although some high frequency components were observed at frequencies greater than 20 kHz, but at much lower levels.

Using numerical model based transmission loss models Source Level estimates taking into account seabed topography and sediment type were made in the region of 224 – 236 dB re 1µPa.m with a mean level of 230 dB re 1µPa.m.

Data source	Pile diameter (m)	Peak-to peak Source Level (dB re 1µPa.m)	N	α (dB/m)	Approx. depth at windfarm (m)
Lynn and Inner Dowsing	2.0	230±6 dB	Seabed topography and sediment / water acoustic characteristics transmission loss estimate		10-15

Table 5.2. Source Level estimates for a 2 m test pile on the Lynn and Inner Dowsing Site.

6 ACOUSTIC FIELD PREDICTION

6.1 INTRODUCTION

The received level of an acoustic field propagating from a source can be described in form

RL(r) = SL(@ 1m) - TL(r)

Where the Received Level (RL) at range (r) in metres is derived from Source Level (SL) and spreading law or Transmission Loss (TL) .

In the case of measurements conducted in-situ, the received level at some range from source is measured. Reversing expression above and using a Transmission Loss model, an estimate of Source Level can then be obtained. With a Source Level and knowledge of Transmission Loss, the received level at various ranges can be estimated.

Careful consideration of the type and frequency content of any propagating signal should be taken into account. In the case of shallow water environments, sound energy from source with interact with the surface and the seabed. These interactions can often lead to complex transmission loss profiles varying for different source types, seabed topography, sediment type, water column acoustic characteristics etc. Therefore complex propagation mechanisms often exist in estimation of acoustic field at various ranges from source particularly in shallow water environments.

As a result, two methodologies for acoustic field prediction have been deployed in this analysis. The first is using a number of methodologies outlined on previous studies on UK windfarm sites. This includes Source Level scale-up estimates from measured pile diameters to 6.0 m diameter pile for current assessment, marine species related Transmission Loss profile estimates and species related perceived Source Level. These methodologies have been derived from presented analysis from various reports and available literature. No critical justification analysis of these methodologies has been carried out as part of this study. The implementation of these methodologies within the Humber Gateway study has however allowed comparison with previously presented studies on UK windfarms.

In addition, an alternate methodology for generating a Source Level estimate for a 6 m pile is presented based on observation of relationship between hammer energy and acoustic radiated energy for marine piling. Using these Source Level estimates, a numerical model based transmission model is employed to estimate transmission loss profiles and therefore received levels at different ranges and depths for the larger diameter pile. These transmission loss models estimate effective losses in both range and depth for the various seabed topographies around the proposed Humber Gateway site including sediment water column acoustic propagation properties. As such, they are felt to more accurately model the environment at the windfarm site.

6.2 METHODOLOGY 1: (SUBACOUSTECH LTD.)

6.2.1 Source Level Estimates

Data from previous studies was considered but analysis of this and current data showed no simple relationship between pile diameter and acoustic Source Level during piling measured at various ranges and therefore potential levels at source. Potential causes of this disparity are variations in the hammer energy used for piles of similar diameter (this data is rarely available) and environmental conditions (sediment type, etc.).

At this time, no directly measured data is available for Source Level for a 6 m diameter driven pile. To allow estimation of potential Source Levels from pile diameters / hammer energies un-measured at this time various approaches were considered and compared.

Previous studies by Nedwell *et al.* (some outlined in detail in section 5) have compared measured Source Level estimates for pile diameters from 0.7 m to 4.7 m, [Abbot *et al.* (2002), Nedwell *et al.* (2002, 2003)]. In addition, recent data, [Robinson and Lepper (2007)], were compared for a 2 m test pile installed on the Lynn and Inner Dowsing site slightly south of proposed Humber Gateway project.

Figure 6.1 shows various measured Source Level estimates for UK windfarm sites. Parvin *et al* (2006) use various curve fits applied to previously estimated Source Level for piles of various sizes. From Figure 6.1 a linear curve fit shows a relatively poor fit to the range of data available. This curve seems likely to overestimate at higher pile diameters and was not forced through zero suggesting a poor match a lower pile diameters. In the case of a 6 m pile, this curve would predict a Source Level estimate of just under 272 dB re 1µPa.m. This estimate becomes even higher and results in a poorer fit to data if curve is forced for zero Source Level for zero pile diameter. Parvin *et al* (2006) then uses dimensional analysis to calculate additional trend curves with Source Level pressure proportional to pile diameter, diameter squared and diameter cubed. These curves were applied to measured data for a specific measured pile diameter / Source Level estimate (4.7 m dia.) taken from the Barrow site. These curves take the form of:

$$SL_{\propto D} \propto p_{ref} D / D_{ref} ,$$

$$SL_{\propto D^2} \propto p_{ref} D^2 / D_{ref}^2 ,$$

$$SL_{\propto D^3} \propto p_{ref} D^3 / D_{ref}^3$$

Respectively, where P_{ref} and D_{ref} are the reference pressure Source Level and diameter for one measured point (i.e. 4.7 m).

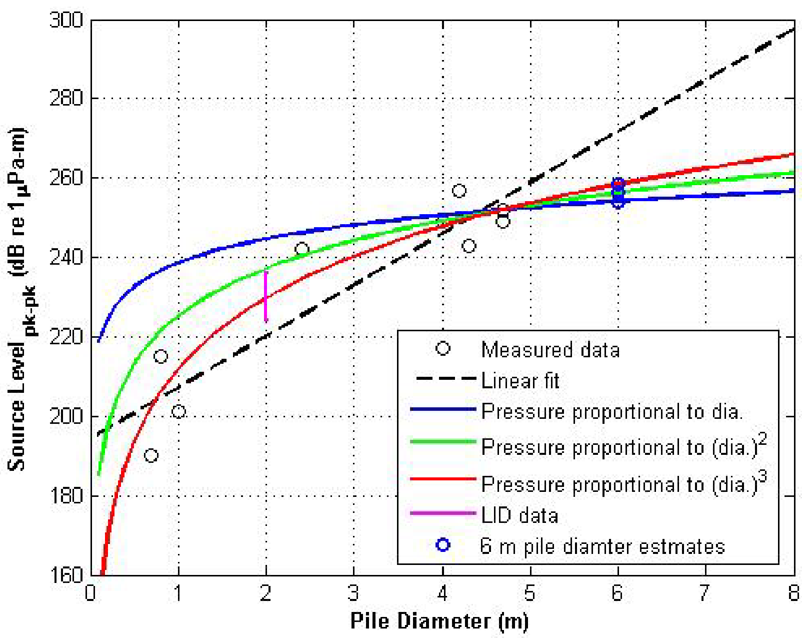

Figure 6.1 Source Level estimates for a 6 m diameter piling operation on the Humber Gateway site [Methodology adapted from Subacoustech report No. 710R0517].

These higher order relationships appear to fit available data better. In particular, the squared and cubic dependences show a much better fit to the available data. It can also be seen that the LID data fit for a 2 m pile falls within the bounds of these latter two trend lines. In this case Source Level values for a 6 m pile diameter range from 254 dB re 1µPa.m for the proportional dependence to 258 dB re 1µPa.m for the cubic dependence.

Parvin *et al* (2006) then uses the square law fit to scale a measured Source Level at 4.3 m to 6.5 m for a similar site. Parvin *et al* (2006) notes that there appears a strong dependence on apparent Source Level estimates on the average water depth of the site. Shallower sites (a few meters) have lower apparent Source Levels than deeper water sites (10 m or more). In this case the measured site used to scale up using square law was deemed in these studies to be similar to the proposed site.

Applying the same methodology to the current case, the square law dependence was used to estimate a peak-to-peak Source Level of 256 dB re 1µPa.m at the Humber Gateway site for 6 m diameter pile. This can been seen as the blue circle on Figure 6.1

6.2.2 Transmission Loss (Geometric and absorption loss model)

Simple spreading loss models are often applied to underwater acoustic assessments in particular cases. In a free field situation where a sound field can propagate uninterrupted in a media assumed to have a uniform sound velocity, density and attenuation spherical spreading can be assumed. This derived in form

$TL(r) = 20\log(r)$ Spherical spreading

In a shallow water ocean environment the volume of the media is bounded by the surface and bottom. Sound energy will initially radiate spherical (assuming a omnidirectional source) before interacting with surface and bottom. If these surfaces are assumed to be perfectly reflecting, energy is reflected back into the water column. This accumulation of trapped sound energy results in higher levels and therefore a lower transmission loss than associated with spherical spreading losses alone. At sufficient range (approx. 10 time water depth) and if the surface and bottom are assumed parallel (i.e. flat seabed) the transmission loss can be described by a cylindrically spreading loss described as

$TL(r) = 10\log(r)$ Cylindrical spreading

In addition, frequency dependant absorption effects are also observed with sound propagation in media. This effect is highly frequency dependant for a given media.

In the case of a simple geometric spreading model at a particular frequency absorption can be included for spherical and cylindrical spreading in forms.

$TL(r) = 20\log(r) + \alpha r$ and $TL(r) = 10\log(r) + \alpha r$

respectively.

However in reality, most seabeds will not act as a perfect reflector. Sound energy can penetrate into the sediment where it may be trapped and absorbed at a different absorption rate (sediment dependant) and or other portions of the energy from the propagating wave may be reflected immediately. Again energy would be lost to the reflect wave propagating within the water column. This loss will be proportional to a reflection coefficient and again related to incident angle, density and sound velocity difference between the two media's (water column - seabed). Sound energy may also enter a sediment layer and return to water column at some later time having been reflected from a sub-surface layer. As previously described the overall sound energy may be additionally attenuated due the complex interactions with interfaces of various media.

In addition, the seabed topography may cause variation in these interactions (incident angle, number of reflections, etc.). These effects can have a dramatic effect of transmission loss estimates particularly in shallow water (10's of m's) if propagated for longer distances (km's). Other effects due to constructive / destructive interference and diffraction / shadowing / beaching can also cause wide variations in observed transmission loss and therefore received levels away from simple geometric spreading law model. These spreading laws however provide useful rules-of-thumb for many underwater applications particularly in free-field environments. Transmission losses however in shallow water environments can however be much more complicated due to increased acoustic field interaction with both the surface and the seabed.

Parvin *et al* (2006) used a geometrical spreading loss model for transmission loss on various UK array sites. These spreading losses were used to propagate away from to derive Source Level to estimate a Received Level at a new range.

Where the Received Level (RL) at range (r) in meter is derived from Source Level (SL) and spreading law or Transmission Loss (TL) from:

$RL(r) = SL(@\ 1m) - TL(r)$

Where TL at range r is in the form:

$TL(r) = N\log(r) + \alpha r$

Data source	Pile diameter (m)	Peak-to peak Source Level (dB re 1μPa.m)	N	α (dB/m)	Approx. depth at windfarm (m)
North Hoyle	4.0	249	17	0.0011	10-15
Scroby Sands	4.2	257	20	0.0030	3-30
Kentish Flats	4.3	243	20	0.0020	5-8
Barrow	4.7	252	18	0.0003	10-20
Burbo Bank	4.7	249	21	0.0047	15

Table 6.1: Geometric spreading law model parameters used for transmission loss estimates on UK windfarm sites.

Table 6.1 above summaries parameters used for N and α used by Subacoustech Ltd on various UK windfarm developments, summarised [Parvin *et al* (2006), Nedwell *et al* (2007)]. N and α for each site are derived using a curve fitting methodology through received levels measured at various ranges. The various transmission losses versus range for windfarm sites used is shown in the Figure 6.2.

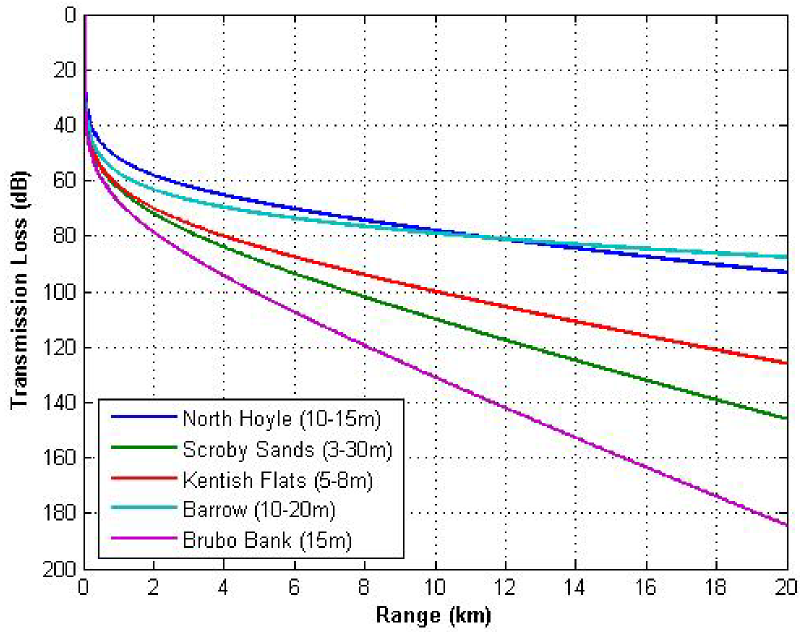

Figure 6.2 Transmission Loss profile estimates for various UK windfarm sites, [Nedwell *et al* (2007)].

N and α in this case are calculated empirically in previous reports by applying a curve fitting algorithm to measured data at different ranges from the pile. In this case N and α effectively include the relative measure for seabed absorption experienced by the propagating wave on the seabed profile and range that the measurements were conducted. This would not however adequately model variations in seabed topography experienced on different transects away from the pile. Similarly this model assumes the received level is uniform in depth for a given range with no frequency dependence similar to that observed due to the effects of attenuation.

6.2.3 Received sound levels (Geometric spreading losses model)

The estimation of the acoustic propagation transmission loss can be used to estimate the Received Level (RL) at various ranges and depths around the array site for a known Source Level. This in turn allows prediction of likely zones of acoustic level above certain thresholds.

The barrow site data was chosen as being of similar water depth condition for replication of estimates for the Humber Gateway project. The process used for determining the dB_{ht} equivalent Source Level is unreported and therefore difficult to replicate for an equivalent 6 m pile diameter. On assumption that identical audiograms and sound propagations conditions were used in reported estimates a linear interpretation was therefore used to estimate an equivalent dB_{ht} Source Level for a 6 m diameter pile for each species. In most cases, this gave an approximate 1 dB reduction in the previously reported dB_{ht} equivalent Source Levels.

Using these species related Source Level estimates Parvin *et al* (2006) then applies a number of geometrical spreading laws to propagate perceived received levels (dB_{ht}) for individual species at different ranges. Using the same methodologies (species transmission loss profiles) as Parvin *et al* (2006) and estimates of perceived species Source Levels for a 6 m diameter pile, the predicted received levels for various species based on a 6 m pile diameter at the Humber Gateway array site based are shown in Figure 6.3.

Species	Peak-to-peak perceived Source Level (dB_{ht} @ 1m) for a 4.7 m diameter pile [based on 4.7 m diameter pile at Barrow offshore windfarm]	Peak-to-peak perceived Source Level (dB_{ht} @ 1m) for a 6.5m diameter pile [based on scale-up estimate of 4.7 m diameter pile at Barrow offshore windfarm]
Cod (*Gadus morhua*)	158	163
Herring (*Clupea herengus*)	175	180
Salmon (*Salmo salar*) *	156	
Dab (*Limanda limanda*)	156	154
Bass (*Dicentrarchus labrax*)	147	152
Bottlenose Dolphin *(Tursiops Truncates*)	203	208
Striped Dolphin (*Stenella Coertuleoalba*)	199	204
Harbour porpoise (*Phocoena phocoena*)	199	204
Common Seal (*Phoca vitulina*)	179	184

Table 6.2 Species based Source Level estimates scaled for a 6.5 m pile diameter. [Data from Subacoustech report No. 710R517: Parvin *et al* (2006)].

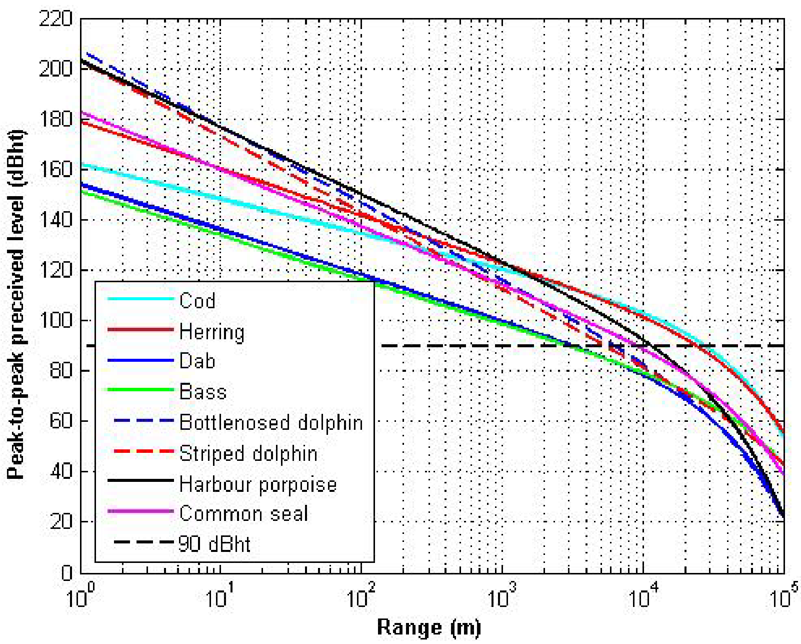

Figure 6.3 Predicted peak-to-peak perceived level (dBht) for marine species from a 6 m piling operation in a deep water site (≥10m).

Species	Peak-to-peak perceived Source Level (dB_{ht} @ 1m) for a 6.5m diameter pile [based on scale-up estimate of 4.7 m diameter pile at Barrow offshore windfarm]	Peak-to-peak perceived Source Level (dB_{ht} @ 1m) for a 6.0 m diameter pile at the Humber Gateway array site
Cod (*Gadus morhua*)	163	162
Herring (*Clupea herengus*)	180	179
Salmon (*Salmo salar*)		
Dab (*Limanda limanda*)	154	154
Bass (*Dicentrarchus labrax*)	152	151
Bottlenose Dolphin (*Tursiops Truncates*)	208	207
Striped Dolphin (*Stenella Coertuleoalba*)	204	203
Harbour porpoise (*Phocoena phocoena*)	204	203
Common Seal (*Phoca vitulina*)	184	183

Table 6.3 Species based Source Level estimates scaled to 6 m pile diameter for the Humber Gateway windfarm site.

6.3 METHODOLOGY 2:

6.3.1 Source Level Estimates

Method 1 relies on several estimates of Source Level based on measurements conducted on a number of windfarm sites. This data at best is widely variable and therefore potentially erroneous in the interpolation using simple curve fitting functions for variables of Source Level and pile diameter alone. Several sources of this variability are acknowledged by previous authors including sediment type, water depth, penetration depth and overall hammer energy. Recent studies, [Robinson *et al* (2007)] have shown that hammer energy may well be of considerable importance in estimating overall acoustic levels in the water column. This data showed a near linear dependence between hammer energy and acoustic energy in the water for a driven monopile. Figures 6.3 and 6.4 show a measured increase of 12 dB in the peak-to-peak level and 8 dB for Sound Exposure Level respectively observed at 57 m from the pile for hammer energy increases of 80 kJ to 800 kJ. After each hammer energy increase, there is a step-up in observed level followed by a slight decreases in level. Once stable this level is however still greater than the observed level before the hammer energy increase, resulting in a net increase in observed received level. This can be postulated as being due to penetration and sediment compression as the pile progresses and therefore likely to be related to sediment type and overall pile penetration depth.

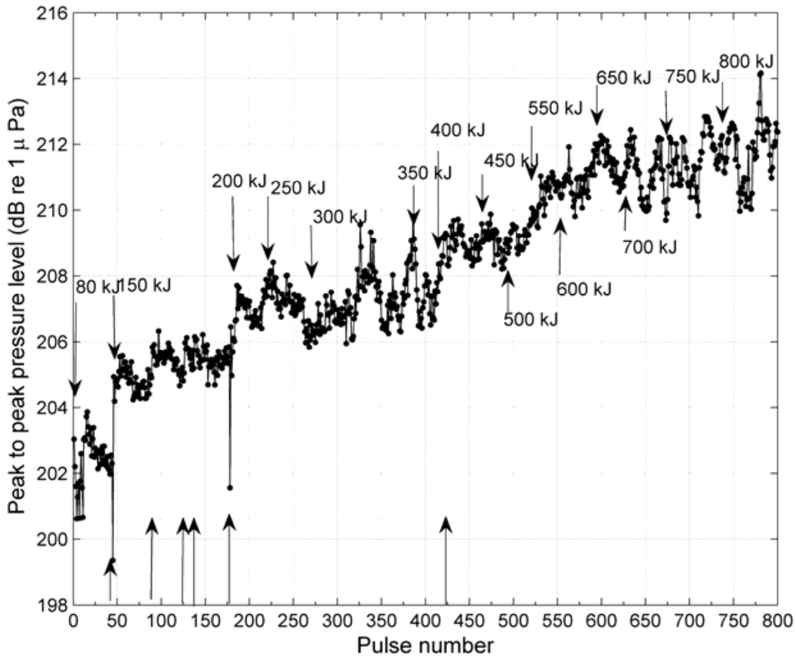

Figure 6.4 Peak-to-peak received level during a piling sequence for increasing hammer energy recorded at a range of 57 m.

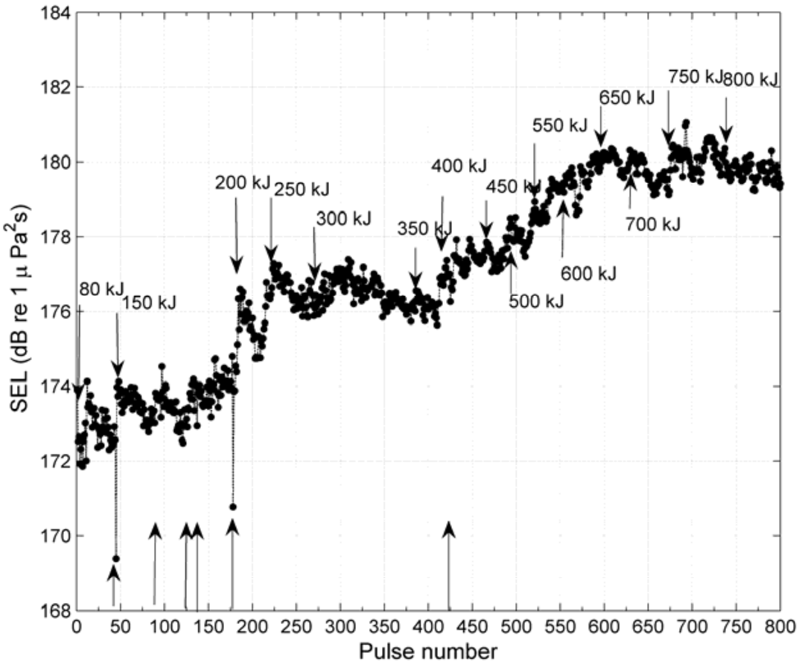

Figure 6.5 Sound Exposure Level received level during a piling sequence for increasing hammer energy recorded at a range of 57 m.

Hammer energy data from previous studies is however rarely reported which makes direct comparison of Source Level estimates at different sites problematic.

As a result, an alternative approach was also considered including a geometrical factor related to overall pile surface area and hammer energy versus Source Level. Firstly a linear interpolation based on pile diameter was used on known Source Levels from various pile diameters. This was justified based on the overall radiating area of a pile with increasing pile diameter in similar water depths. Using this approach and using the mean Source Level from a 2 m pile a linear scaling (three fold increase) to a 6 m pile would give an equivalent Source Level increase of 9.5 dB.

Secondly the effect of hammer energy increase in the planned 6 m pile constructions were compared to observed effects of hammer energy variations during a 2 m pile construction in a previous study, [Robinson *et al*., (2007)]. Figure 6.6. shows the observed pulse energy in joules (J) versus the applied hammer energy during the 'soft start' procedure with a hammer energy increase from 80 kJ to 800 kJ. This shows a relatively linear relationship between acoustic pulse energy and equivalent hammer energy. For an estimated maximum hammer energy of a 6 m pile of 1800 kJ returning to Figure 6.6. would give a projected increase to an equivalent acoustic pulse energy of 5.741 kJ for the 6 m pile based an equivalent 2.55 kJ pulse energy measured for the 2 m pile. This increase in acoustic pulse energy therefore relates to equivalent increase in Source Level of ~4 dB for the 6 m pile compared with the 2 m.

The combined (sum) 13.5 dB of the 9.5 dB increase due to change in pile diameter (2m to 6m) and additional 4 dB due to increased hammer energy were then applied to Source Level estimates for a full scale (6 m / 1,800 kJ hammer energy) pile construction.

It should be noted that these estimates for likely hammer energy and equivalent Source Levels are based on a single detailed observation of a start up procedure for a 2 m pile at a different site of similar water depth and sediment type where a strong correlation between hammer energy and equivalent Source Level was observed. A good approximation from the data available is a linear relationship between pile diameter and acoustic Source Level, but there is considerable uncertainty in the estimation. The above approach however was taken as a best estimate to the likely Source Levels that may be observed at the Humber Gateway site for a 6 m diameter pile.

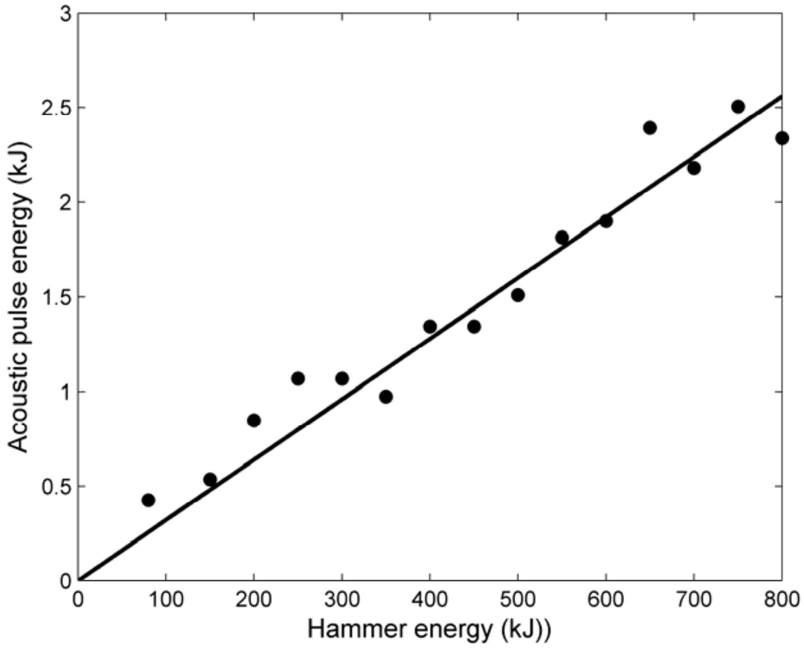

Figure 6.6 Measured hammer energy versus acoustic pulse energy.

For Source Level estimates, three primary acoustic parameters for acoustic received level amplitude were considered. These are peak pressure in pulse (expressed as peak positive pressure (P_{pk+}), peak negative pressure (P_{pk-}), and peak-to-peak pressure (P_{pk-pk}); RMS (root mean square) pressure averaged over a pulse duration (P_{rms}); and the Pulse energy content (expressed as a pulse pressure squared integral in Pa^2s) or Sound Exposure Level (SEL).

The mean peak-to-peak Source Level for a 2 m pile [Robinson et al (2007)] was found in the range 224 dB re 1 μPa.m to 236 dB re 1μPa.m. Giving a mean value of peak-to-peak Source Level of 230 dB re 1μPa.m. Comparison of the differences in peak-to-peak to RMS and SEL measured levels made at a short range from a previous study was then used to calculate the equivalent RMS and Energy (SEL) Source Levels from the estimated peak-to-peak Source Level value. The mean differences of the measured peak-to-peak, RMS and SEL measurements at the shorter range (< 60 m) for actual measurement of a -18 dB for RMS and -33 dB for SEL below peak-to-peak levels was observed.

An equivalent RMS Source Level of 230 - 18 = 212 dB re 1 μPa.m was therefore estimated for the 2 m pile case. Similarly an equivalent SEL Source Level for the 2 m pile was estimated as 230 - 33 = 197 dB re 1 $\mu Pa^2s.m$.

The scale-up factor of 13.5 dB for a 6 m / 1,800 kJ pile construction was then applied to the test pile SEL and RMS Source Levels giving an equivalent SEL Source Level of 197.5 + 13.5 = 211 dB re 1 $\mu Pa^2s.m$ and RMS Source Level of 212.5 + 13.5 of 226 dB re 1 μPa.m. The mean test pile data Source Level estimate of 230.5 dB re 1 μPa.m could be scaled up to a peak to peak Source Level of 244 dB re 1 μPa.m.

Again based on 2 m diameter 'soft start' data an estimate of reduction of hammer energy from 1,800 kJ to 100 kJ (12.2 dB reduction) gives an estimated 12.2 dB reduction in the equivalent Source Levels.

The resulting peak-to-peak, RMS and SEL Source Level estimates for a 6 m diameter pile / 1,800 kJ hammer energy are summarised in Table 6.4.

	Estimated 6 m diameter pile / 1,800 kJ equivalent Source Level (method 2)		
	Peak-to peak (dB re 1 μPa.m)	RMS (dB re 1 μPa.m)	SEL (dB re 1 $\mu Pa^2s.m$)
Method 1 6m Source Level estimate	256	NA	NA
Method 2 6m Source Level Main piling sequence [1,800 kJ]	244 ± 6dB	226 ± 6dB	211 ± 6dB
Method 2 6 m Source Level Soft start' [100 kJ] (12.2 dB reduction in hammer energy)	232 ± 6dB	214 ± 6dB	199 ± 6dB

Table 6.4. 6 m pile diameter Source Level estimates. Methodologies 1 & 2 comparison.

It should also be noted that this type of stepping increase in hammer energy or 'soft start' is often part of standard piling operations with increasing hammer energy until a maximum is reached over time. This resultant variation in measured received levels due to variations in Source Level, should be considered in any measurements conducted at different ranges at different times in a piling sequence and consequent Source Level estimates.

6.3.2 Transmission Loss (seabed topography, sediment characteristics model)

Two-dimensional Parabolic Equation models were used for each topography / sediment profile. The PE code algorithm provides a high level of accuracy and computational efficiency for many problems. This method has been successfully applied to numerous underwater propagation applications. CTD data obtained during ambient noise measurements (phase 1) showed that the shallow water environment was well mixed with no layering. The water column was therefore modelled as an iso-velocity layer with uniform density and velocity based on phase 1 measurements. Absorption within the water column was modelled using an attenuation factor 0.002 $dBkm^{-1}$ at 200 Hz.

Bottom sediment samples (taken across the array and surrounding site prior to pile construction) gave the typical sediment sample as a gravel / sand mix with a mean ratio of 2:1 (mean values 54 sites 61.6 % gravel 35.9 % sand) [Internal report. "Baseline Study of marine Ecology at the Humber Gateway Offshore Wind Farm Development", (2006)]. Using this information the sediment was defined as a single homogenous composite layer with an acoustic compressional sound velocity of 1,750 ms^{-1}, Density of 1,965 kgm^{-3} and attenuation factor of 0.67 $dB\lambda^{-1}$ [Hamilton (1980, 1987), Jensen *et al,* (1993)]. Below a depth of 40 m the model was terminated with an absorbing layer to avoid spurious reflections from the models edge. Models were run for a 200 Hz wide-angle, continuous source placed at mid-water depth. This frequency represents the frequency of the peak energy content observed from previous piling operations, [Robinson *et al.* (2007)] and therefore considered the worse case. However higher frequencies were also modelled up to 1 kHz. The level of these frequencies at source were considerably lower than peak levels observed at 200 Hz and therefore were not felt to impact on overall impact assessment estimates. Typical piling noise spectral content is shown in Figure 5.4 for a 2 m test pile. This can be compared with audiometric data in section 4.4. This data was consistent with observation of piling noise spectra from other studies. Analysis of 200 Hz component was therefore considered sufficient in this current study.

A uniform grid spatial resolution of 0.75 m in range and 0.25 m in depth was used throughout the models.

Once the environment was defined, each model was run in sequence. The resultant pressure matrix (depth x range) is then converted to Transmission Loss normalized to a point 1m in front of the source at the source depth. Horizontal range profiles were then processed at varying depths. Comparisons between these and cylindrical and spherical spreading loss curves including absorption in the water column were made. These curves were again normalized to the transmission loss at a point 1m in front of the source at the source depth.

Seabed topography for the water-sediment boundary along each profile was estimated using UK HO S57 chart data 2006.

A series of two-dimensional models were implemented using a Parabolic Equation (PE) based algorithm based on the RAM code, [Collins, (1994), and Malme *et al*, (1998)]. This provides a profile of transmission loss in both range and depth for a range of bearings from the array site. In the case of variable seabed profiles and differing seabed sediment types, this potentially offers more accuracy in the prediction of loss from a source along a specific profile than the use of other simplified spreading loss models such as the use of cylindrical spreading (10 x log(range)) and absorption α x (range), [Urick, (1983)].

The model predicts surface and bottom reflections, refractions, water column and sediment absorption and subsequent constructive and destructive interference effects that may exist in a stable field. The model is however based on a single frequency continuous wave source providing a stable field profile. In the case of the short duration impulsive emissions observed during piling operations these losses can be considered representative of a 'worst case' loss profile. Simple spreading loss models do not consider the modeled effects of energy absorption by sediment layers. The PE model was therefore felt to potentially provide a greater accuracy in prediction of transmission loss with range and therefore likely source and received level estimates.

Figure 6.7 shows a series of profiles (P1 - P15) based on the perimeter of the Humber Gateway array site. Each of the profiles begins at the closest pile location on the perimeter of the array site. The pile location (profile start), range and bearing are summarized in Table 6.5 Working on a 'worst case' basis the modeling of inner piles in all directions was deemed unnecessary and the profiles were chosen as representative of the highest potential impact on the surrounding area around the array during construction.

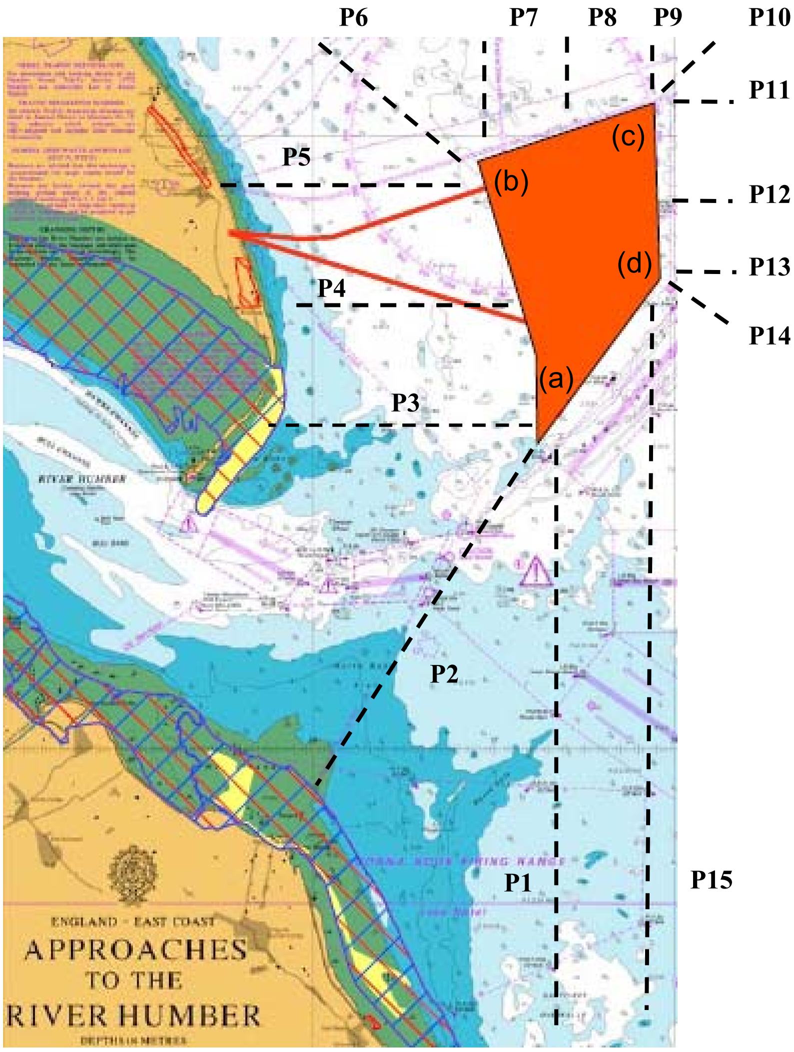

Figure 6.7 Transmission Loss modelling profiles surrounding Humber Gateway construction site.

Figure 6.8 shows example Transmission Loss model results for profile (P4) which runs from the middle (North-South) of the array site westerly towards the shoreline for a 200 Hz signal. The darker line shows the seabed topography. The source is placed mid water at 11 m from surface, shown on the left of the Figure. The model then runs left to right (for increasing range from source) indicating a relatively flat seabed out to around 4.5 km and then a gradual upslope to the shoreline for a further 3.5 km. The lower transmission loss provides a higher likely received level at different points from the source for a given Source Level. The profile shows a relatively smooth field propagation from the mid water source with highest levels closer to the source depth. Below the water-sediment boundary, some absorption of the source energy by the sediment layer can be observed. Some of the energy at the boundary may be reflected back into the water column resulting in complex interference field structures observed on some profiles. For this profile in the water column, an average drop in level of around 60 dB was observed out to 4.5 km from source across all depth profiles. At the very shallow water (< 2 m) site, a drop of around 90 dB below Source Level was observed at a range of greater than 8 km.

Profile	Start Location	Latitude (d:m:s) [WGS84]	Longitude (d:m:s) [WGS84]	Bearing (deg. true N 0^0)	Range (km)
P1	a (pile 46)	N 53:36:15	E 0:16:28	180^0	15 km
P2	a (pile 46)	N 53:36:15	E 0:16:28	225^0	To shore
P3	a (pile 46)	N 53:36:15	E 0:16:28	270^0	To shore
P4	a-b midpoint	N 53:37:50.3	E 0:15:53.2	270^0	To shore
P5	b (pile 78)	N 53:39:19	E 0:15:19	270^0	To shore
P6	b (pile 78)	N 53:39:19	E 0:15:19	270^0	To shore
P7	b (pile 78)	N 53:39:19	E 0:15:19	0^0	15 km
P8	b-c midpoint	N 53:39:43.9	E 0:17:25.4	0^0	15 km
P9	c (pile 2)	N 53:40:21	E 0:19:39	0^0	15 km
P10	c (pile 2)	N 53:40:21	E 0:19:39	45^0	15 km
P11	c (pile 2)	N 53:40:21	E 0:19:39	90^0	15 km
P12	c-d midpoint	N 53:39:20.5	E 0:19:41.8	90^0	15 km
P13	d (pile 80)	N 53:38:14	E 0:19:36	90^0	15 km
P14	d (pile 80)	N 53:38:14	E 0:19:36	135^0	15 km
P15	d (pile 80)	N 53:38:14	E 0:19:36	180^0	15 km

Table 6.5. Transmission Loss model profiles.

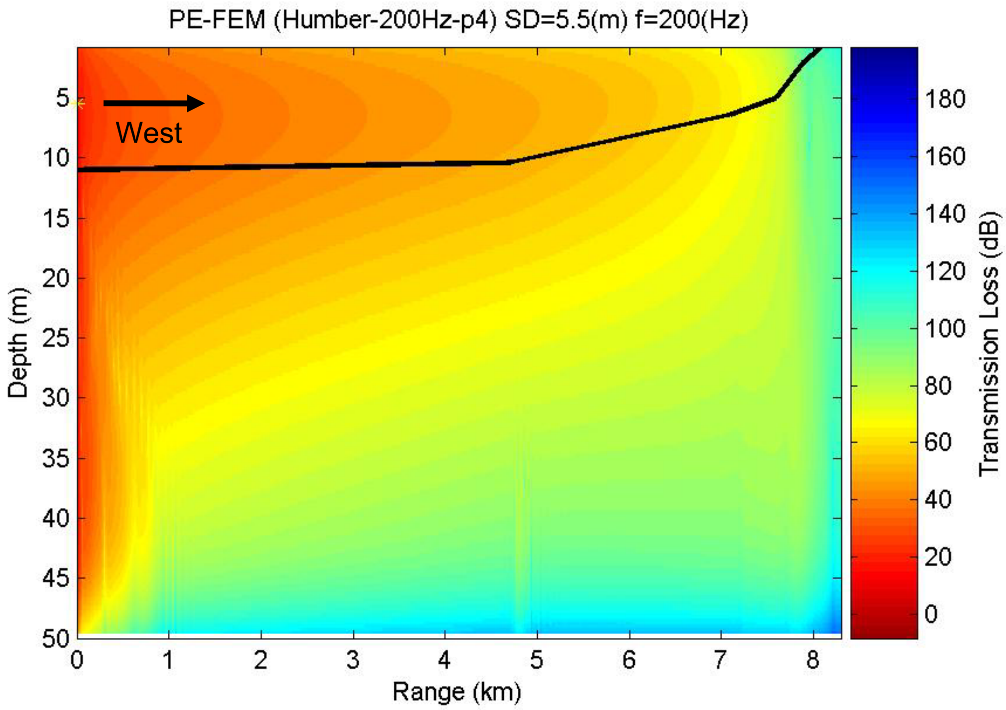

Figure 6.8. P4 East-West transmission loss profile from array site to shore.

This profile allows the assessment of the likely acoustic levels throughout the water column taking into account the seabed topography and water and sediment characteristics.

Comparison can be made with simplified water column models for cylindrical and spherical spreading and water column absorption. In the case of the spherical spreading source, if no interference from reflections from surface or bottom are assumed, (free-field) a 20 x $\log_{10}$(range) solution can be used. In addition a linear factor (α x range) for absorption in the water column can be included to give a total transmission loss of $\log_{10}$(range) + α x range. This can be seen as the lower red dashed curve. At 200 Hz, an absorption factor (α) of around 2 x 10^{-3} dB/km was used. In a shallow environment (range ~ 10 x water depth) sound energy can be reflected back between surface and seabed resulting in less loss. In this case the loss profile is better described as a cylindrical spreading function. Again a simple cylindrical spreading case can sometimes be assumed giving, with absorption, a total transmission loss of 10 x $\log_{10}$(range) + α x range shown as the upper dashed red line. At 200 Hz the effect of absorption in the water column is relatively low at the shorter ranges investigated (around a 2 dB additional loss in 100 km).

Figure 6.9 shows five depth profiles (from P4) distributed at 1m from the surface, ¼ depth (at source), mid-water (at source), ¾ depth (at source) and 1 m from water / sediment interface. These profiles initially show a loss close to that of spherical spreading which quickly (within 10 m) becomes a loss level just above that of cylindrical spreading consistent with spreading in a shallow water environment with a lossy sediment layer. If the surface and seabed were to act as perfect reflectors, the profile for a flat seabed would follow the 10 x $\log_{10}$(range) + α x range profile exactly. The loss of energy into the sediment however results in the slightly higher overall loss profiles measured in the water column. From about 1 km from source the effects of much higher sediment absorption factors can be seen from the water / sediment interface. This interface is not assumed to be a rigidly delineated boundary. A smoothing factor is used to move the acoustic properties from that of the water column to that of the sediment layer. This more closely represents the water – sediment boundary on a real seabed where water saturated sediment eventually becomes a sediment layer in its own right. Because the absorption factor in gravel sand mix sediment is relatively high these effects are seen in the slightly higher losses observed within the water column. In the latter case, all of the profiles are below an equivalent of 15 log (range) at a range of ~6.5 km and a much more rapid loss is observed as the upslope is encountered resulting in more water-sediment interactions in the propagating signal.

By comparison, Figures 6.10 and 6.11 show a west to east profile (P12) where an initial gentle up-slope out to around 4 km is replaced by a variable down slope as the profile moves into deeper water. Losses throughout the water column of less than 60 dB are seen at a range of 15 km. Again this is consistent with losses somewhere between cylindrical spreading (10 x log (range)) + absorption and spherical spreading (20 x log(range)) + absorption. The effect of deepening water and seabed down slope results in less water-sediment interactions and therefore lower observed losses due to sediment attenuation.

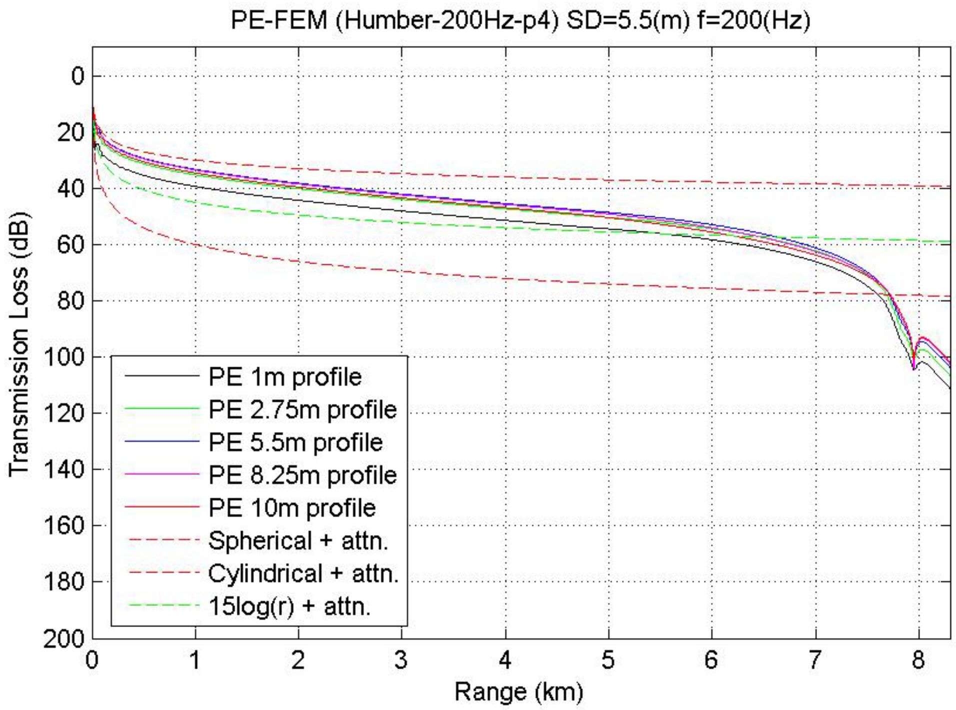

Figure 6.9. P4 East-West transmission loss depth profiles.

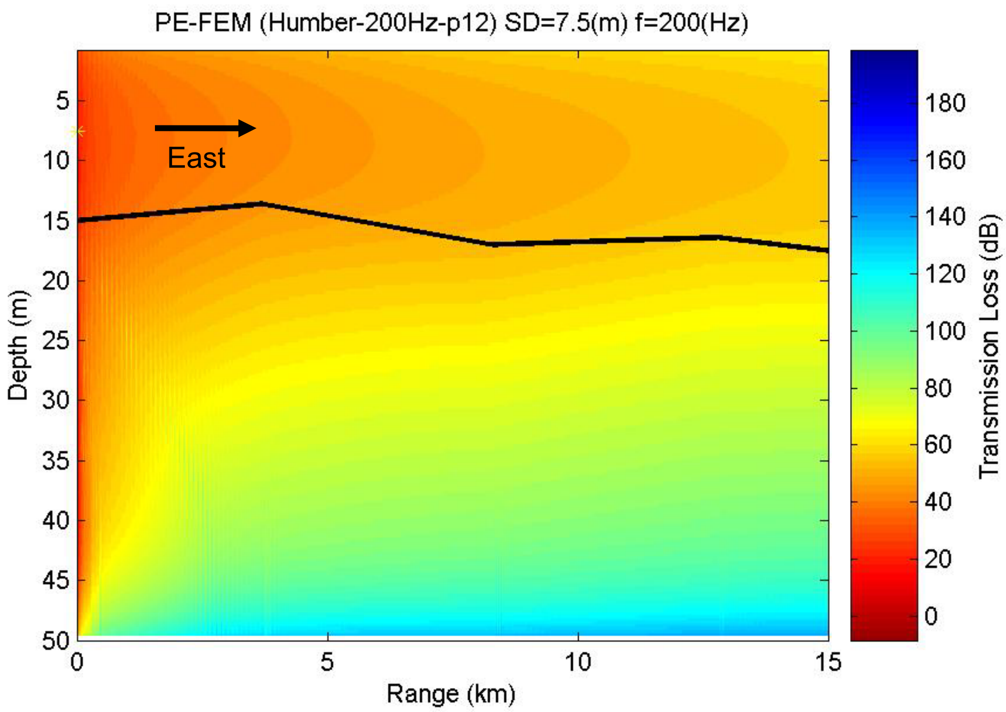

Figure 6.10. West to East Transmission Loss profile (P12).

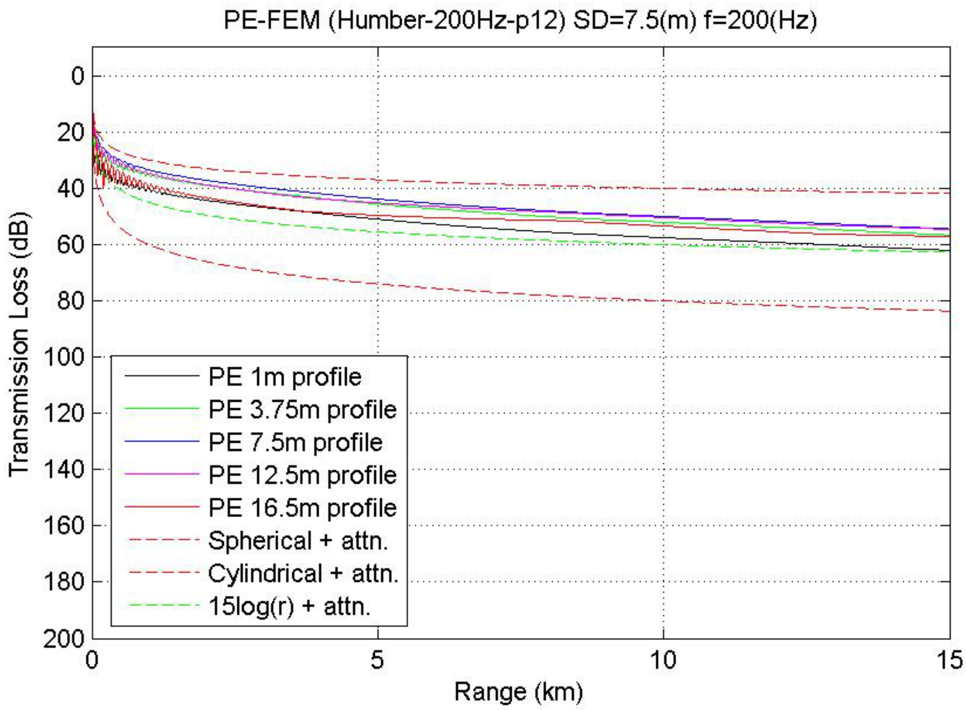

Figure 6.11. West to East Transmission Loss depth profiles (P12).

The effect of the slight rise up to a peak at around 4 km from source causes a slight down trend in depth in the minimum loss profiles after this range, filling in any potential shadowing effects that may have occurred behind this peak. This effect can be seen more clearly in Figure 6.12 as profile P14 travels southeast crossing the deep water shipping channel within 2 km. No major shadowing effects are observed as acoustic energy fills this channel from both surface-bottom reflections and diffraction effects. After this deep water channel the relatively gently upslope results in a profile similar to that seen on the shoreward side of the array in profile P4. The interaction of the surface and bottom reflected energy with the direct path from source also results in a relatively complex field structure within the channel. However the minimum observed loss in the channel is around 40 dB below Source Level still above the equivalent cylindrical spreading and absorption loss. The minimum loss and therefore highest potential received level occurs below the left hand ledge of the channel at a depth of around 24 m.

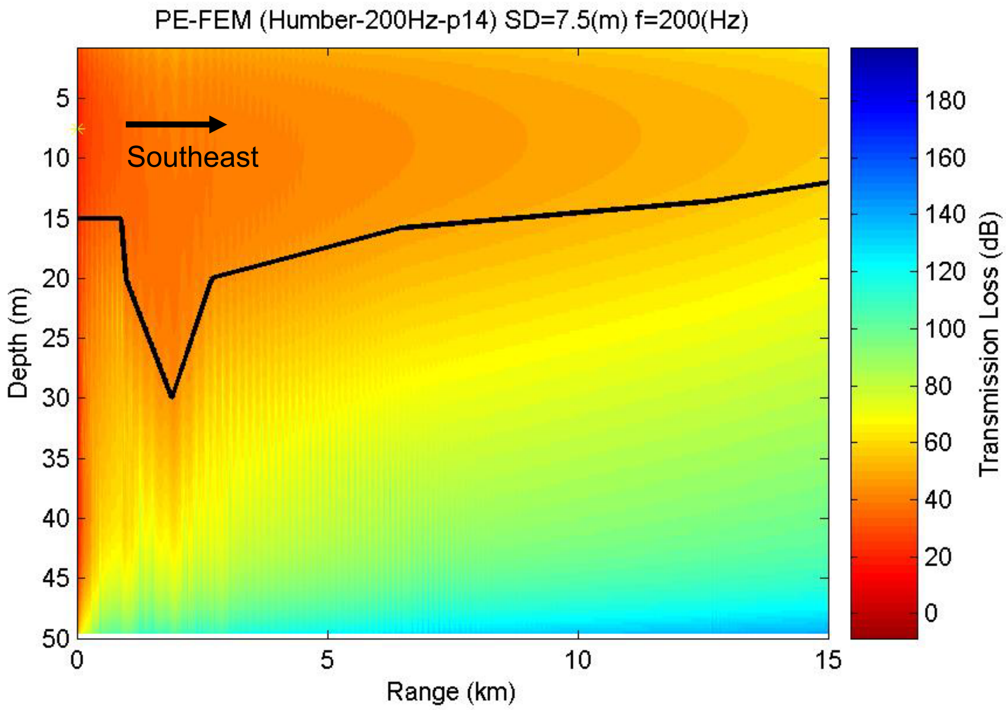

Figure 6.12 South-easterly Transmission Loss profiles (P14).

The transmission loss results for each profile were then stored and used to make received level estimates around the array site.

Received sound levels

The two cases of SEL Source Level (211 dB re 1 μPa^{2}s.m & 199 dB re 1 μPa^{2}s.m) were then applied to the previously calculated transmission loss curves for each profile. Figures 6.13 and 5.14 show the full field and range profiles for five depths distributed throughout the water column, SEL Received Level estimates for a P2 profile (south west from point 'a' across the Humber Estuary towards the southern shoreline). This is for a main piling sequence with equivalent SEL Source Level of 211 dB re 1 μPa^{2}s.m. The top panel of Figure 6.13 shows the depth-range field for the P2 profile. The lower panels and Figure 6.14 show individual range profiles at depths 1m from surface, ¼ water depth, mid-water, ¾ water depth and 1m from the deepest bottom depth.

Each depth profile observed in profile P2 shows a Received Level below 180 dB re 1 μPa^{2}s by around half a kilometre (maximum ~ 665 m for the mid water profile) for an SEL Source Level of 211 dB re 1 μPa^{2}s.m and below 160 dB re 1 μPa^{2}s within 5.5 km. The highest levels are generally observed in the mid-water profile at the same level as the source. Each of the profiles then show a rapid reduction in received level between 5-7 km from source due to the slight rise and fall in the seabed profile. This then stabilises to a profile a little above and similar to spherical spreading before the final 'beaching effects' are observed around 12 km. In this case received levels within 3 km of the beach are less than 140 dB re 1 μPa^{2}s.m.

This can be compared with a north-south profile crossing the deeper water shipping channel (profile P1) shown in Figures 6.15 and 6.16 where the level at all depths is below 180 dB re 1 μPa^{2}s.m within 650 m of source and below 140 dB re 1 μPa^{2}s.m in less than 11 km from source. This is similar to the profile P14 shown in Figure 6.12 also crossing the channel. In both cases levels in excess of 160 dB re 1 μPa^{2}s.m are seen within the shipping channel.

Figure 6.17 by comparison shows easterly profile (P10) where lower losses are experienced moving into deeper water. In this case the level again drops below 180 dB re 1 μPa^{2}s.m within 615 m. The profile is then more stable with levels throughout the water column below 160 dB re 1 μPa^{2}s.m at 13.2 km from source with a maximum level of around ~159 dB re 1 μPa^{2}s.m at 15 km.

Estimates of received level versus range for each Source Level, outlined in Table 6.5, both for main piling estimates and a 'soft start' were then made. Estimates of the equivalent RMS and peak-to-peak levels can be made using scaling factors outlined in section 5.3.1 and the equivalent range above a threshold for each case. Direct comparison of individual range profiles could then be made between each Source Level for the scale-up pile and scale-up + soft start cases.

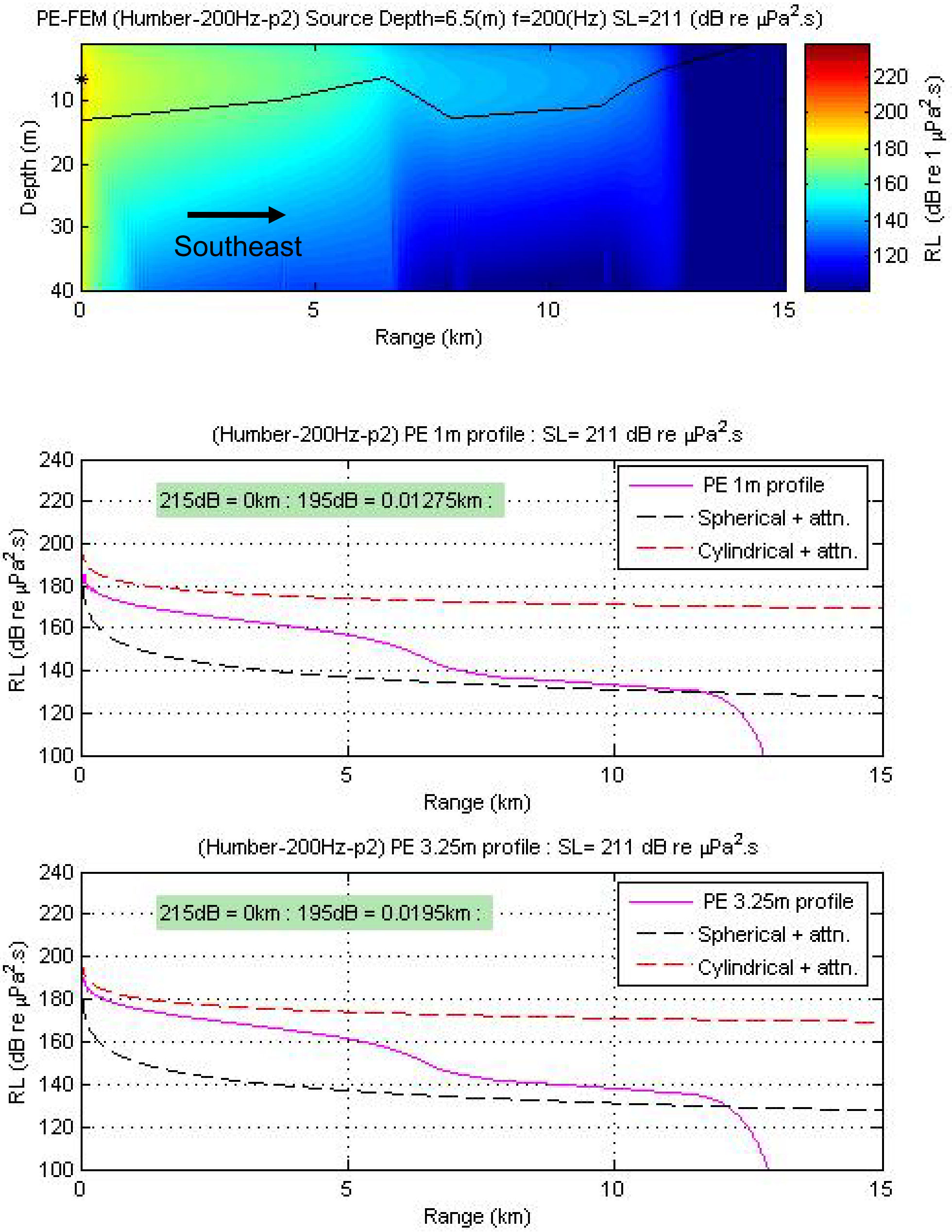

Figure 6.13 Received Level range profile for 211 dB re 1 μPa^{2}s.m Source Level and a P2 transmission loss profile.

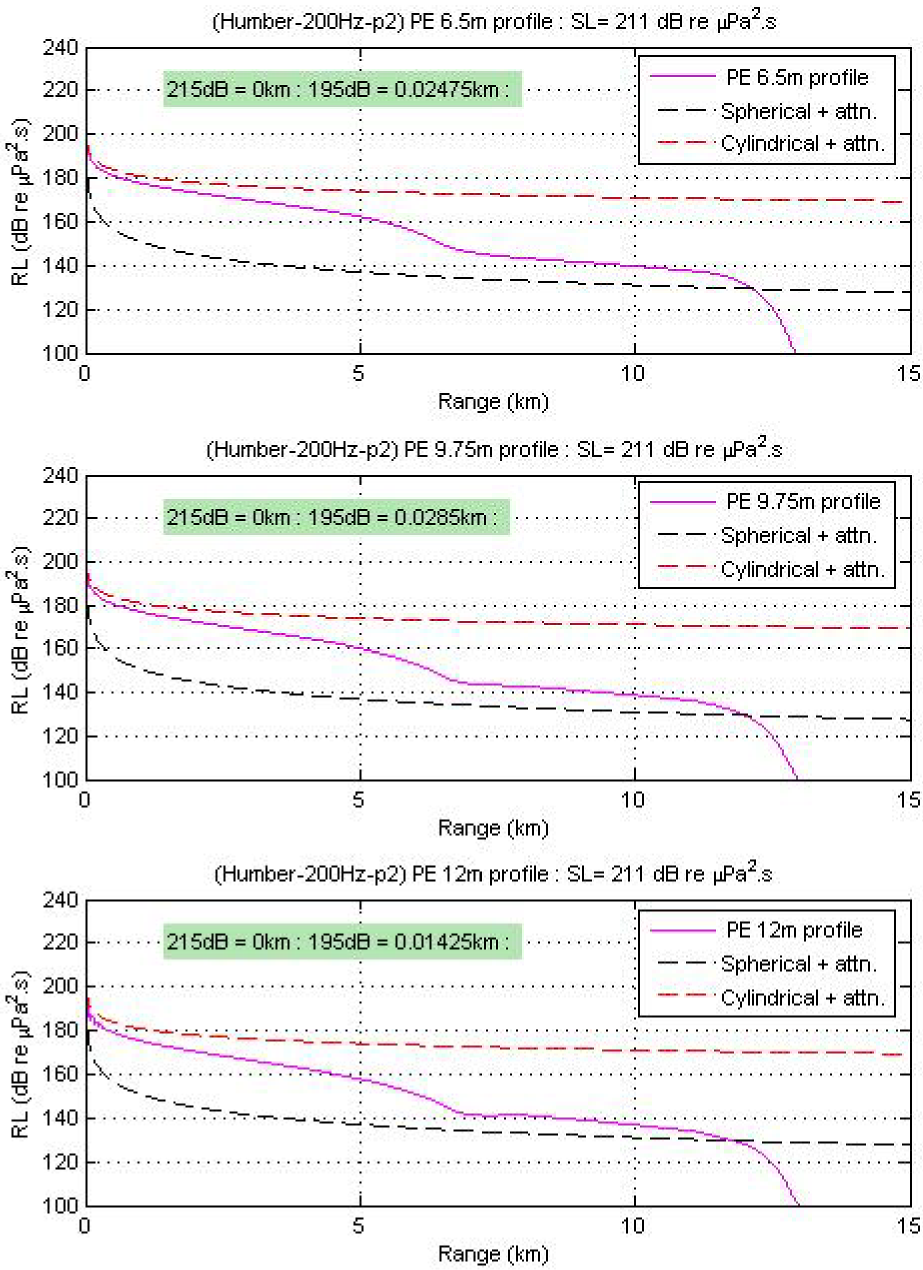

Figure 6.14. Received Level range profile for 211 dB re 1 µPa^{2}s.m Source Level and a P2 transmission Loss profile.

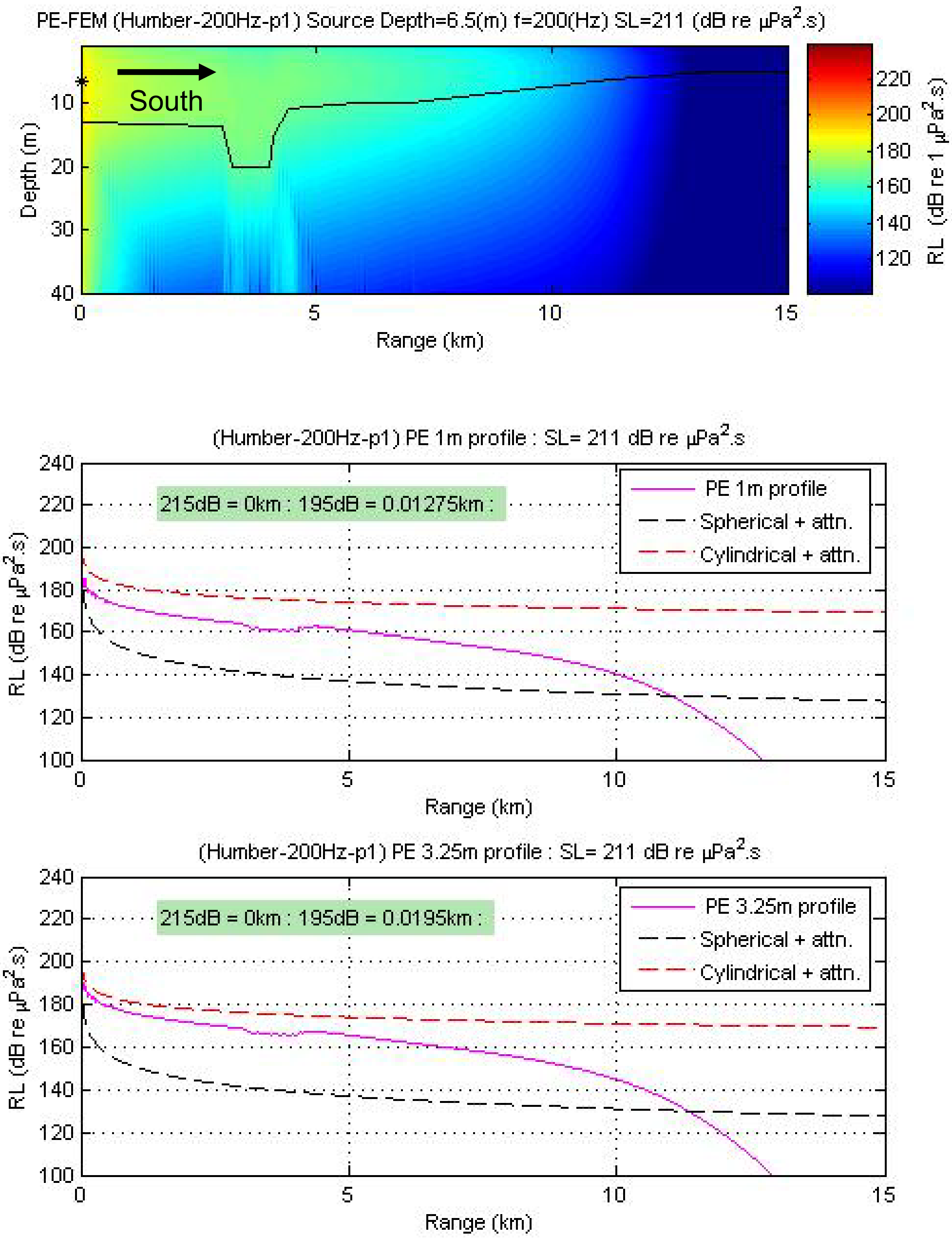

Figure 6.15 Received Level range profile for 211 dB re 1 μPa^{2}s.m Source Level and a P1 Transmission Loss profile.

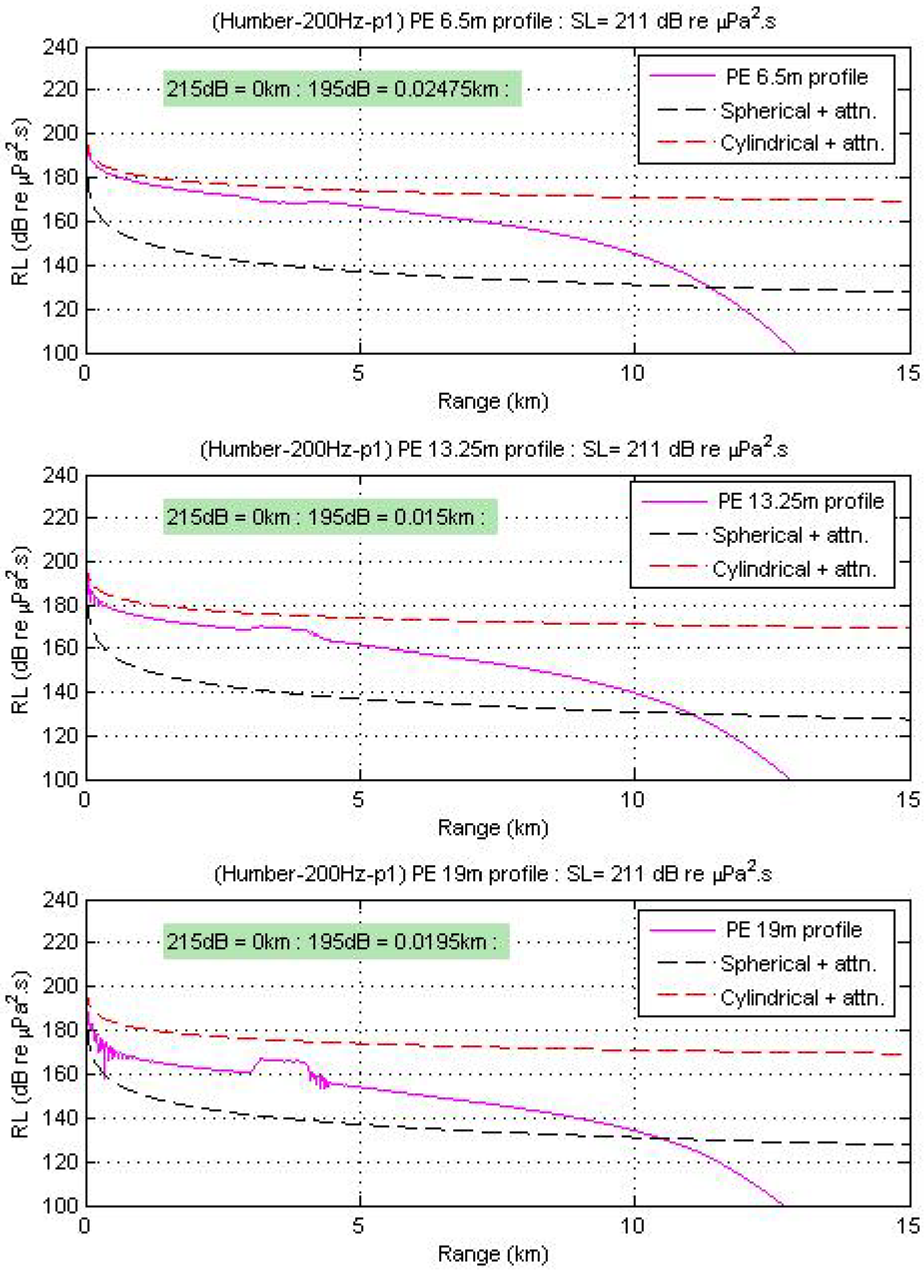

Figure 6.16. Received Level range profile for 211 dB re 1 μPa^{2}s.m Source Level and a P1 Transmission Loss profile.

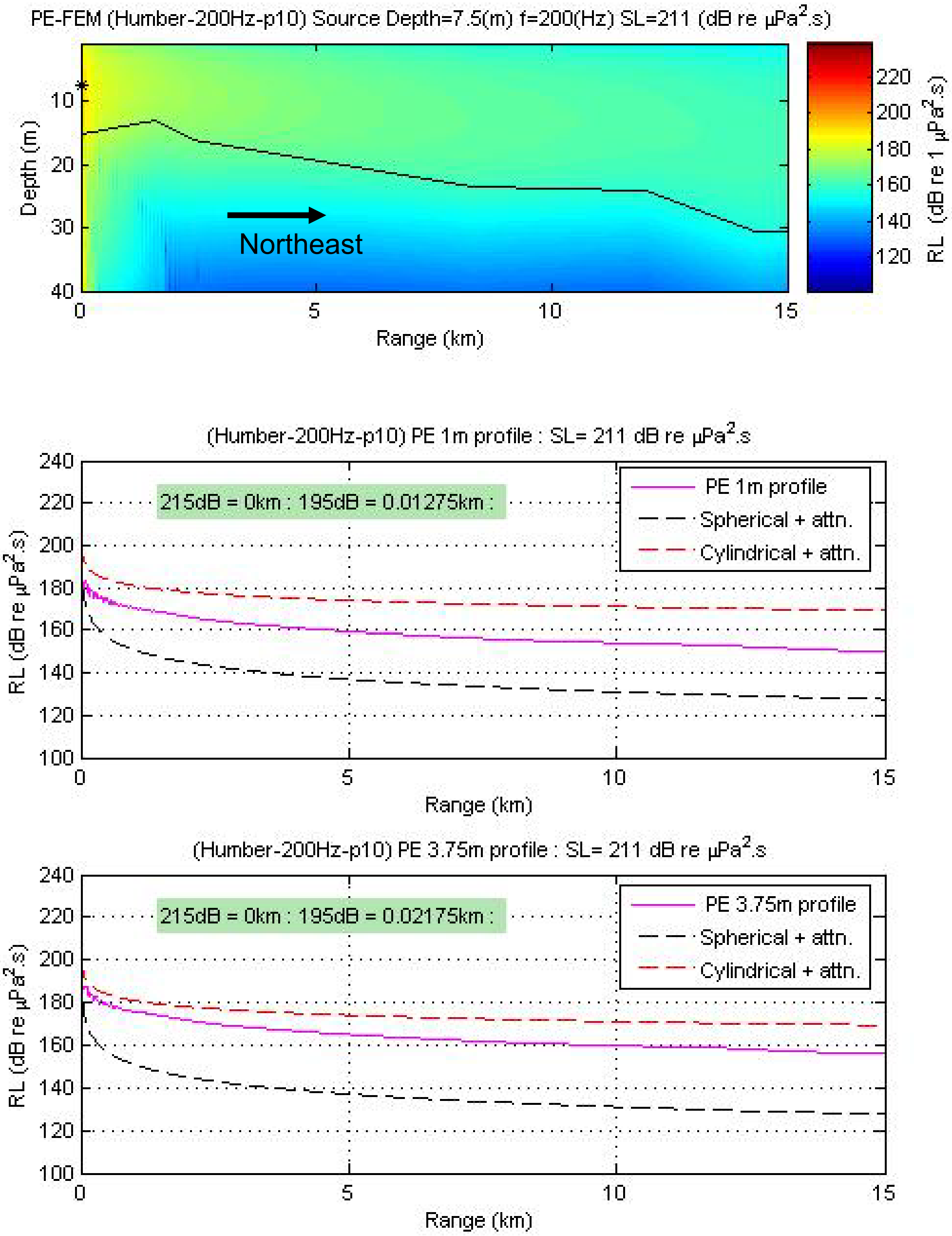

Figure 6.17 Received Level range profile for 211 dB re 1 μPa^{2}s.m Source Level and a P10 Transmission Loss profile.

Figure 6.18 shows the all modelled transmission Loss profiles around the Humber Gateway array site. The effects of the shallow water beaching particularly to the West of the array shows a rapid increases in transmission loss at longer ranges. Similarly Figure 6.19 shows in considerable variation in transmission losses in range 5-30 m from source for individual profiles.

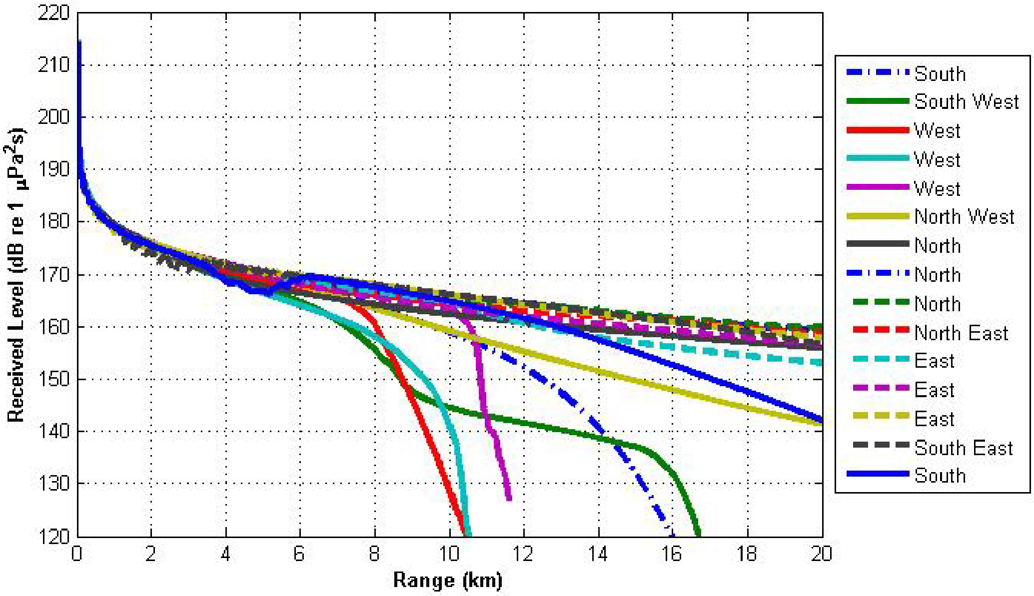

Figure 6.18 Mid-water variation in transmission loss profile around the Humber Gateway array site.

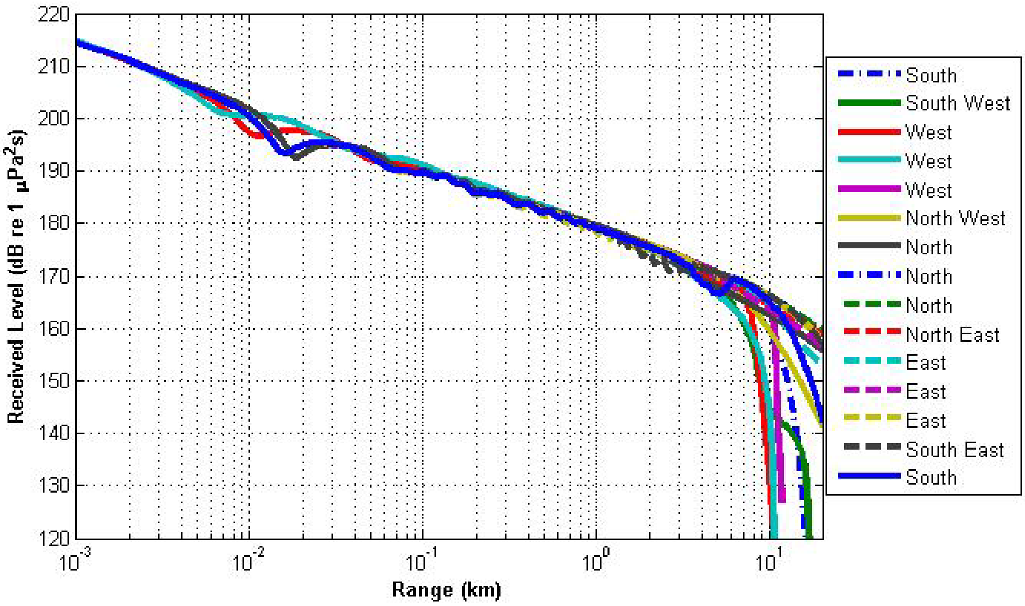

Figure 6.19 Mid-water variation in transmission loss profile around the Humber Gateway array site.

7 LETHAL AND PHYSICAL INJURY IMPACT ASSESSMENT FOR 6 M DIAMETER PILING OPERATION

7.1 INTRODUCTION

The threshold range estimate is defined as the maximum range from source that a Received Level in excess of a specific impact criteria is observed. Richardson *et al* (1995) described 4 zones of impact.

- The zone of audibility (these are within which the sound is both above the animals hearing threshold and detectable above background noise).
- The zone of responsiveness (the region within which behavioural reactions in response to the sound occur).
- The zone of masking (the zone within which a sound level may mask biologically significant sounds).
- The zone of hearing loss, discomfort, or injury (the area within which sound level is sufficient to cause threshold shifts or hearing damage).

Two common examples of thresholds used in the later case are Permanent Threshold Shift (PTS) classed as a level A harassment (Injury) in the Marine Mammal Protection Act and Temporary Threshold Shift (TTS). Other criteria for a behavioural response include at a fixed level above hearing threshold (dB_{ht}) and more recently the Marine Mammal Noise Exposure Criteria Group have published recommendations for injury criteria for different signal types based on both peak pressure of an un-weighted signal and frequency weighted accumulated exposure (SEL), [Southall *et al* (2007)]. The SEL thresholds are frequency weighted for various marine mammal hearing groups including low frequency cetaceans, mid-frequency cetaceans, high-frequency cetaceans, pinnipeds in water and pinnipeds in air, Figure 7.1.

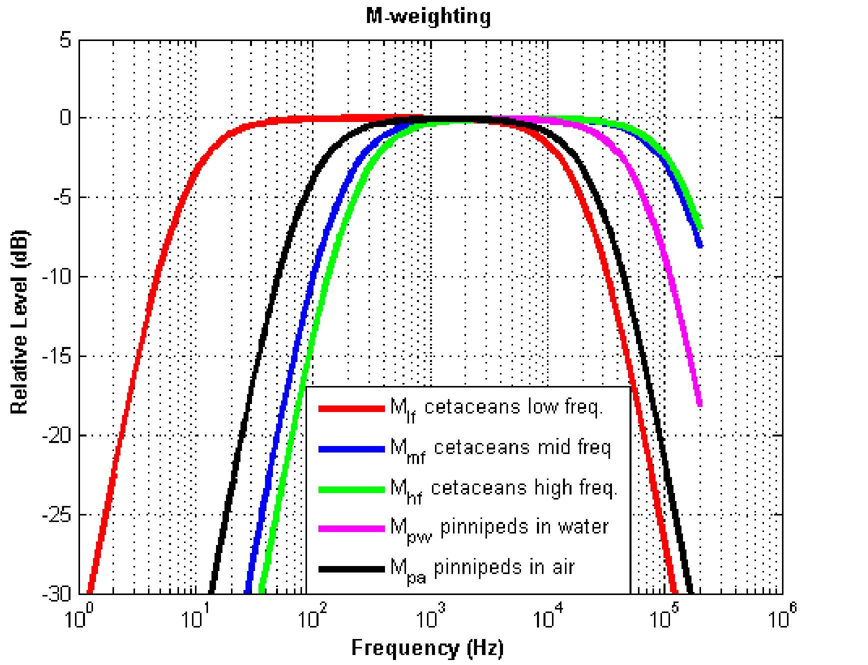

Figure 7.1 Hearing-weighting functions for marine mammals (M-weighting).

As a mitigation measure, prediction of range or exposure volume within the water column at which acoustic levels may be above or equal to certain levels is vital. This would potentially define impact zones and therefore aid any mitigation processes that were to be implemented. Although studies have been conducted on marine mammal and fish species hearing for many years, large gaps in data in terms of auditory abilities, behavioural response, etc. to acoustic stimuli still exist. A review of the current knowledge and data needs covering operation and construction of wind farms and effects on marine mammals was undertaken by Madsen *et al.* in (2006). Additional recent work by Carstensen *et al*., (2006) discusses the impact of offshore wind farm construction on the harbour porpoise. Other studies, [Gordon *et al.* in (2004)] have also reviewed the effects of seismic emissions on marine mammals. A number of recent studies have looked at the effects of piling and construction noise on fish species, [Abbott *et al.*, (2004), Hastings *et al.* (2005) and Popper *et al*., (2006)].

Similarly, little open access data exists to date on the temporal / spectral and amplitude characteristics of various piling operations and implications to marine species. This subject was again reviewed by Richardson *et al* (1995) and more recent reports by Nedwell, *et al.*, (2003) and (2004), McHugh (2005), *et al*., and Robinson *et al* (2007) and others have contributed to knowledge in this area.

Although these and other studies have improved the state of knowledge considerable uncertainties still exist in many aspects of potential acoustic impact on marine species As a result these are areas of very active research and assessment from several quarters. This report has therefore endeavoured to use the current best state of knowledge in the areas involved.

7.2 INJURY CRITERIA (METHODOLOGY 1: SUBACOUSTECH LTD)

To allow comparison with auditory injury criteria from previous studies, the methodologies outlined by Parvin *et al* (2006) were implemented to calculate a time varying dB_{ht} for a species. This is then used to calculate a continuous equivalent level dB_{ht} Leq. Parvin *et al* (2006) then use a singe strike injury criteria of 130 dB_{ht} Leq. For repetitive sounds over a 5 hour period this level is adjusted to equivalent noise dose of 92 dB_{ht} Leq.

Figure 7.2 shows the equivalent continuous sound level (dB_{ht} Leq) for a deep water site for a 6.0 m pile for a deep water site. Data was taken from the Barrow site [Parvin *et al* (2006)], then adjusted from a 6.5 m to 6.0 m pile diameter using methodologies outlined in section 6.2. The auditory injury predicted ranges for each species are shown in Table 7.1. based on the 92 dB_{ht} Leq criteria. In this case auditory injury for both herring and cod could occur out to ranges 1.7 and 1.53 km respectively and the harbour porpoise to 1.6 km. The bottle nosed dolphin however has a lower impact range of 435 m. Also using this criteria the impact range for a harbour seal is around 253 m.

The above predictions assume no fleeing animal response and identical above hearing thresholds for injury for each species.

Species	Peak-to-peak perceived Source Level (dB_{ht} @ 1m) for a 6 m diameter pile	Auditory injury range (92 dB_{ht} Leq) (km)
Cod (*Gadus morhua*)	162	1.53 km
Herring (*Clupea herengus*)	179	1.7 km
Dab (*Limanda limanda*)	154	0.184 km
Bass (*Dicentrarchus labrax*)	151	0.046 km
Bottlenose Dolphin *(Tursiops Truncates*)	207	0.435 km
Striped Dolphin (*Stenella Coertuleoalba*)	203	0.448 km
Harbour porpoise (*Phocoena phocoena*)	203	1.6 km
Harbour Seal (*Phoca vitulina*)	183	0.253 km

Table 7.1 Summary of auditory injury range for a 6.0 m diameter piling operation in a inshore deep water site based on methodologies outlined by Pavan *et al.* (2006).

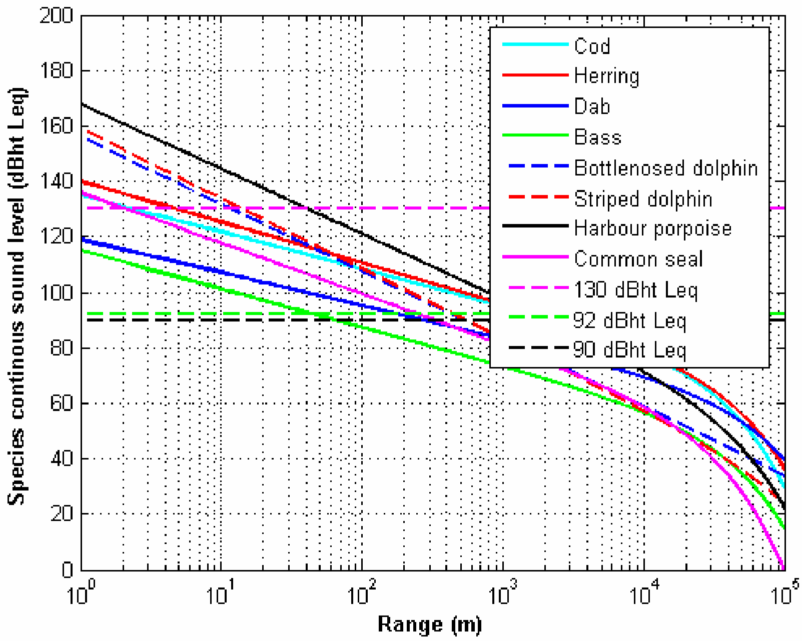

Figure 7.2 Predicted equivalent sound level (dB_{ht} Leq) with range for a 6.0 m pile diameter in a deep water inshore site.

7.3 INJURY CRITERIA (METHODOLOGY 2)

7.3.1 Marine Mammals

7.3.1.1 Cetacean

The primary species of interest for this current study is the harbour porpoise (*Phocoena phocoena*) and bottlenose dolphin (*Tursiops truncates*). In 2006, the National Marine Fisheries Service (NMFS), USA proposed the use of a PTS level for accumulated Sound Exposure Level (SEL) of 215 dB re 1 μPa^{2}s and 195 dB re 1 μPa^{2}s for TTS, [NOAA, (2006)], for all cetaceans based on the work of Schlundt et al. (2000). In this case, exposure durations for SEL were 1 s meaning direct comparison with computed Sound Exposure Level (SEL) levels was possible. Pulse repetition was greater than 1 s therefore the levels would be numerically almost identical to the 90% energy criteria used within this and previous studies. This replaced the earlier proposed RMS thresholds, of 190 and 180 dB re 1 μPa [NMFS (2003)].

Taking the 215 dB re 1 μPa^{2}s (PTS) threshold and the 195 dB re 1 μPa^{2}s (TTS) mean and maximum range estimates for all profiles estimates (section 5.3) for a single impact in excess of this level can be made. This was done for the estimated Source Level for both the main piling sequence (SEL Source Level 211 dB re 1 μPa^{2}s.m) and for the start of the soft start (SEL Source Level 199 dB re 1 μPa^{2}s.m). Taking these thresholds, a maximum range from pile for levels equal to or greater than the threshold can be computed for each range-depth profile for a single impact. The range at which the 215 dB (PTS) and 195 dB (TTS) occur are then calculated for each depth profile. These results are shown numerically on each of the profile plots and as a vertical line at the appropriate range. The upper panel of Figure 6.17 shows the mid-water (typically highest intensity) profile for a 211 dB re 1 μPa^{2}s.m Source Level for the P10 profile. In this case, levels in excess of the PTS threshold would not occur for a single impact and TTS could occur at ranges less than 24 m from source. The mean and average estimates for all profiles and depths for maximum range for single impact risk of TTS are giving in the upper two rows of Table 7.2 for both full and soft start Source Levels.

The above criteria are however based on accumulated exposure where each additional hammer strike must be added to give a total exposure level. This accumulation can be modelled for a specific number of hammer strikes, main piling sequence Source Level, soft start etc. A receiver (animal) can also be allowed to move away from the source area at an assumed swim speed and start position giving an estimate to a point where accumulated exposure to a PTS or TTS level may be encountered.

	Main piling (SL 211 dB re 1 μPa^{2}s.m)		Soft start (199 dB re 1 μPa^{2}s.m)	
	Maximum	Mean	Maximum	Mean
SEL 215 (dB re 1 μPa^{2}s (PTS))	Not exceeded	NA	Not exceeded	NA
SEL 195 (dB re 1 μPa^{2}s (TTS))	32 m	18.9 m	3 m	1.4 m

Table 7.2. Single exposure maximum range in excess above SEL thresholds for PTS, TTS and behavioural responses.

<u>Fleeing animal model for accumulated exposure</u>

Figure 7.3. shows an accumulated exposure scenario where the animal starts at a range of 2 m from source. A linearly soft-start is carried out for 600 hammer strikes with a 10 s interval

(shown as dark dots on the upper three panels) starting from 199 dB re 1 μPa^{2}s.m Source Level increasing to 211 dB re 1 μPa^{2}s.m Source Level. After this, a main piling sequence of a further 3,600 hammer strikes (red dots on upper three panels) occurs at a constant Source Level of 211 dB re 1 μPa^{2}s.m at a 2 s strike rate. Four thousand hammer strikes were assumed a worst case for a typical piling situation. In many cases pile 'refusal' would occur before this number is reached. The animal is modelled moving away (fleeing) from the source at a swim speed of 1.5 ms^{-1} up to a maximum distance of 15 km (it is not assumed that the animal will continue moving indefinitely). The upper panel shows the accumulated exposure versus range, with approximately one third of the exposure occurring in the first 500 m from source. At a maximum range, accumulated exposure continues with in this case the total exposure in excess of the TTS threshold of 195 dB re 1 μPa^{2}s after 455 hammer strikes. Panels two to four show the accumulated energy versus time and strikes and animal position versus time respectively.

	Main piling (SL 211 dB re 1 μPa^{2}s.m)		Soft start (199 dB re 1 μPa^{2}s.m)	
	Maximum	Mean	Maximum	Mean
SEL 215 dB accumulated 4,000 strikes with soft start (1.5 ms^{-1} swim speed)	Not exceeded	NA	NA	NA
SEL 195 dB accumulated 4,000 strikes with soft start (1.5 ms^{-1} swim speed)	3 m	NA	NA	NA

Table 7.3. Accumulated exposure maximum range in excess above SEL thresholds for PTS, TTS and behavioural responses.

If the start position is moved to 3 m from the source and everything else is kept constant, a TTS level exposure is not experienced in 4,000 hammer strikes in this case. The actual level at which TTS occurs however is highly dependant on numerous variables including start position, start and main sequence level, swim speed, maximum range, repetition rate and propagation loss within the water column. The above model is based on a 15 x log (range) spreading loss. In many cases, particularly in the westerly profiles, estimated Transmission Losses were even higher than the above model resulting in potentially lower Received Levels and therefore lower exposure levels. A 15 x log (range) loss model was chosen as being close to the long-range lowest transmission losses observed from the numerically modelled data.

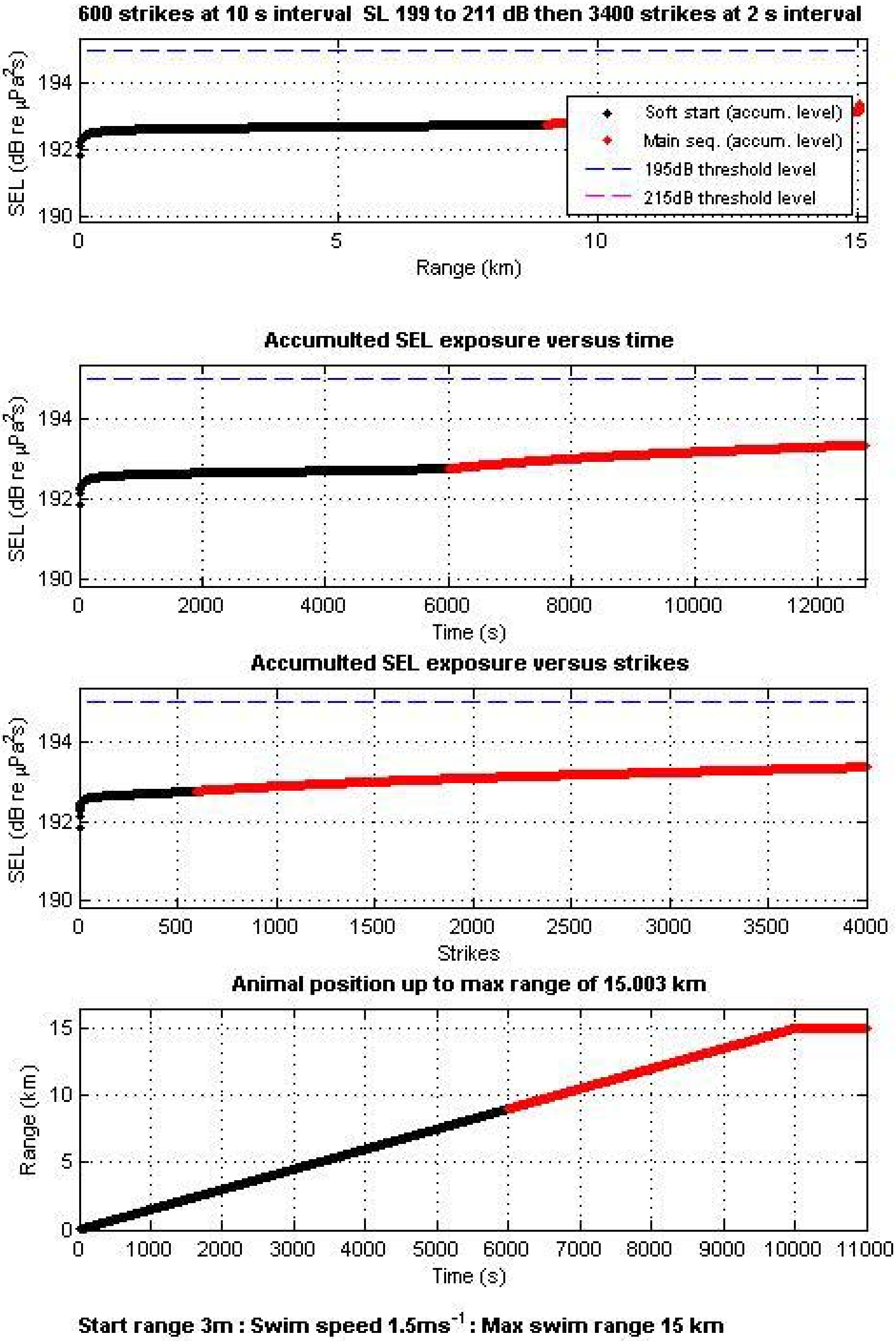

Figure 7.3. Accumulated SEL exposure model for 211 dB re 1 μPa^{2}s.m maximum Source Level with soft start. Start range of 3 m or greater results in avoidance of TTS threshold 195 dB re 1 μPa^{2}s.

7.3.1.2 Pinnipeds

The two primary species of interest in this study are the Grey or Atlantic Seal (*Halichoerus gyrpus*) and the Common or Harbour Seal (*Phoca vitulina*). The Grey Seals are of particular interest as one of the UK's largest breeding sites is at Donna Nook on the Lincolnshire cost just south-west of the proposed wind farm site. Both are present in the waters off the Humber Estuary.

Very little published work is available on the effects of impulsive sound source on pinnipeds. Richardson *et al,* reviewed responses to seismic sources in 1995. Only anecdotal encounters are reported at this time. It is appreciated that whilst there are differences, seismic airgun emissions provide a strong transient signal with many similarities to that of driven piling emissions. Observations of responses to seismic systems may therefore be applicable to piling noise assessment. In these cases, the seals are not reported to having acted strongly to a seismic airgun source. In 1998, Thompson *et al* conducted controlled exposures on both harbour and grey seals for 1 hour using small airguns whilst monitoring the behavioural response of tagged animals. The harbour seals initially showed a fright response, and avoidance behaviour (swimming away from the source) and stopped feeding however this was short lived and the animals quickly returned to normal behaviour after the sound ceased. Similarly, the grey seals showed an avoidance behaviour (some animals hauled out). Most of the animals returned to pre-emission behaviour within two hours of the noise stopping.

The harbour seal has relatively good hearing at frequencies below 1 kHz with a hearing threshold around 96 dB re 1 μPa, [Kastak & Schusterman (1999)] which can be compared with the bottlenose dolphin (*Tursiops truncatus*), of around 130 dB re 1 μPa at 100Hz, [Johnson (1967)].

In 2003, the USA National Marine Fisheries Service, [NMFS (2003)] criteria defined the zone of injury for small cetaceans as the range at which received level had fallen to 180 dB re 1 μPa (RMS) and for seals as 190 dB re 1 μPa (RMS) for a single impact. Recent work by Nachtigall *et al*, (2004) has shown a TTS caused by a broadband exposure of around 160 dB re 1 μPa (RMS) in a bottlenosed dolphin. This suggests that the 180 dB and 190 dB RMS criteria may need to reviewed for both cetaceans and pinnipeds. More recent regulation has used a SEL based criteria as outlined in section 4.1.1.

Kastak *et al,* (2005) suggested an onset of TTS at a level of 131 dB re 1 μPa^{2}s above sensation level for pinnipeds based on trials on Californian sea lions (*Zalophus californaus*), northern elephant seals (*Mirounga angustirostris*) and a harbour seal. Kastak suggests a TTS onset level for the pinnipeds in the range 183 - 206 dB re 1 μPa^{2}s based on the hearing sensitivity of the animals being tested. Using the 183 dB re 1 μPa^{2}s level as the most precautionary absolute threshold level for the harbour seal similar accumulated models were run for a seal at different ranges, Source Level swim speed etc. All other accumulated SEL model parameters were kept identical to previous trials (i.e. 1.5 ms^{-1} swim speed, soft start level 199 dB re 1 μPa^{2}s for 600 strikes and 3400 strikes at full power).

SL (dB re 1 μPa^{2}s)	Start range	Comment
211 dB + soft-start	300 m	183 dB re 1 μPa^{2}s threshold exceeded in 1,536 strikes
211 dB + soft-start	4,020 m	183 dB re 1 μPa^{2}s threshold NOT exceeded
200 dB + soft-start	3 m	183 dB re 1 μPa^{2}s threshold NOT exceeded

Table 7.4. Accumulated estimated SEL exposure for a harbour seal.

The first two cases in Table 7.4 show a 211 dB re 1 μPa^{2}s.m Source Level including a soft start as in the previous model. In both cases, the accumulated exposure exceeds the 183 dB

TTS within 1,536 strikes. Due to the asymptotic nature of the accumulated exposure curve the highest changes take place at shorter ranges. A reduction of 11 dB to 211 dB re 1 µPa²s.m equivalent Source Level can reduce a safe range of greater than 3 m from source to not exceed the 183 dB re 1 µPa²s threshold in 4,000 hammer strikes. Figure 7.4 shows the total accumulated exposure for 4,000 hammer strike model versus range for the above two cases. What is not yet established with the accumulated exposure criteria is a recovery period. The human equivalent has a defined recovery period where full recovery can be made. The effect of recovery period in marine mammals is still under investigation and is not included in the current models outlined.

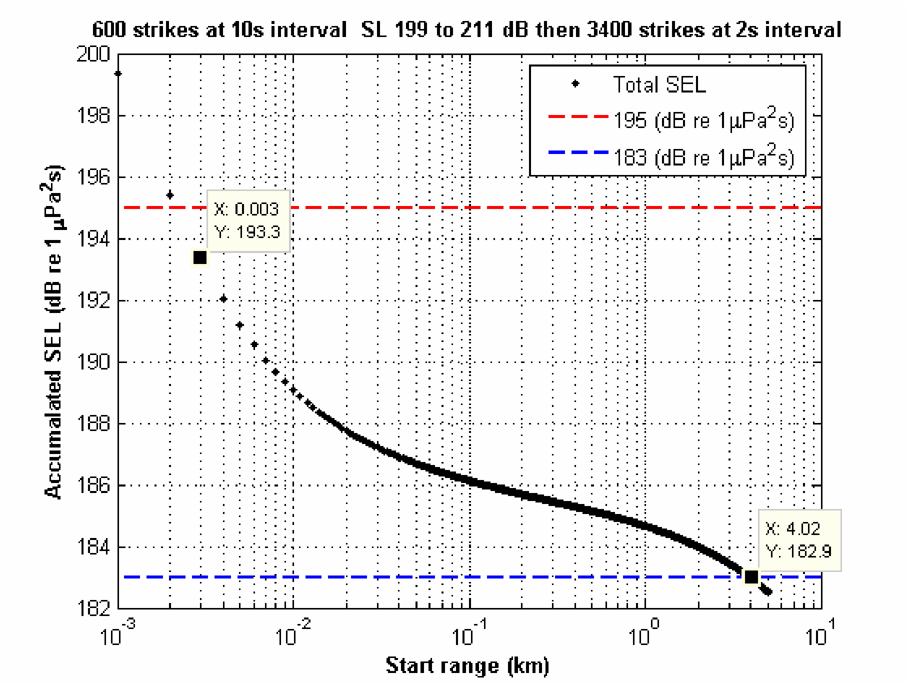

Figure 7.4. Accumulated SEL exposure model for 211 dB re 1 µPa²s.m maximum Source Level with soft start versus start range in relation to TTS threshold 195 dB re 1 µPa²s (cetaceans) and 195 dB re 1 µPa²s (pinnipeds in water).

7.3.2 Fish – Injury criteria

A number of studies have been conducted and reviewed on the hearing of the species of interest in this study including, herring (*Clupea harengus*), European sea-bass (*Dicentrarchus labrax)* and Atlantic salmon (*Salmo salar*), [Nedwell (2006), Abbott (2004)]. No specific data on the behavioral or auditory characteristics of the lemon sole (*Microstomus kit)* were found at the time of press. However, several authors including Jones (2007), discuss current average audiograms for a wide range of families ranging from odontocetes, pinnipeds, fish and human divers in a discussion on accumulate exposure models. These studies have led to the establishment of several generalized risk criteria methodologies.

Nedwell (2004) discusses the use of a dB_{HT} criteria based on a weighting factor related to auditory perception for individual marine species. An alternate approach is discussed by Popper *et al*. (2006), in the paper titled “An Interim Criteria for Injury of Fish Exposed to pile driving Operations: A white paper”. The author outlines what is believed to be a comprehensive summary of the effects of piling construction on various fish species. A dual approach of SEL measurements for a single strike combined with criteria for peak sound pressure is employed very similar to the noise marine mammal criteria methodology outlined by the Marine Mammal Noise Exposure Group. The threshold levels outlined by Popper *et al* are defined as a single strike SEL of 187 dB re 1 µPa²s and a peak level of 208 dB re 1 μPa_{pk}.

Using the criteria outlined by Popper and a SEL Source Level of 211 dB re 1 $\mu Pa^2 s.m$, an estimate can be made of the maximum range from source for an exposure in excess of 187 dB re 1 $\mu Pa^2 s$ for a single strike for all range and depth profiles using the previously computed transmission loss curves.

Source Level (SEL)	Impact range for received level in excess of SEL threshold 187 dB re 1 $\mu Pa^2 s$	
	Maximum	Mean
211 dB re 1 $\mu Pa^2 s.m$ (maximum level)	170 m	89 m
199 dB re 1 $\mu Pa^2 s.m$ (soft start)	140 m	8.4 m
Source Level (peak)	**Impact range for received level in excess of peak threshold 208 dB re 1 μPa_{pk}**	
	Maximum	Mean
238 dB re 1 $\mu Pa_{pk}.m$ (maximum level)	566 m	317 m
226 dB re 1 $\mu Pa_{pk}.m$ (soft start)	45 m	28 m

Table 7.5. Single impact SEL and peak pressure risk zone estimates for fish species.

Using the peak-to-peak Source Level of 244 dB re 1 $\mu Pa.m_{pk\text{-}pk}$ and 232 dB re 1 $\mu Pa.m_{pk\text{-}pk}$ (soft start) outlined in section 3.3, the peak Source Level s are calculated by subtracting 6 dB. Note: previous studies have shown that peak positive and peak negative pressures for piling noise are on average very similar and approximately 6 dB below peak-to-peak level. Equivalent Peak Source Level s of 238 dB re 1 µPa.m (pk) and 226 dB re 1 µPa.m (pk) are then used to estimate Received Level at a range and depth based on Transmission Loss curves.

Table 7.5 summarises the maximum ranges below which TTS exposure may occur for both the SEL and peak criteria as outlined by Popper. In the case of the SEL criteria, exposure at ranges of less than 170 m can be considered as being at risk to the onset of TTS. This range is extended to 566 m using the peak pressure criteria. Note the maximum ranges presented for onset of a TTS threshold are computed for all ranges and depths for all profiles based on seabed topography and sediment / water acoustic properties and maximum range reported in Table 7.5.

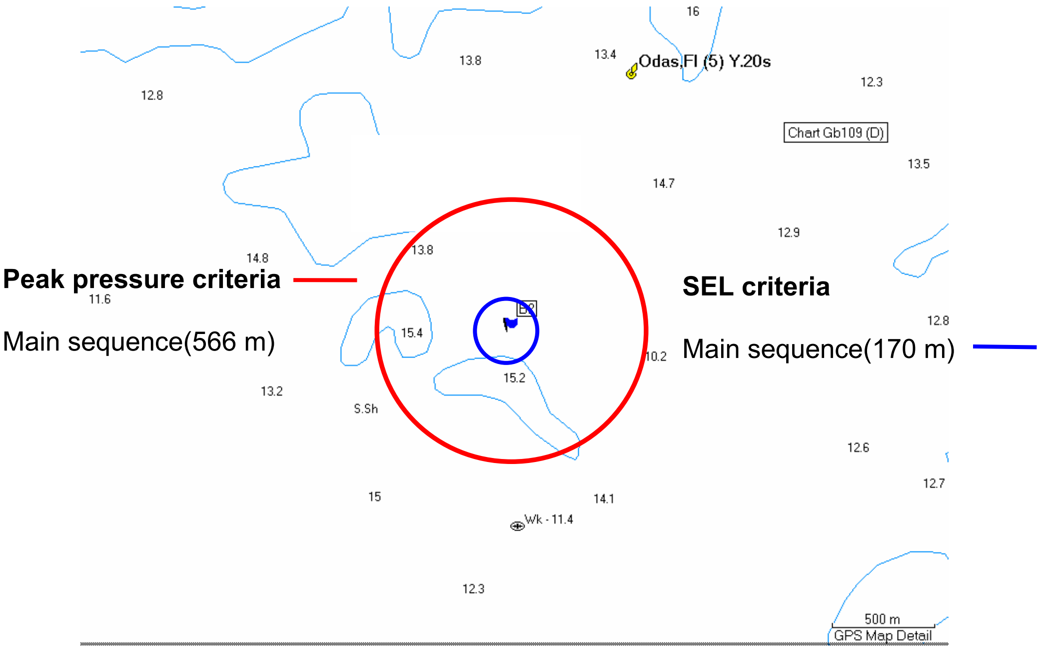

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Figure 7.5 Impact zone prediction for injury criteria for fish, [Popper *et al*. (2006)].

7.3.3 Crustacea

At time of writing, very little data was available on the acoustic impact potential on crustaceans. Pye and Winsor (2004) reported for the American lobster *Homarus americanus,* that immature lobsters of both sexes were able to detect sounds in the range 20 – 1,000 Hz whilst mature lobsters showed two distinct audiometric sensitivity peaks at 20 - 300 Hz and 1,000 – 5,000 Hz. Both mature sexes also emit sounds, particularly in larger adults indicating a potential role in mating behaviour. Based on hearing response for adults particularly in the band 20 – 300 Hz, potential masking effects could occur for this species due to piling noise` emissions. However because the exact nature of the role of these sounds and the relationship to UK species is currently not known, no direct conclusions on acoustic impact could be drawn.

A very recent study [Lovell *et al.* (2007)] claims to be the first audiometric data reported for a prawn (*Palaemon serratus)*. The audiogram for a prawn is given in the range 100 Hz to 3 kHz. No direct conclusions on impact of acoustic emissions on these and other crustacean could be made at this time.

8 BEHAVIOURAL IMPACT ASSESSMENT FOR 6 M DIAMETER PILING OPERATION

8.1 INTRODUCTION

A sound level threshold related to the effect above hearing threshold of an individual species was described by Nedwell *et al*, outlined in [Nedwell *et al*, 2004c]. The dBht (species) level is estimated by applying a species specific filter related to the hearing capabilities of that species. This methodology therefore defines a single number or level to describe the potential effects of sound on that species.

8.2 90 dB_{HT} BEHAVIOURAL RESPONSE CRITERIA

Using a 90 dBht reference level and Transmission Loss profiles outlined in section 5.2 for a 6m pile, range estimates for levels in excess of 90 dB_{ht} for each species were estimated. Figure 8.1 shows both marine mammal and fish species relative perceived Received Level with range. This can be compared with the 90 dB_{ht} level (horizontal dashed line). Range estimates for a behavioural response based on this criterion are then given in Table 8.1. Using this criterion, both cod and herring show a potential behavioural response out to approximately 27 and 24 km respectively. Similarly, the harbour porpoise has a behavioural response range up to a distance of greater than 11 km. The common seal also may show a behavioural response out to around 9 km. The impact zone in relation to the array site for fish species is shown in Figure 8.2. For cod and herring this shows a significant area around the Humber Estuary using a impact zone estimated on a pile in centre of array site. Figure 8.3 shows the impact zones for the various marine mammal species under analysis. In this case, the impact zone for the harbour porpoise extends across the Humber Estuary for a pile in centre of the array. Similarly the impact zone for a common seal extends to within 7-8 km of the seal colony at Donna Nook (shown as blue solid line). If the centre of the impact zone is moved to the closest pile to Donna Nook (South West corner of the array site), this range is reduced to around 5-6 km (shown a blue dashed line).

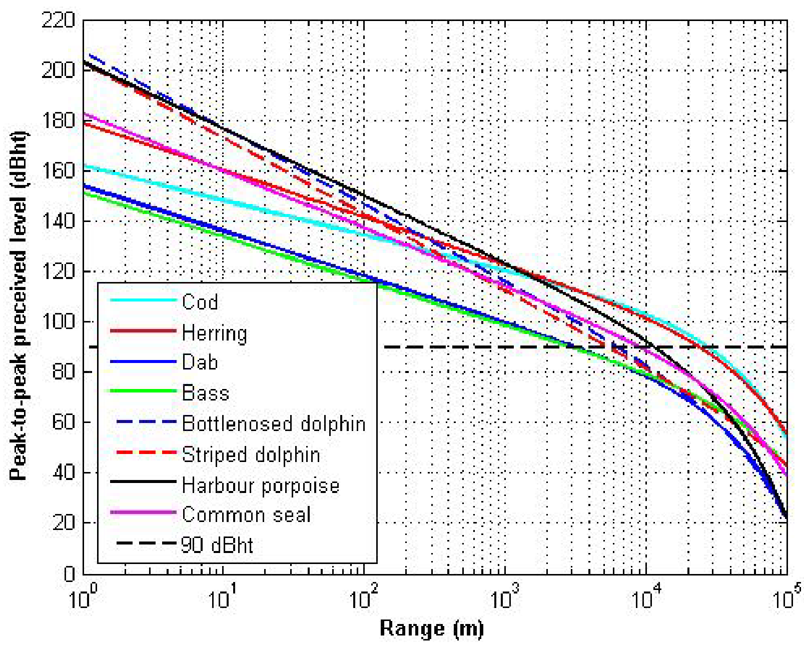

Figure 8.1. Predicted peak-to-peak perceived level (dBht) for marine species from a 6 m piling operation in a deep water site (≥10m).

Species	Peak-to-peak perceived Source Level (dB$_{ht}$ @ 1m) for a 6 m diameter pile	Behavioural Impact 90 dB$_{ht}$ range (km)
Cod (*Gadus morhua*)	162	27.4 km
Herring (*Clupea herengus*)	179	23.8 km
Dab (*Limanda limanda*)	154	3.15 km
Bass (*Dicentrarchus labrax*)	151	2.91 km
Bottlenose Dolphin *(Tursiops Truncates)*	207	6.2 km
Striped Dolphin (*Stenella Coertuleoalba*)	203	5.3 km
Harbour porpoise (*Phocoena phocoena*)	203	11.4 km
Common Seal (*Phoca vitulina*)	183	8.9 km

Table 8.1 Impact range estimates for various marine species.

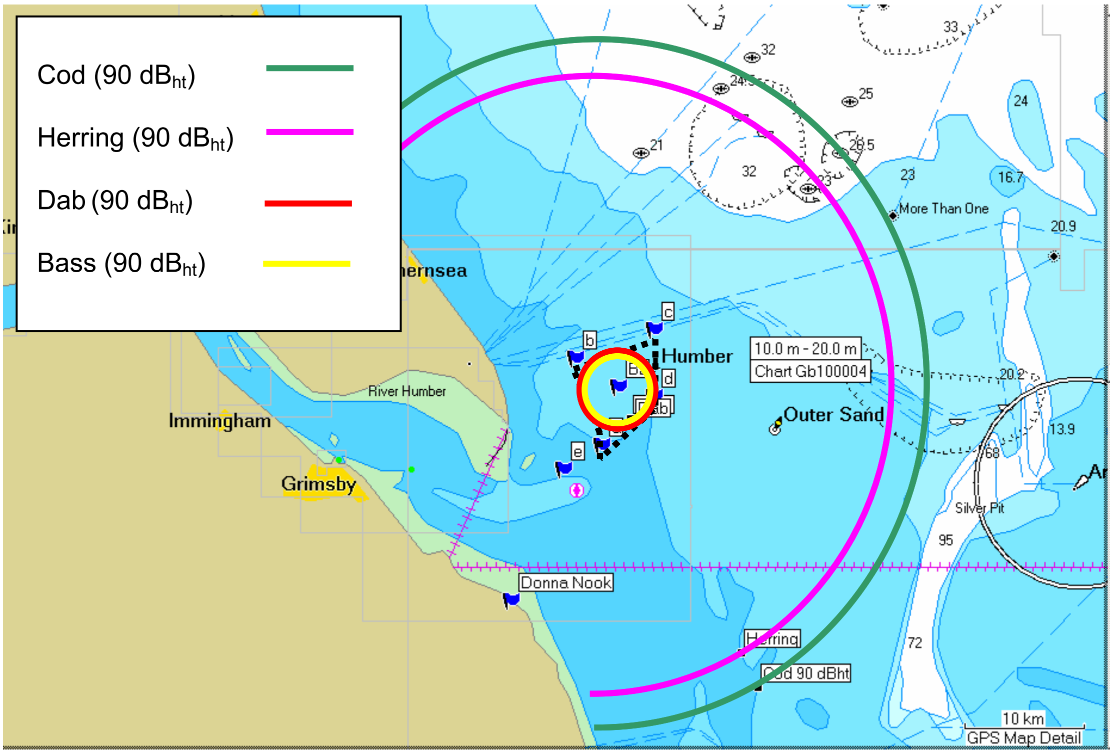

Figure 8.2 Behavioural impact range estimates for various fish species.

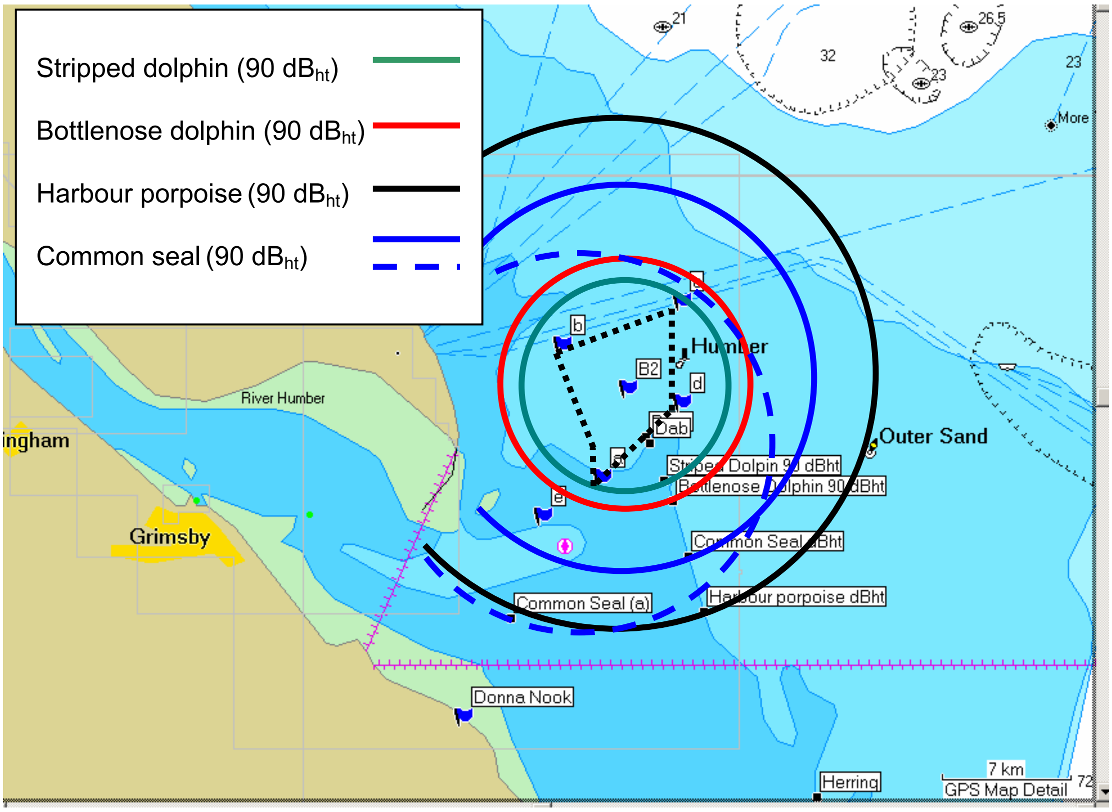

Figure 8.3 Behavioural impact range estimates for various marine mammal species.

8.3 Piling noise to ambient noise comparison for Humber Gateway site

A direct comparison of potential piling noise in relation to ambient acoustic field data was conducted. Figure 8.4 shows the maximum, minimum (blue traces) and mean (red trace) ambient noise measurements across the Humber array site obtained during baseline noise trials conducted in February 2007 (NPL report [DQLAC (RES)017]). The black dashed trace shows a theoretical spectral distribution for piling noise recorded at short range. The curve represents the average short range spectral distribution taken from data obtained from piling measurements at a range of less than 60 m. Note: The shape and distribution of this curve will vary with range particularly at the higher frequencies, with the higher frequency components more readily attenuated at greater distances due to absorption, [Urick, (1983)]. The more dominant low frequency components however are less affected and therefore less attenuated at longer ranges, altering the overall spectral distribution. The spectral levels were then scaled to represent the potential spectral distribution from a 6 m diameter pile using 1,800 kJ hammer energy using the methodology outlined in section 5.3.

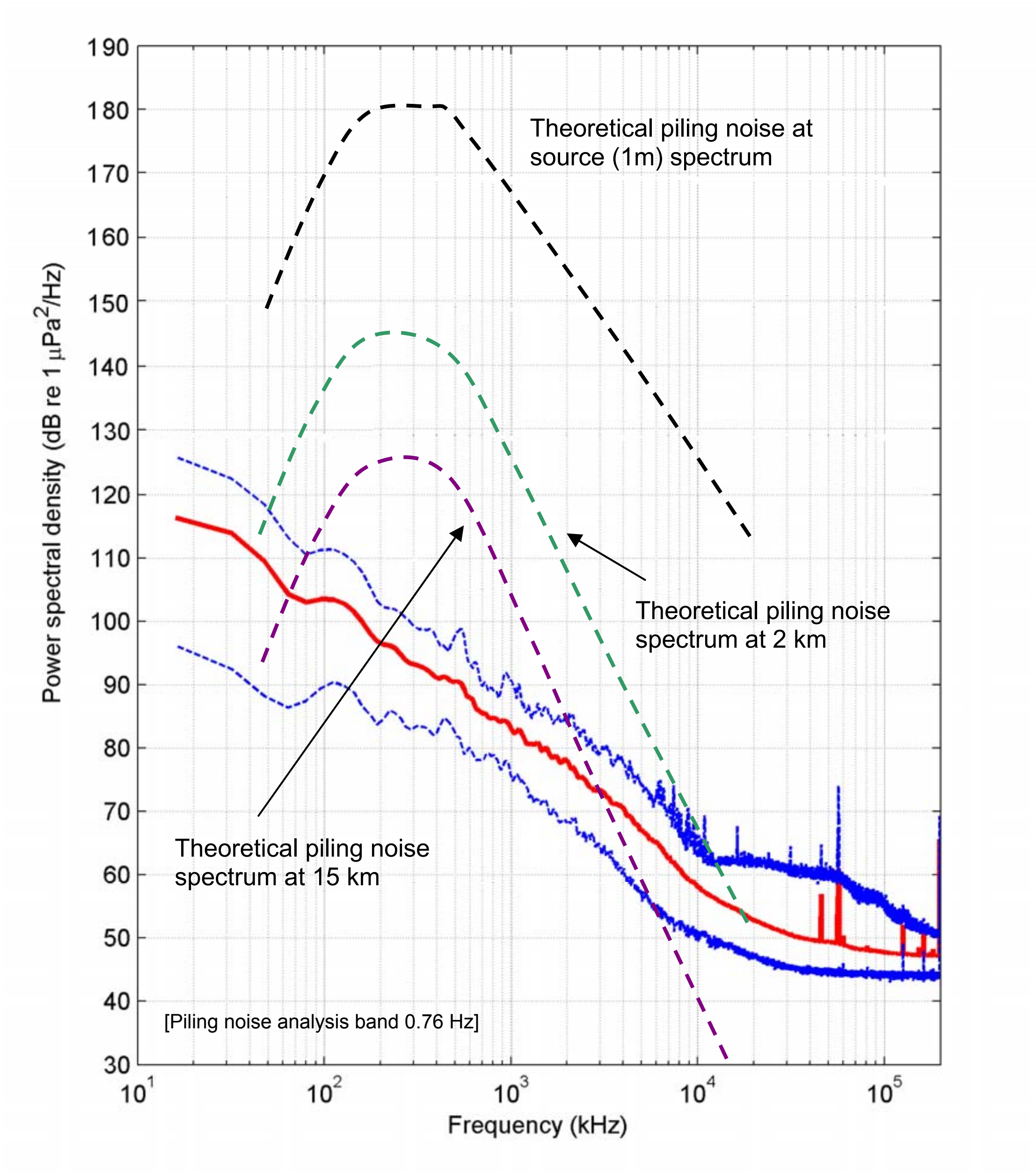

Figure 8.4. Mean (red), maximum and minimum (blue dashed) ambient noise profiles obtained across the Humber array site and theoretical spectral level and distribution (black dashed) of single impact piling noise at source for a 6 m diameter / 1800 kJ hammer energy, theoretical spectral distribution (green dashed) at 2 km from source and theoretical spectral distribution (purple dashed) 15 km from source.

Figure 8.4 shows that the dominant frequency components for driven piling noise at source between 200-500 Hz with theoretical levels 80 - 90 dB above the mean ambient noise floor. At a range of 2 km from source (green dashed trace, Figure 8.4), using Transmission Losses associated with a west-east profile (P12, Figure 6.12), the level at 200 Hz (peak observed frequency) would be around 35 dB lower therefore approximately 50 dB above mean ambient noise in the same frequency band. However higher frequency components (greater than 10 kHz) are below or close to the maximum observed noise in this band across the array site. A west-east profile (away from shore into deeper water) was selected as the worst case, lowest Transmission Loss, greatest Received Level situation. By comparison, the east-west (towards shore) profiles, for example P4, Figures 6.8 – 6.9, show similar Transmission Losses to the westerly profiles up to range of around 5 km with greater Transmission Losses, meaning lower Received Levels at higher ranges due to increased sediment interaction and beaching effect.

At 15 km, using a westerly profile the higher frequency components (> 10 kHz) are below the equivalent ambient noise in this band at the array site. In this case the peak (200 Hz profile) is now around 27 dB above mean ambient in the same band. By comparison, piling noise components in the band close to 400 Hz are approximately 35 dB above the equivalent ambient noise band, due to the increase in ambient noise towards lower frequencies. Both profiles (2 km and 15 km) show a higher attenuation at higher frequencies due to absorption effects. At ranges from 2 km onwards piling noise components at frequencies greater than 2 kHz are below the mean ambient noise distribution across array site. It should however be noted that the ambient noise is based on the Humber array site and therefore may not fully represent ambient noise at greater ranges. However the ambient noise measurements made towards the Donna Nook seal colony (Figure 4.13, (NPL report [DQLAC (RES)017])) at a range of 11.1 km from the most southerly tip of the array site, shows a very similar noise profile to the array site for noise in bands greater than 500 Hz. Levels potentially slightly higher (5 dB) were however observed in the band 100-300 Hz reducing the difference between piling noise components and the baseline noise levels in the same band.

9 UNCERTAINTY ANALYSIS

9.1 BACKGROUND

Analysis of uncertainty is a well established discipline with standard procedures [BIPM 1995]. However, in making an estimate of the noise radiated by a proposed piling operation, there are potentially large sources of uncertainty which are difficult to quantify. This makes it very difficult to ascribe uncertainty error bars to the predictions. However, it is valuable to consider the sources of uncertainty and attempt to make crude evaluations so that broad bounds may be placed upon the estimates.

There are two general classes of uncertainty. Type A uncertainty is sometimes described as the “random uncertainty” and may be assessed by making related measurements of a quantity and examining the statistical spread in the results. Type B uncertainty is sometimes referred to as the “systematic uncertainty” and represents the potential for systematic bias in a measurement (for example caused by incorrect instrument calibration).

9.2 SOURCES OF UNCERTAINTY

There are considerable sources of uncertainty in making an estimate of the noise radiated from marine piling. The process of assessing impact involves several steps: (i) estimating the Source Level from previous reported measurements and any scaling factors applied; (ii) calculating the Transmission Loss using a propagation model; (iii) calculating the metrics used to quantify the biological effect, including accounting for the hearing sensitivity of the animal; (iv) establishing the threshold to be used for the biological effect to become important.

9.2.1 Source Level estimate

<u>Accuracy of previous measurements</u>

The estimates of Source Level are predicated upon the measurements made of the Source Level in previous studies. Unfortunately, the previously reported measurements are rarely accompanied by uncertainties. In the measurements by Robinson and Lepper (2007), values of 230 ± 6 dB re 1 μPa at 1 m were reported. However, here the uncertainty was increased due to the small number of measurement ranges possible in the night-time study. It may be possible to improve upon this Figure, but 6 dB seems a reasonable estimate to take.

The accuracy of the Source Level measurement inevitably depends upon the accuracy of the hydrophone and instrumentation calibration. However, there is also a strong dependence on the propagation model adopted when deriving the Transmission Loss to obtain the effective pressure level at 1 m range. This is a critical factor, the accuracy of which is rarely considered. For example, in the report by Parvin *et al* (2006), two different lumped parameter models are used (with and without a term for absorption) which lead to differences of between 13 dB and 29 dB in the estimated Source Level (for measurements at North Hoyle and Kentish Flats respectively). This illustrates the need to use the most accurate model available, subject to the availability of sufficient data on the local environment.

<u>Scaling factor for pile size</u>

The source in the case of marine piling is very complex, with noise being radiated from the surface of the pile itself, and with noise also being launched directly into the sea-bed by the impact of the pile through the sediment. Currently, a good model does not exist for such a complex distributed source, and representations of the source in terms of simplified idealised sources such as point sources and line sources is likely to limit the accuracy of predictions. This is particularly true for the acoustic field close to the pile (in the near-field), and possibly for greater ranges where sound propagating through the sea-bed re-enters the water column.

Examination of the previously measured data for both UK windfarm sites and other international sites is not sufficient to develop a robust empirical relationship between pile size (diameter) and Source Level . This is because each of the previous studies has been undertaken in different locations, with different sea-bed types, environmental conditions, water depths and hammer energies. This does not constitute a systematic study of the dependency on pile size since these other influential parameters are also varying, and some of these parameters are simply not reported in the studies.

In this report, the approach of Parvin et al (2006) has been adopted in order to facilitate comparison with previous studies. This leads to a scaling factor of approximately 5 dB and it is likely that the uncertainty would be of the same order. To better understand the process, some further research work to develop a physical model of the noise generation mechanism during marine piling is highly desirable.

Hammer energy

Perhaps unsurprisingly, the greater the energy of the hammer blow, the more acoustic energy is launched into the water and the sea-bed. Robinson and Lepper (2007) show a roughly linear relationship between acoustic pulse energy and hammer energy over a soft start period. However, to use this predicatively is not straightforward since the relationship is with pulse energy and not peak pressure. Nevertheless, this should not be a major source of uncertainty (perhaps contributing 2 dB).

9.2.2 Propagation models

The accuracy of the propagation model will have a major influence on the overall uncertainty in the prediction. In general, a lumped parameter model conforming to the general type "RL=S–N.log(r)– α.r" will have limitations in some applications since it cannot deal with dependence on acoustic frequency, sea-bed properties, and bathymetry (depth). This is discussed further in Section 2.4.3. For the shallow water environments encountered in the area of the Humber estuary, the numerically modelled mode approach has the potential to provide good accuracy since it can be made to incorporate the effects of variable bathymetry, sound speed profiles and frequency dependent absorption. However, such models have disadvantages in that they require a large amount of input data to describe the bathymetry, sound speed profiles, and sediment properties in the local area. Such information may not be available, and any model is only as accurate as its input data. Time domain models (such as finite difference models) are also good candidate models, but again they require input data as for the modal approach. The more sophisticated models have been shown to have reasonably high accuracy if the input data is good, but this is not always available, and a compromise must usually be made.

In addition, extra uncertainty is generated by the fact that the conditions surrounding the site may change with time due to currents, tides, seasons, etc. This makes the Transmission Loss estimates even more uncertain, with ball-park uncertainty values of anything from 3 dB to 30 dB possible depending on the model chosen, availability of input data, and variability of parameters such as bathymetry and sea-bed type in the area.

9.2.3 Metrics

The frequency weighting used in the metrics will inevitably suffer from some uncertainty. There should be relatively little uncertainty in the calculation of the parameters themselves. However, the audiometric data which underpins the metrics will have considerable uncertainty. Indeed, audiograms do not exist for all species that may be affected. Parvin *et al* (2006) and Nedwell *et al* (2004) present a good discussion of this issue with specific reference to the dB_{ht} metric, concluding that errors of between 10 dB and 30 dB are possible depending on the species and the frequency. In some cases, there are various “rival” audiograms which disagree, requiring one to be selected. In other cases, a species without an audiogram may require a “surrogate” species to be substituted. Although attempts are made to mimic the dB(A) metric used for humans, insufficient information is available for this to be done with high accuracy (for example, no equivalent of the 40 phon loudness curve is available for marine species).

In the case of the M-weighting proposed by the noise criteria group, the attempt is to use an equivalent of a dB(C) human metric which has been used for assessing the effect of high level noise. Here the audiogram data is aggregated into classes of animal with four basic categories presented each with an audiogram [Southall *et al* (2007)]. The use of these standard weightings removes the conflict between alternative audiograms and standardises the methodology. However, by using classes of animal instead of individual species, errors may be introduced if a species is an outlier in the distribution of audiograms.

9.2.4 Thresholds

The choice of effect threshold clearly has a bearing on the accuracy of the estimate of biological effect since the level chosen may not be accurate for a given species, and the levels must be chosen on limited evidence. Choosing a threshold based on species-specific information on the animal hearing (audiogram data) clearly has merit, particularly for behavioural effects. However, the choice of level is still a difficult problem. Various levels have been suggested [Southall *et al* (2007), NMFS (2003), NOAA (2006), Nedwell *et al* (2006), Parvin *et al* (2006)]. The 90 dBht level has been shown to have some validity for fish [Nedwell (2007b)] but has a much weaker correlation with mammal behaviour. The error from choosing an inappropriate threshold level will depend on the species, but could be anything from 5 dB to 20 dB.

10 SUMMARY

A study has been undertaken to predict the likely acoustic field produced by marine piling to during construction of the proposed Humber Gateway offshore windfarm, and its likely effect on marine life. The study assumes a 6 metre diameter pile is used. Two methodologies have been implemented. The first (Methodology 1) follows the approach adopted for some previous studies of this type, in particular that of Parvin et al 2006 (work conducted by Subacoustech Ltd for the Thames Developers' Consortium). The second approach (Methodology 2) uses a different methodology for injury criteria based on SEL metrics and thresholds used more frequently outside the UK.

The results from methodology 1 reported here were chosen to follow the approach adopted for a previous UK study of this type, that of Parvin *et al* 2006 (work conducted by Subacoustech Ltd for the Thames Developers' Consortium). It should be noted that this should not be taken as an indication that the authors believe other approaches are inferior, each methodology has strengths and weaknesses. The decisive factor in the choice of the inclusion of this methodology in this report was the desire of the customer to have direct comparability with previous UK studies.

Estimates of maximum range from source for instantaneous Received Level and accumulated exposure (fleeing animal model) were then made around the site for various risk threshold levels. The various criteria used are derived from the best available scientific knowledge for various marine species and where appropriate, can be compared with previously assessed impact zones from other UK windfarm sites. Zones of risk or range from source estimates are then given for each of these risk criteria for cetaceans, pinnipeds and fish species.

For Methodology 1, a scaling factor estimate for Source Level is derived using an empirical model based on previous measurements of acoustic radiation from construction for various pile diameters. In this way, a Source Level estimate may be made for a 6 metre diameter pile (currently no measurements are available for such a pile). These Source Level estimates are then applied to simple "lumped-parameter" geometrical Transmission Loss models to allow estimation of potential Received Levels at ranges from the source. Frequency weightings are applied to the Received Levels to account for the hearing variation in specific species using the dB_{ht} metric. The threshold criteria applied for injury and behavioural effects are those used in the previous studies, [Parvin *et al* (2006)].

Using Methodology 1,a peak-to-peak Source Level at the Humber Gateway site for 6 m diameter pile was found to be 256 dB re 1µPa .m.

Using Methodology 2, a Source Level scaling factor estimate for a 6 metre pile is derived taking into account both pile size and hammer energy used. Transmission Loss profiles are then estimated using a more sophisticated distributed numerical model based on the Parabolic Equation. These Transmission Loss profiles take into account seabed topography, sediment and water column acoustic characteristics, and were evaluated on multiple bearings and start positions. These profiles were selected using, as a source, the closest individual pile appropriate in each profile bearing to allow worst case assessment of the field around the entire array for all pile construction. The two dimensional range-depth Transmission Loss profiles then became the basis of estimated Received Level field around the array during full-scale construction. This analysis showed that the typical Transmission Loss profile was well modelled using a parabolic equation numerical model solution. This Transmission Loss is felt to more accurately model real conditions around the array site than application of simpler spreading and absorption model due to the extra consideration given to the effects of sediment absorption, shallow-water approaches to land and sub-surface sandbars.

Using Methodology 2, a likely hammer energy of 1,800 kJ for a 6 m diameter pile was assumed and an extrapolation was made based on results for different pile diameters, and known hammer energies, from previous studies. This data and analysis of previous studies was then used to make a Source Level estimate of 244 dB re 1 µPa.m (peak-to-peak) and 211 dB re 1 µPa²s.m (Sound Exposure Level). Soft start Source Level s of 232 dB re 1 µPa.m (peak-to-peak) and 199 dB re 1 µPa²s.m (Sound Exposure Level) were estimated for a 12.5 dB reduction in hammer energy from 1,800 to 100 kJ. These levels were then applied to the Transmission Loss profiles around the array site allowing estimation of Received Levels in both range and depth. Comparisons were then made with baseline ambient field measurements conducted across the array site and in a location towards Donna Nook. At peak level frequency of 200 Hz theoretical levels of 85 dB above mean ambient noise were estimated. At an off-shore range of 15 km this level is reduced to 27 dB above the mean ambient noise in the same band. Frequency components in the band close to 400 Hz remain around 35 dB above mean ambient noise level in the same band.

Results for Methodology 1

Injury criteria: Methodology 1: (Subacoustech Ltd)

To allow comparison with auditory injury criteria from previous studies the methodologies outlined by Parvin *et al* (2006) were implemented to calculate a time varying levels in dB_{ht} for a species. This is then used to calculate a continuous equivalent level dB_{ht} Leq. Parvin *et al* then use a singe strike injury criteria of 130 dB_{ht} Leq. For repetitive sounds over a 5 hour period this level is adjusted to equivalent noise dose of 92 dB_{ht} Leq [Parvin *et al* (2006)].

Figure 10.1 shows the equivalent continuous sound level (dB_{ht} Leq) for a deep water site for a 6.0 m pile for a deep water site. Data taken from Barrow site, [Parvin *et al* (2006)], then adjusted from 6.5 m to 6.0 m pile diameter using methodologies outlined in section 6.2. The auditory injury predicted ranges for each species are shown in table 10.1 based on the 92 dB_{ht} Leq criteria. In this case auditory injury for both herring and cod could occur out to ranges 1.7 and 1.53 km respectively and the harbour porpoise to 1.6 km. The bottlenose dolphin however has a lower impact range of 435 m. Also using the criteria, the impact range for a harbour seal is around 253 m. To conform to the procedure in Parvin *et al* (2006), the above predictions assume no fleeing animal response and identical "above-hearing" injury thresholds for each animal (130 dB_{ht} or 92 dB_{ht}, the dB_{ht} metric already accounting for the audiogram of the animal).

Species	Peak-to-peak perceived Source Level (dB_{ht} @ 1m) for a 6 m diameter pile	Auditory injury range (92 dB_{ht} Leq) (km)
Cod (*Gadus morhua*)	162	1.53 km
Herring (*Clupea herengus*)	179	1.7 km
Dab (*Limanda limanda*)	154	0.184 km
Bass (*Dicentrarchus labrax*)	151	0.046 km
Bottlenose Dolphin *(Tursiops Truncates*)	207	0.435 km
Striped Dolphin (*Stenella Coertuleoalba*)	203	0.448 km
Harbour porpoise (*Phocoena phocoena*)	203	1.6 km
Harbour Seal (*Phoca vitulina*)	183	0.253 km

.Table 10.1 Summary of auditory injury range for a 6.0 m diameter piling operation in a inshore deep water site based on methodologies outlined by Pavin *et al.* (2006).

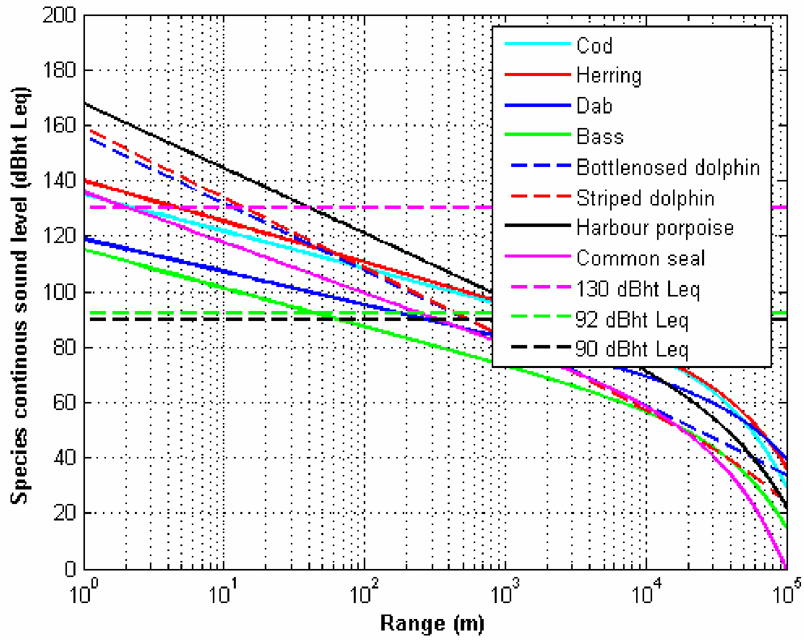

Figure 10.1 Predicted equivalent sound level (dB_{ht} Leq) with range for a 6.0 m pile diameter in a deep water inshore site.

Behavioural criteria: Methodology 1: (Subacoustech Ltd)

Using a 90 dBht reference level and Transmission Loss profiles outlined in section 8.2 for a 6m pile, range estimates for levels in excess of 90 dB_{ht} for each species were estimated. Figure 10.2 shows both marine mammal and fish species relative perceived Received Level with range. This can be compared with the 90 dB_{ht} level (horizontal dashed line). Range estimates for a behavioural response based on this criteria are then given in table 10.2.

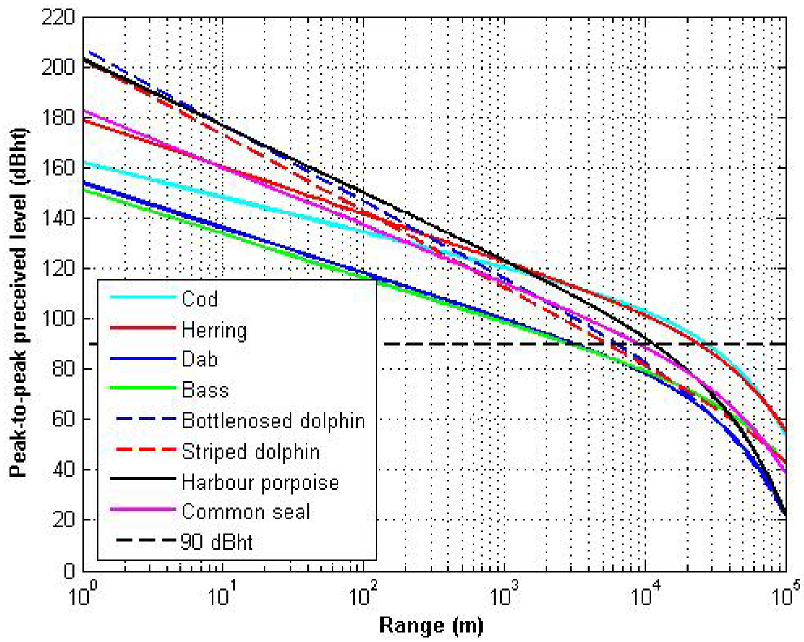

Figure 10.2. Predicted peak-to-peak perceived level (dBht) for marine species from a 6 m piling operation in a deep water site (≥10m).

Species	Peak-to-peak perceived Source Level (dB$_{ht}$ @ 1m) for a 6 m diameter pile	Behavioural Impact 90 dB$_{ht}$ range (km)
Cod (*Gadus morhua*)	162	27.4 km
Herring (*Clupea herengus*)	179	23.8 km
Dab (*Limanda limanda*)	154	3.15 km
Bass (*Dicentrarchus labrax*)	151	2.91 km
Bottlenose Dolphin (*Tursiops Truncates*)	207	6.2 km
Striped Dolphin (*Stenella Coertuleoalba*)	203	5.3 km
Harbour porpoise (*Phocoena phocoena*)	203	11.4 km
Harbour Seal (*Phoca vitulina*)	183	8.9 km

Table 10.2 Behavioural impact range estimates for various marine species.

Table 10.2 shows the potential behavioural impact based on the 90 dB$_{ht}$ (species) criteria for marine mammal species out to around 11.4 km for the harbour porpoise and 6.2 km for the bottlenose dolphin. Similarly for the harbour seal, a potential impact range exists out to around 9 km Taking the most south-westerly pile position, this impact zone is potentially within 5-6 km of the Donna Nook seal colony. For various fish species a wide range of potential impact zones are observed range from 3 km for bass to in ~24 km for herring and 27 km for cod. The later cases would cover a potential impact zone for this criteria ranging across the Humber Estuary.

Results for Methodology 2

Injury criteria: Methodology 2:

Two main marine mammal groups are considered cetacean and pinnipeds. In the case of cetaceans, the bottlenose dolphin and harbour porpoise are consider species of interest and harbour and grey seal for pinnipeds. Tables 10.3 and 10.4 below summarise the various impact ranges for various criteria.

In the case of the harbour porpoise Received Levels in excess of Permanent Threshold Shift (PTS) threshold for a single impact would not be achieved on any profile in range or depth and Temporary Threshold Shifts (TTS) could only occur at a maximum range of less than 32 m for a single impact based on the NMFS criteria.

In addition, an accumulated exposure model was implemented taking into account the summed effects of successive hammer strikes and a geometrical spreading loss for attenuation over range. In this case, estimates of maximum starting ranges required for an animal to avoid TTS and PTS thresholds for a certain number of hammer strikes were made. In the case of 4,000 hammer strikes and a Source Level of 211 dB re 1 μPa^{2}s.m analysis showed a TTS threshold of 195 dB re 1 μPa^{2}s can be avoided for ranges from source of greater than 3 m. This model includes at Source Level ‘soft start’ and allows the animal to move away from the source at a constant rate (i.e. swim speed). The PTS threshold would not be exceeded at this Source Level with a soft-start in the above scenario of 4,000 strikes.

In the case of pinnipeds, identical accumulated exposure models were run for a lower 183 dB re 1 μPa^{2}s TTS threshold, [(Kastak 2005)]. For 4,000 hammer strikes, the TTS threshold would be exceeded at starting ranges of less than 4.02 km. An at risk (TTS) zone of less than 3 m from source could be achieved under the same conditions if the effective Source Level was lowered by 11 dB. These models illustrate the relative differences made in changes in Received Level by movements made close to the source (away from the source) compared to movement at greater ranges in the same direction and duration.

Marine Mammals NMFS (2006) / Kastak *et al,* (2005) Injury criteria (PTS TTS)		
Single impact for all Transmission Loss profiles		
	Threshold	Range
Bottlenose dolphin	SEL 215 (dB re 1 μPa^{2}s (PTS)) (NMFS 2006)	Not exceeded
Bottlenose dolphin	SEL 195 (dB re 1 μPa^{2}s (TTS)) (NMFS 2006)	32 m
Harbour porpoise	SEL 215 (dB re 1 μPa^{2}s (PTS)) (NMFS 2006)	Not exceeded
Harbour porpoise	SEL 195 (dB re 1 μPa^{2}s (PTS)) (NMFS 2006)	32 m
Accumulated exposure fleeing animal model 4,000 hammer strikes with ‘soft start’ (1.5 ms^{-1} swim speed)		
	Threshold	Range
Bottlenose dolphin	SEL 215 (dB re 1 μPa^{2}s (PTS)) (NMFS 2006)	Not exceeded
Bottlenose dolphin	SEL 195 (dB re 1 μPa^{2}s (TTS)) (NMFS 2006)	3 m
Harbour porpoise	SEL 215 (dB re 1 μPa^{2}s (PTS)) (NMFS 2006)	Not exceeded
Harbour porpoise	SEL 195 (dB re 1 μPa^{2}s (TTS)) (NMFS 2006)	3 m
Harbour Seal	SEL 183 (dB re 1 μPa^{2}s (TTS)) [Kastak *et al,* (2005)]	4,020 m
Grey Seal	SEL 183 (dB re 1 μPa^{2}s (TTS)) [Kastak *et al,* (2005)]	4,020 m

Table 10.3. Injury criteria SEL risk zone estimates for marine mammal species for a 6 m diameter pile.

In the case of fish species, a dual energy and peak level criteria were used. At full hammer energy (1,800 kJ), a single impact maximum zone of risk (TTS) is defined for distances less than or equal to 170 m for a single impact energy-based criteria. The zone of risk was extended to 566 m using a peak pressure threshold, table 10.4. The threshold used is based on studies of various fish species. A discussion on hearing responses of two crustacean species is provided. Both species have hearing capabilities in the acoustic emission range of the piling noise but no direct conclusions on acoustic impacts for local crustacean species could be drawn at this time.

Source Level (SEL)	Impact range for Received Level in excess of SEL threshold 187 dB re 1 µPa^{2}s for fish species	
	Threshold	Range
211 dB re 1 µPa^{2}s.m (maximum level)	SEL (187 dB re 1 µPa^{2}s)	170 m
Source Level (peak)	Impact range for Received Level in excess of peak threshold 208 dB re 1 µPa$_{pk}$ for fish species	
	Threshold	Range
238 dB re 1 µPa$_{pk}$.m (maximum level)	(208 dB re 1 µPa$_{pk}$)	566 m

Table 10.4. Injury criteria SEL and peak pressure risk zone estimates for fish species for a 6 m diameter pile.

Piling / ambient noise comparison

Figure 10.3 illustrates that the dominant frequency components for driven piling noise at source between 200-500 Hz with theoretical levels 80 - 90 dB above the mean ambient noise floor. At a range of 2 km from source using Transmission Losses associated with a west-east profile (P12) the level at 200 Hz (peak observed frequency) would be around 35 dB lower therefore approximately 50 dB above mean ambient noise in the same frequency band. Higher frequency components (greater than 10 kHz) are below or close to the maximum observed noise in this band across the array site. A west-east profile (away from shore into deeper water) was selected as the worst case, lowest Transmission Loss, greatest Received Level situation. By comparison, the east-west (towards shore) profiles, for example P4, shows a similar Transmission Losses to the westerly profiles up to range of around 5 km with greater Transmission Losses, meaning lower Received Levels at higher ranges due to increased sediment interaction and beaching effect.

At 15 km, using a westerly profile the higher frequency components (> 10 kHz) are below the equivalent ambient noise in this band at the array site. In this case, the peak (200 Hz profile) is now around 27 dB above mean ambient in the same band. By comparison, piling noise components in the band close to 400 Hz are approximately 35 dB above the equivalent ambient noise band due to the increase in ambient noise towards lower frequencies. Both profiles (2 km and 15 km) show a higher attenuation at higher frequencies due to absorption effects. At ranges from 2 km onwards, piling noise components at frequencies greater than 20 kHz are below the mean ambient noise distribution across array site. It should however be noted that the ambient noise is based on the Humber array site and therefore may not fully represent ambient noise at greater ranges. However the ambient noise measurements made towards the Donna Nook seal colony (Figure 4.13, (NPL report [DQLAC (RES)017])) at a range of 11.1 km from the most southerly tip of the array site shows a very similar noise profile to the array site for noise in bands greater than 500 Hz and levels potentially slightly higher (5 dB) in the band 100-300 Hz reducing the difference between piling noise components and the baseline noise levels in the same band.

This report presents best current knowledge at time of writing and established methodologies to provide an estimate of potential impact for various marine species for a 6 m piling operation on the Humber Gateway windfarm site. The report includes various methodologies providing detailed analysis of the potential sound field around a piling operation and comparison of this predicted field with various impact exposure criteria for cetaceans, pinnipeds and fish species. These criteria are then used to estimate zones of impact for various marine species around the array site. Analysis is also provided on the relationship of likely piling noise in relation to measured ambient noise for the site and likely effects with increasing range and uncertainty analysis of the various results presented.

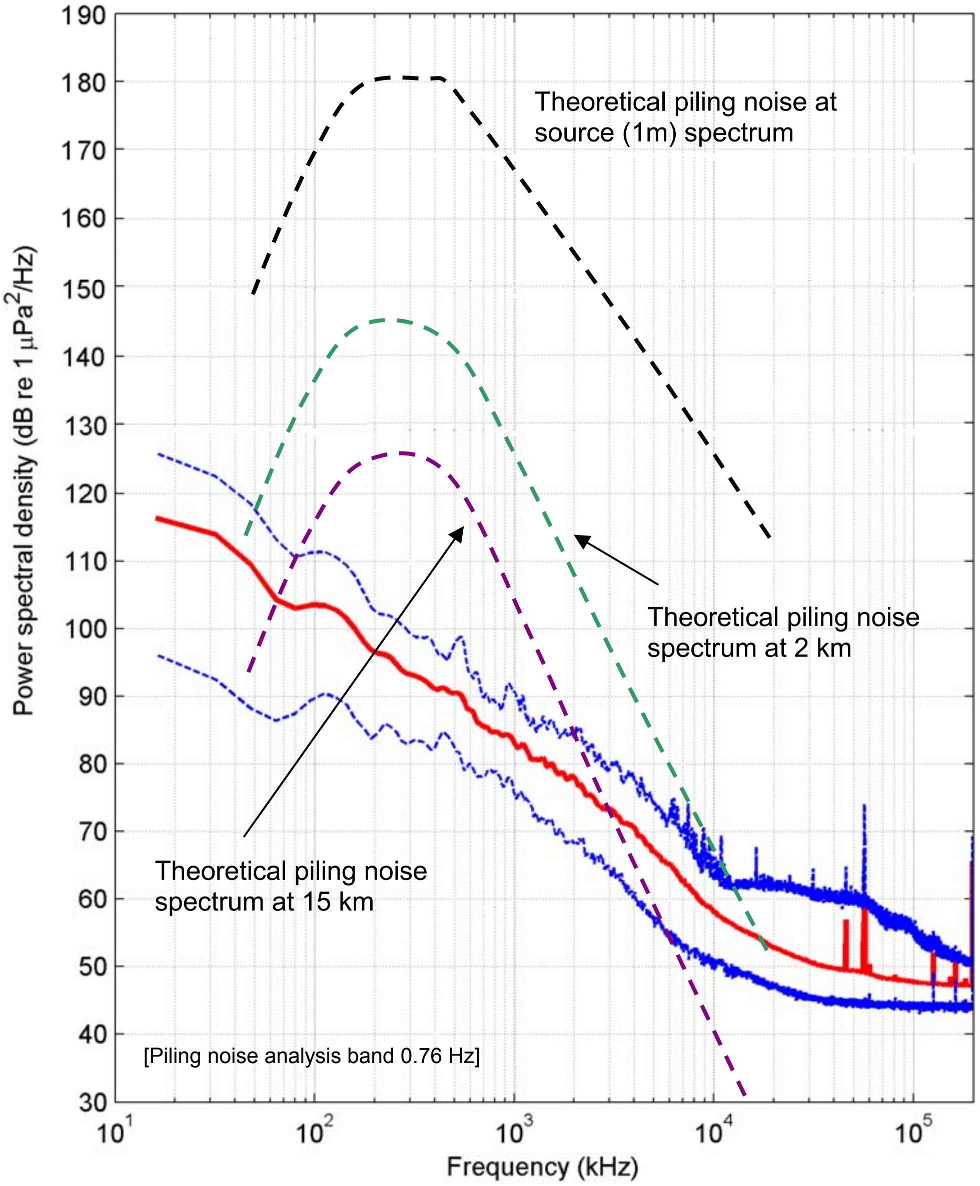

Figure 10.3. Mean (red), maximum and minimum (blue dashed) ambient noise profiles obtained across the Humber array site and theoretical spectral level and distribution (black dashed) of single impact piling noise at source for a 6 m diameter / 1,800 kJ hammer energy, theoretical spectral distribution (green dashed) at 2 km from source and theoretical spectral distribution (purple dashed) 15 km from source.

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